Introduction

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Overhead Lines look back to a long history from the first AC transmission in 1891 with 15 kV, Figure 1.1, to the 1000 and 1200 kV AC lines of today, Figure 1.2. This unique and this exciting development has been tracked and supported by Cigré in general and the Study Committee for Overhead Lines in particular. Chapter 2 "History of Overhead Lines in Cigré" describes in detail this successful "partnership". From its very beginning in autumn 1921 Cigré aimed to provide a forum for technical studies on the generation, transmission and distribution of electric energy. In this sense Cigré brought together, on one hand, equipment manufacturers and operators of power plants and transmission lines and electric energy producers, consultant engineers and engineers of major public administration bodies on the other. In addition 1931, coincidentally the year the Study Committee of Overhead Lines was established, Cigré put in place a monthly journal named "Electra", which is still the printed (today also the electronic) voice of the association. It is at the least remarkable, that in 1946, Cigré was the first technical organization in the world which organized an international conference and brought together worldwide experts who had the enormous task to rebuild electrical infrastructure after the perils of the second world war. In 2000 as another landmark and as a key element in the new approach to communication, the "Conference des Grands Réseaux Électriques à haute tension" became the "Conseil International des Grands Réseaux Électriques", that it changed from a "Conference" to a "Council" and its scope was extended also to lower voltages. At the same time the areas covered by Cigré's field of action were redefined. Cigré now covers not only conventional technical expertise but also economic and environmental aspects.

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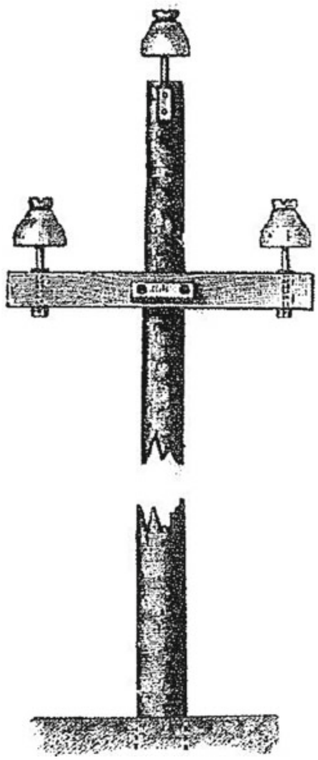


Figure 1.1 Wood pole of the first 15 kV AC line between Lauffen/Neckar to Frankfurt/Main (1891).

An Overhead Transmission Line is a very complex structure often spanning thousands of kilometers, crossing different weather zones and being subject to huge electrical, mechanical and environmental stresses. Because of this it is very important that in the management of a transmission line from conception to decommissioning to realize the nature of the line as a device (or system) and to ensure management structures do not compromise any aspect of the life cycle. Chapter 3 "Planning and Management Processes" covers the various management concepts that should be employed as well as the processes for line design, construction and maintenance.

The following Chapters of the book cover many of these processes in detail. For instance Chapter 4 on "Electrical Design" contains all the basic information needed for the electrical design of a transmission line. Subjects covered include such diverse topics such as Surge Impedance and Surge Impedance Loading, Insulation Coordination, Electric and Magnetic Fields and also Electric Parameters of DC Lines which show the breadth of knowledge required for the proper design of a line. Specific emphasis is given to the importance of the natural power as a key design factor. Especially nowadays with the advent of HTLS (High Temperature Low Sag) conductors it is worth to remember that their higher thermal capacity cannot be utilized except for relative short lines, Figure 1.3. Also the aspects of proper grounding of transmission line towers, eminently important for personal safety, as well as the issues of insulation coordination and Corona are given the place they deserve. Finally the increasing use of DC-lines for long distance transmission is adequately and in detail addressed.

Figure 1.2 1200 kV AC line at Bina test station in India (Photo: Alberto Pigini).

