Overhead Lines

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Abstract Existing overhead lines of the transmission grid have been designed to build up a network or to strengthen it—as it was seen at the time of their erection. Due to the liberalization of the electricity market in the last years, the demand for production and consumption of electricity has changed. Also, more and more renewable energy sources (wind, solar, water) need to be integrated into the exiting transmission grid. Overloads of the lines must be prevented. Several ways to overcome these problems exist. Among them are:

- build new lines
- change of components on existing lines (e.g. other conductors with higher current capacity)
- increase the line voltage on existing lines (e.g. from 220 to 380 kV) or change from AC to DC
- application of thermal rating and dynamic line rating on existing lines.

The chapter gives an overview which possibilities to strengthen the OHL grid exist and which approaches can be seen for the future. Other possibilities than OHL exist of course, but this is not the scope of Study Committee B2 "Overhead Lines" and will be covered by other Study Committees. For high voltage, extra high voltage and ultra-high voltage, the big majority of new lines will be overhead and will especially remain the most used technique to transport electric energy over long distances with high capacity. Long-term reliability, long service life, cost efficiency and consideration of environmental aspects are required. Modern approaches, materials, methods and design help to fulfil these requirements.

On behalf of CIGRE Study Committee B2.

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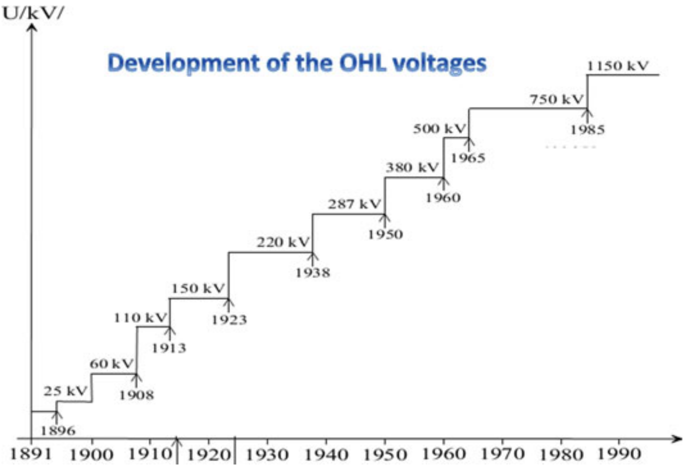
1 Introduction

Overhead lines (OHL) play an important role for the power system of the future and its challenges. They are the oldest and—till today—the most commonly used transmission method worldwide to transport bulk electrical energy over big distances on land. Extra high-voltage lines may exceed a route length of 1000 km for the transport of several 1000 MW per electric circuit in AC or DC, up to voltages of 1.150 kV. The development of OHL voltages over the years is presented in Picture 1.