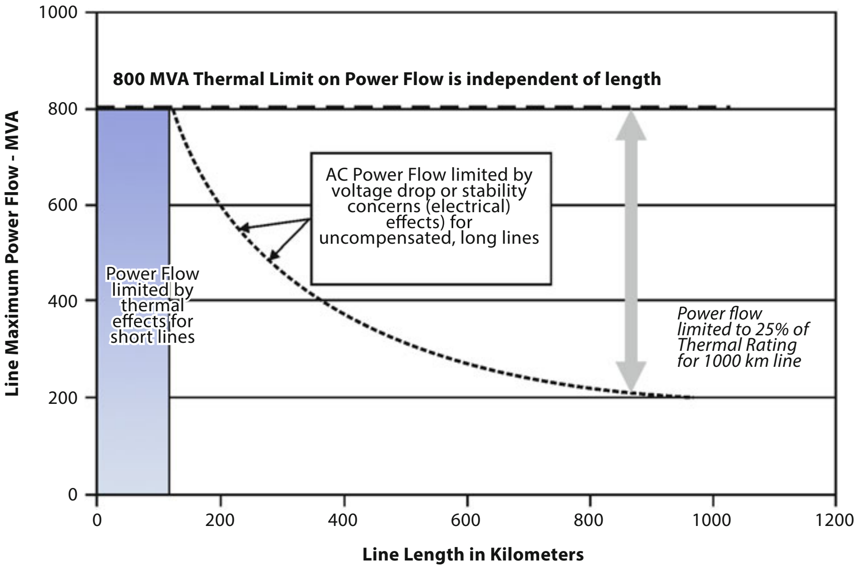


Figure 1.3 300-400 kV Transmisison Line max Power Flow dependence on length.

Overhead Transmission Lines are insofar unique, as they encompass mechanical design issues of equal importance, and research interest, as the electrical issues above. "Structural and Mechanical Design" is thus the focus of Chapter 5. This Chapter is an excellent example on the pursuing of new venues by Cigré and also on the cooperation between Cigré and other leading international organizations, in this case IEC, a strategy successfully pursued up to these days. The subject is reliability based design (RBD), an issue started in Cigré more than 40 years ago under the auspices of Study Committee 22, the predecessor of SC B2. Further technical development was pioneered by a joint effort between Cigré and IEC leading to a milestone in 1991 when IEC 8261 entitled "Loading and Strength of Overhead Lines" was published, introducing reliability and probabilistic concepts for calculation of loading and strength requirements for overhead line components Figure 1.4, a major improvement compared to deterministic methods and nowadays widely used worldwide. A good part of Chapter 5 deals extensively with the calculation of meteorological loads on line structures notably wind and ice loads, followed by an explicit calculation or tower top and mid-span clearances, demonstrating nicely the already mentioned multidisciplinary nature of a line, as the clearances are significant for the proper electrical functioning of the line. The Chapter concludes with quite a specific subject, i.e. the design and use of load control devices for containing possible cascade failures and explains the influence of line parameters on line security.

Chapter 6 "Environmental Issues" is, in addition to providing very valuable information on this nowadays very central subject, a good example of the interdisciplinary way Cigré works, as it encompasses important input from other Study Committees, notably SC C3 (System Environmental Performance). Overhead Lines and environmental issues and their interaction have been under consideration within Cigré for many years. In this sense the issues covered in this chapter range from permit

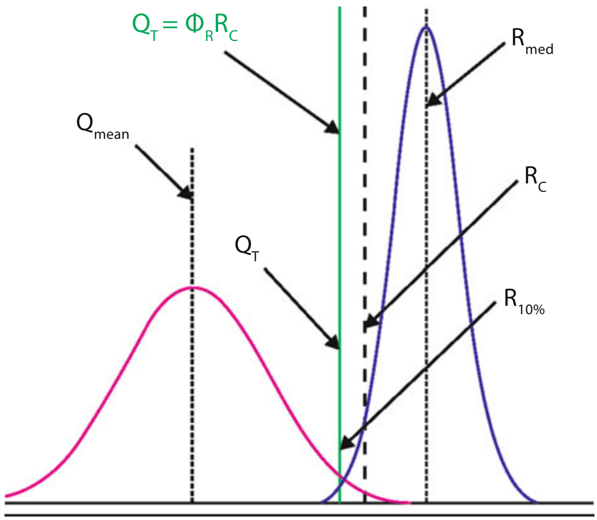


Figure 1.4 IEC 60826 reliability based design philosophy.

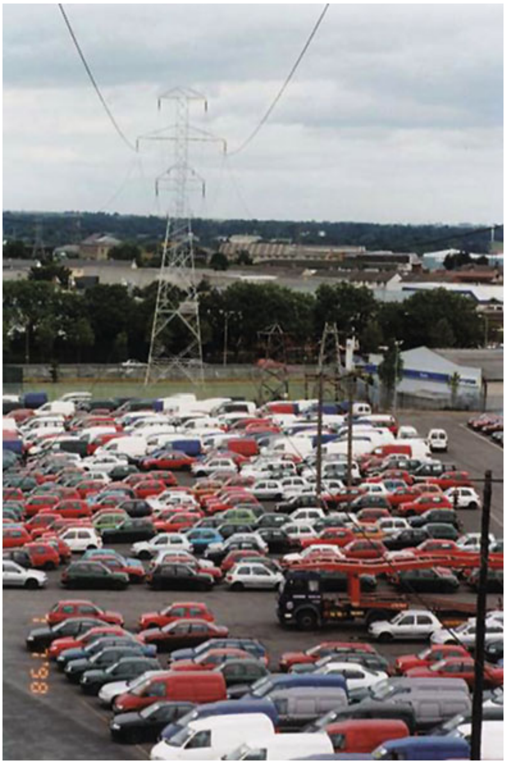


Figure 1.5 A double circuit 110 kV line corridor used as a car park in an industrial area (Ireland).

procedures, environmental impact assessments and consultation methodologies for Overhead Line projects to mitigation of environmental impacts be they visual, ecological, on land use or of construction and maintenance. Extensive space is given to the development of reduced visual impact designs and aesthetic designs, a subject further expanded in Chapter 12 "Supports" and to multiple use of Overhead Line corridors, Figure 1.5. Last but not least all issues associated with field effects inclusive of the debates on EMF and mitigation measures are presented including Corona, Radio and Television Interferences and ion current phenomena associated with DC.

For a better assessment of the meteorological loads acting on a transmission line and presented in Chapter 4, it is important to understand the weather and its interaction with a line. This is exactly the subject of Chapter 7 "Overhead Lines and Weather". Therein not only the basic mechanisms of the different weather phenomena, as for example the creation of a cyclone, a thunderstorm or the different icing procedures, which can have detrimental effects on a line, Figure 1.6, are well explained, but also the ever increasing, and worrying, influences to the weather due to changes in global climate are adequately covered. The chapter further includes information on the application of numerical weather prediction models, a subject of increasing interest thanks to the recent advances in information and data managing techniques.

Figure 1.6 Rime icing on a 420 kV line in Norway, 1400 m above sea level.

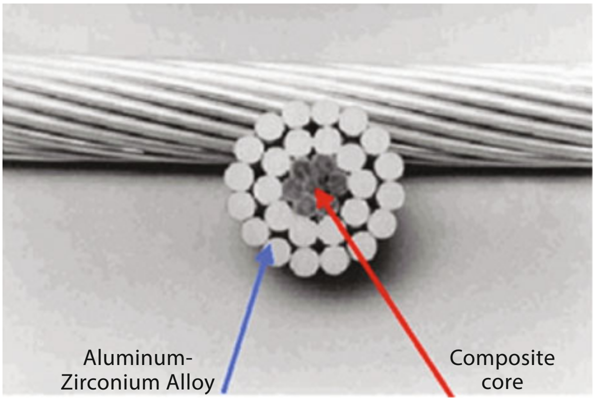


Figure 1.7 ACCR conductor showing the stranded metal composite core.

Conductors are the only active component of a line, i.e. the one component involved in the transmission of electric power and their costs, including the associated fittings, can reach up to 50% of the total line investment costs. Because inadvertently they generate Ohmic losses, their properties influence significantly also the operating costs of a line. It is thus no wonder that many Cigré Working Groups have over the years investigated them. The summary of their findings is given in Chapter 8 "Conductors". This chapter focusses on the following three areas:

- Calculation of AC resistance
- Sag-tension calculations
- Conductors for operation at high temperature

Regarding the latter, it has been astonishing to follow, how many innovative conductor concepts have been created in the last years, Figures 1.7 and 1.8, following the need to increase the power transfer capacity of a line with minimal changes of the structure of the line.

Figure 1.8 ACCC conductor showing its carbon fiber thermoset resin core.

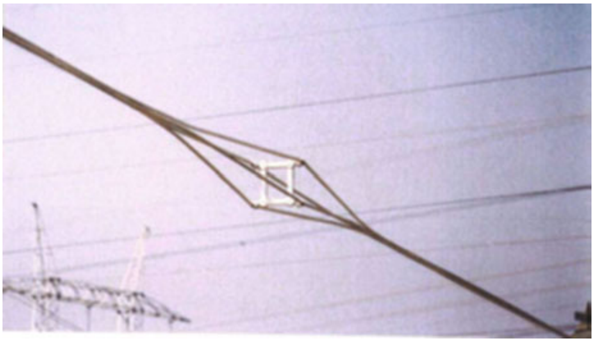


Figure 1.9 Short circuit test of spacer damper.

Line components to anchor, clamp, connect (join), damp and repair the conductor are collectively known as "Fittings". They are extensively covered in Chapter 9. The chapter starts with a detailed section on the various manufacturing and finishing processes of such fittings to continue with the electrical stresses they have often to endure, such as Corona, short circuits, Figure 1.9, and contact deterioration. The latter are of increasing interest due to the elevated conductor temperatures applicable nowadays. Another important issue is the test methodology developed within Study Committee B2 for testing "old" fittings, i.e. fittings which have been for long time in service, in order to decide on their usability. This goes hand in hand with the extensive coverage of repair methods and the related hardware, also covered in this chapter.

Conductor vibrations have plagued transmission line engineers since the early days of overhead line transmission. In particular when the copper conductors originally used started being replaced in the twenties, because of economic considerations, by ACSR (Aluminium Conductors Steel Reinforced), vibration damages have been so heavy, that the use of the latter has been seriously questioned. The

Figure 1.10 Wear and failure of conductor strands due to spacer clamp loosening.

understanding of the vibration phenomenon and its detrimental effects on line conductors, Figure 1.10, has been thus for innumerable years a focus area of studies within Cigré and it is not exaggerated to state, that quite a number of seminal papers and state of the art Technical Brochures have been produced by Cigré experts and published for the first time by Cigré. It is thus no wonder that Chapter 10 "Conductor Motions" turned out to be the lengthiest of this book. The following examples might illustrate Cigré's legacy in this field: a) the concept of the lifetime estimation of conductors undergoing Aeolian vibrations, Figure 1.11, b) the EDS principle followed by the safe design tension method, Figure 1.12, and c) the energy balance principle (EBP) for the calculation of the vibration activity. This chapter evidently includes also details on other types of wind-induced motions such as sub-span oscillations and galloping, valuable information on conductor self-damping and external damping devices (e.g. Stockbridge dampers and spacer dampers) as well as a section dedicated to mechanical effects of short circuit loads on conductors and line hardware, a phenomenon occurring mainly at the physical interface of lines and outdoor substations.

The following Chapter 11 "Insulators" is equivalent to Chapter 10 as far as originality and value of published information by Cigré is concerned. As for conductor vibrations, also in the field of insulators, Cigré has played a pioneering role over the years. And doubtlessly, the fact that Composite Insulators, a relative new, for Overhead Line time frames, technology has advanced tremendously in the last decades is due largely to the work of Cigré. This Chapter covers surveys (a very powerful and frequently used Cigré tool which takes advantage of the unique international character of the organization) on many topics, on screening tests on aged porcelain and glass insulations, service experience of composite insulators), standardization issues (where Cigré Working Groups have prepared the basis for many IEC Standards) and design recommendations (for instance for the proper Corona and power arc protection of insulator strings), Figures 1.13 and 1.14.

For many years "Supports", the subject of Chapter 12, were more or less equivalent to steel lattice towers and Cigré Working Groups have delivered important contributions on their proper design philosophy, static and dynamic loads, structural modeling and analysis, calculations and dimensioning, including advanced tools and techniques, materials and standards but also detailing, fabrication and prototype testin, g not to mention types and causes of defects and industry repair practices. The last years though, increased awareness to transmission line structures and

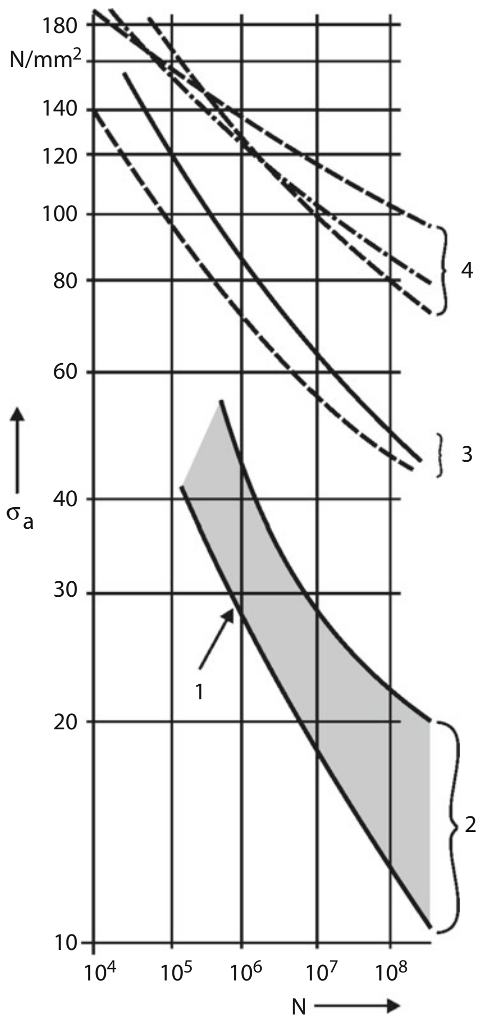


Figure 1.11 S-N curves (Woehler curves) for individual wires and for stranded conductors. 1. Safe border line 2. Aluminium based conductors 3. Pure aluminium individual wires 4. Aluminium alloy individual wires

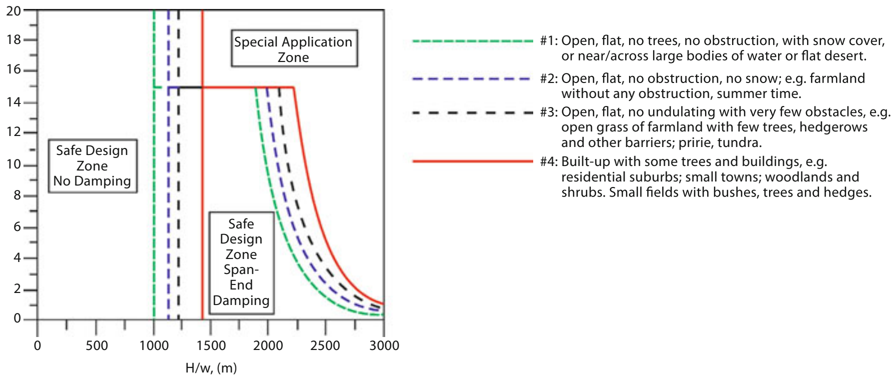


Figure 1.12 Recommended safe design tension for single aluminium based conductors.

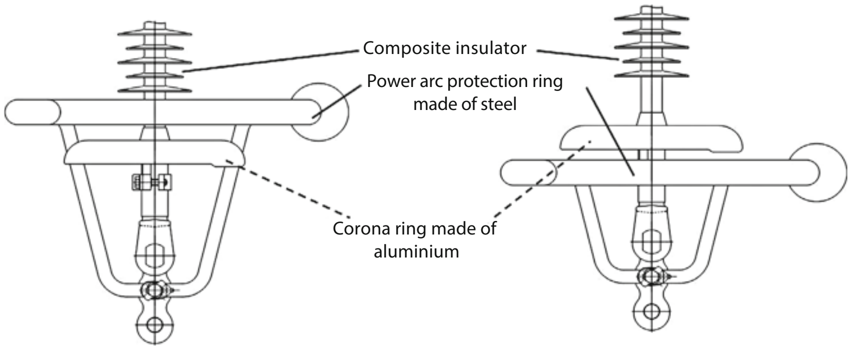


Figure 1.13 Coordination between Corona and power arc protection: correct (left), incorrect (right).

Figure 1.14 Scale comparison between a porcelain longrod, a cap and pin and a composite insulator.

environmental concerns by the public, have propelled the development of so called landscape or aesthetic towers, some of them very unique, Figure 1.15. For these innovative solutions Cigré has collected worldwide examples and presented them in a very informative Technical Brochure (TB 416, "Innovative Solutions for Overhead Line Supports") in 2010. The chapter concludes with information on steel monopoles, often used for compact lines, Figure 1.16, concrete poles and wood poles, while work on supports with high-tech materials like composites is just starting.

Another "classic" component of a line is "Foundations", presented comprehensively in Chapter 13. Foundations are evidently –and in every sense of the word- very "basic" for the reliability and the structural integrity of a line and thus they are addressed with great care. Quite unique is the fact that for foundations, because of the variable soil conditions, from rocks to swamps and to undisturbed mother soil, over the length of a line, site investigations during the design phase of a line project are absolutely necessary. This is also one of the three pillars of this chapter, the other two being foundation design (basic theory, static and dynamic loadings, foundation types, Figure 1.17, and their interaction with the surrounding ground) and the post-mortem examination of failures with related risk assessment, Figure 1.18.

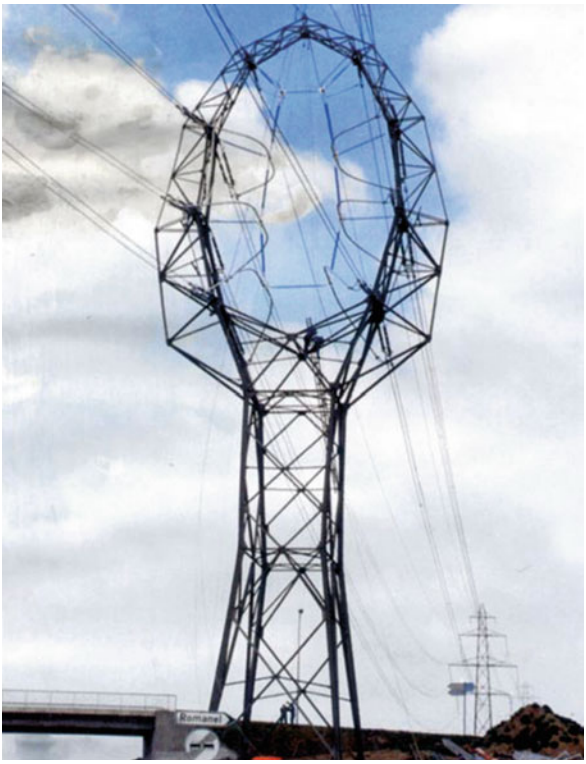


Figure 1.15 Pylone Raquette in west Switzerland.

Figure 1.16 Visual comparison of 420 kV conventional and compact lines side by side carrying the same power in Dubai/UAE.

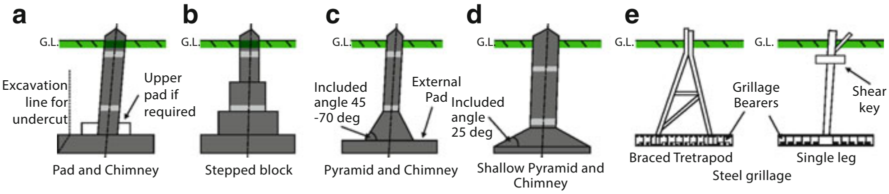


Figure 1.17 Spread Footings Foundations.

Figure 1.18 Failure of a 500 kV suspension tower drilled shaft foundation.

Probably for the first time in transmission line literature the concept of "Overall Line Design", part of ongoing Cigré work, is given such a prominent place as in Chapter 14. Therein one can find the complex, sometimes unexpected interactions and interdependencies of the decisions taken during the design phase of a line. For instance while phase spacing increase (as for example in compact lines) is beneficial for the SIL (surge impedance loading) of a line and the mechanical loads of the line supports and foundations, it has negative effects on Corona and AN/RIV, as both increase, Figure 1.19. While this is understandable form basic physical principles, other interdependencies are not so obvious. For example by lowering the knee-point temperature of an ACSR conductor (this is the temperature at which the slope of the sag-temperature curve changes), the longer the sag relationship will follow the steel core, resulting in a higher temperature and lower sag condition. This is possible for conductors with annealed aluminium wires and also with so-called Gap-conductors, both costing more than

	SIL	Corona	Mechanical loading	Thermal rating
Phase spacing decrease				
Large Al area/cond (less conductors)				
Diameter bundle increase				
High steel content				

Figure 1.19 Relationship between actions taken in line design and effect on SIL, Corona, Mechanical loading and thermal rating.

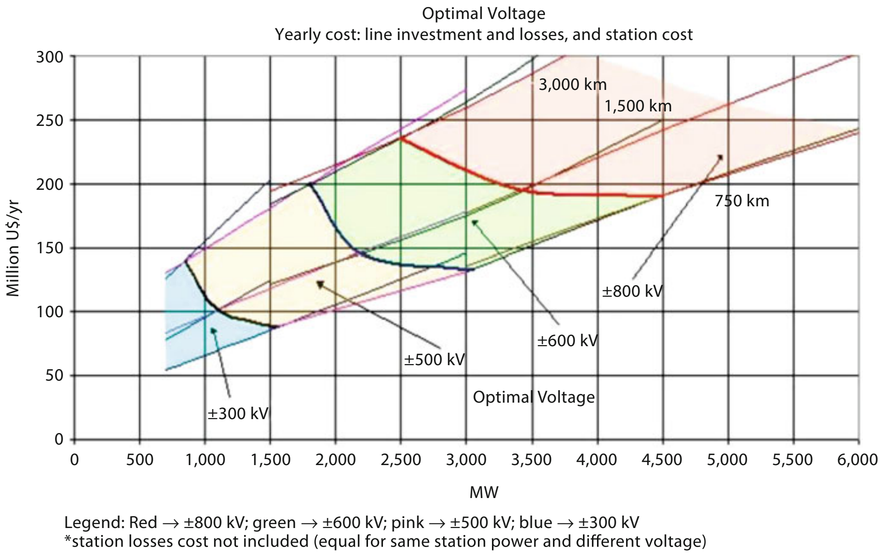


Figure 1.20 Optimal voltage as a function of converter station power and line length.

conventional conductors. This leads to the second part of this chapter, where a methodology for line optimization is given by introducing a suitable composite indicator for comparison of the different design options including cost aspects. The methodology can be also applied to HVDC lines in continuation of previous Cigré work, Figure 1.20).

Traditionally Cigré has dealt more with design and field experience issues than with the construction of a line. This short-coming is thankfully rectified with Chapter 15 "Construction". Therein practical aspects of line construction are addressed providing an concise picture of the most common construction activities and installation techniques used in installation of an overhead transmission line. Special attention is being paid to construction activities requiring

Figure 1.21 Trailer mounted payoffs and a truck mounted bullwheel for tension stringing.

either high degree of accuracy or those posing high safety risks to construction crews. Items covered include line survey, Right-Of-Way (ROW) clearing and site access, assembly and setting of foundations, structure assembly and erection including insulators, hardware and fittings, conductor stringing and as-built inspection, Figure 1.21.

On the other hand "Maintenance", as presented in Chapter 16, has attracted over the years the interest for quite a few Cigré Working Groups, such as the joint (with SC B3, "Substations") Working Group on "Live work - a Management Perspective" and the recently created Working Group on "The Use of Robotics in Assessment and Maintenance of OHL", an exciting new option in overhead line maintenance. Proper and efficient maintenance starts with the formulation of a maintenance strategy. This should include the prioritizing of the transmission lines in the network, carrying out periodic inspections, setting-up a data base storage and retrieval systems (otherwise sooner or later the results of the inspections would be lost) and the -management- decision, whether maintenance work should be done in-house or outsourced and done on live or de-energized lines. The core of maintenance work is the condition assessment of line components. The Chapter continues with valuable information on such assessment for the line conductors including joints and fittings, the insulators, the supports and the foundations. Special attention is then given to the use of carts for in-span work, Figure 1.22, such as the repair or replacement of spacers, dampers, aircraft warning markers, followed by a detailed description of the costs and benefits of live line work versus de-energized methods with interesting examples of typical live work operations. The chapter closes with the use of Robotics based on input from an ongoing Cigré working group, Figure 1.23.

With the advent of liberalization of the electricity markets in the last years, a holistic view of overhead lines as an asset has become a reality and a necessity.

Figure 1.22 Cart used on a horizontal twin bundle.

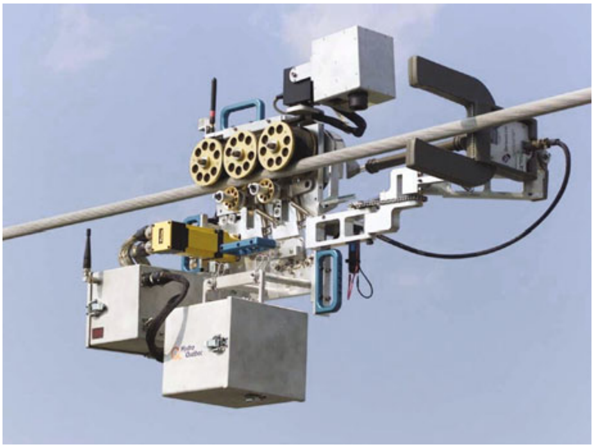


Figure 1.23 Photo of the LineROVer robot inspecting a transmission line.

The importance of "Asset Management" for electric utilities and network operators is well demonstrated in Chapter 17. In the past decisions on the management of existing overhead transmission lines were frequently based on the qualitative judgment of experienced individuals. This chapter quantifies such decisions using risk management techniques and presents methodologies for estimating costs and risks associated with various actions required for proper management of an overhead transmission line asset such as adequate inspections, analysis of a database of the conditions of the transmission line components, cost factors, safety and regulatory and environmental considerations. Management actions to be considered include risk reduction, risk acceptance and risk increase also well described in Cigré TB 175. The chapter concludes with important information for establishing and updating of databases, as this will lead to an improvement of transmission line availability and reliability and give the owner a better insight as to the remaining life expectancy and future operating costs of their transmission assets.

Liberalization and the opening of the markets has also led, together with the tremendous increase in renewables in the last years, and in combination with serious objections by the public to new transmission corridors, to the development of a new field in overhead line techniques, the "Uprating and Upgrading" of Chapter 18. The purpose of this chapter is to provide a general overview of the economic and technical considerations in order to facilitate decisions for uprating and upgrading of overhead lines. Upgrading will increase the original structural strength and thus decrease the probability of failure of a line. Uprating on the other hand will improve the electrical characteristics and thus also increase the power transmitted over the line. The latter is nowadays of particular importance and is basically accomplished by increasing the thermal rating and/or the voltage rating of the line in question. Of specific interest is the information provided for the world's first AC/DC hybrid line, which is going to be presented during this Cigré session (Paris 2014), Figure 1.24.

For the same reasons, i.e. increased demand for power transfer and at the same time public resentments against new line corridors, has favored in recent years the combination of "Overhead Lines and Underground Cables" in particular for higher voltage levels. This is the theme of the concluding Chapter of this book. Its scope is to give an overview and comparison between Overhead Lines (OHL) and

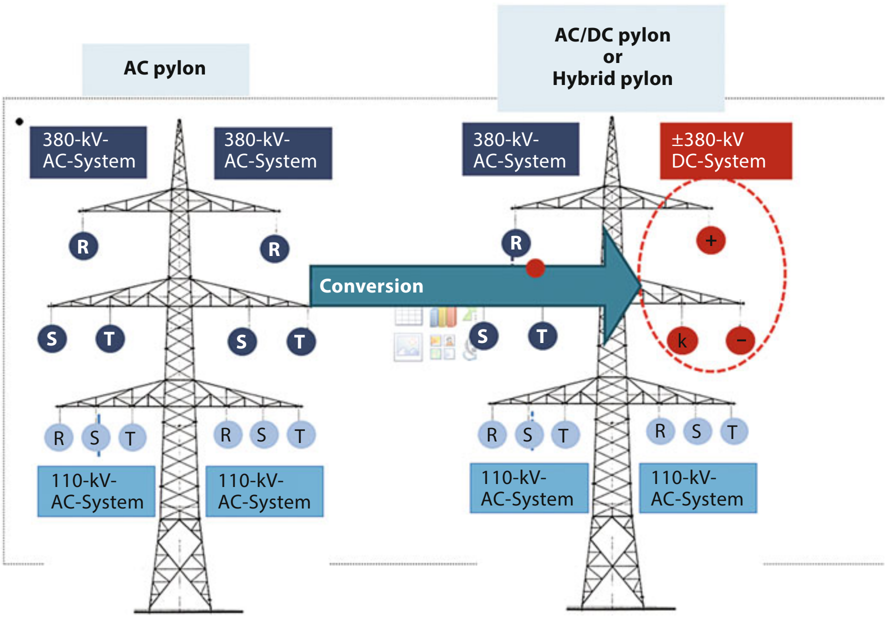


Figure 1.24 Conversion of a double circuit of a 380 kV AC line to a hybrid 380 kV AC/±400 kV DC line.

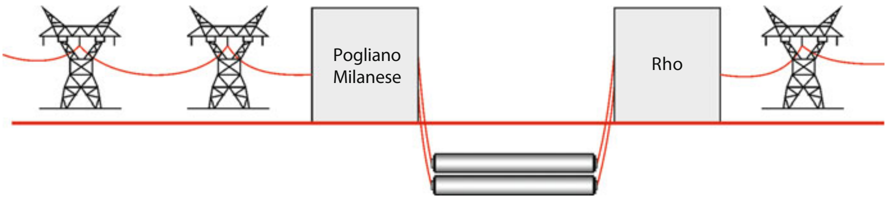
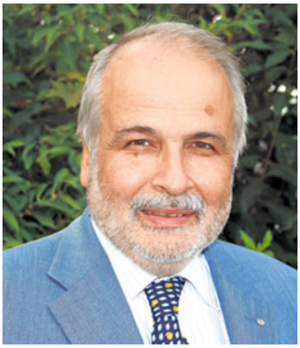


Figure 1.25 Example of a partial undergrounded line route (Italy).

Underground Cables (UGC) regarding techniques, costs, failure rates, operating issues and life expectancy with the objective to provide a sound technical base for discussions (which are unfortunately often controversial) and to present the newest developments and outlooks for both technologies, Figure 1.25. It is a very happy coincidence, that the other book of the Cigré Green Book Series, is the book prepared by Study Committee B1 "Underground Cables" on "Accessories for HV Extruded Cables". In this way the coexistence of both important transmission technologies for bulk power transfer is very visibly documented, as well as the excellent cooperation between the two related Study Committees.



Konstantin O. Papailiou studied electrical engineering at the Braunschweig University of Technology and civil engineering at the University of Stuttgart. He received his doctorate degree from the Swiss Federal Institute of Technology (ETH) Zurich and his post doctoral qualification as lecturer (Dr.-Ing. habil.) from the Technical University of Dresden. Until his retirement at the end of 2011 he was CEO of the Pfisterer Group in Winterbach (Germany), a company he has served for more than 25 years. He has held various honorary positions in Technical Bodies and Standard Associations, being presently Chairman of the Cigré Study Committee "Overhead Lines" (SC B2). He has published numerous papers in professional journals as well as coauthored two reference books, the EPRI Transmission Line Reference Book - "Wind -Induced Conductor Motion" and "Silicone Composite Insulators". He is also active in power engineering education, teaching Master's level courses on "High Voltage Transmission Lines" at the University of Stuttgart and the Technical University of Dresden.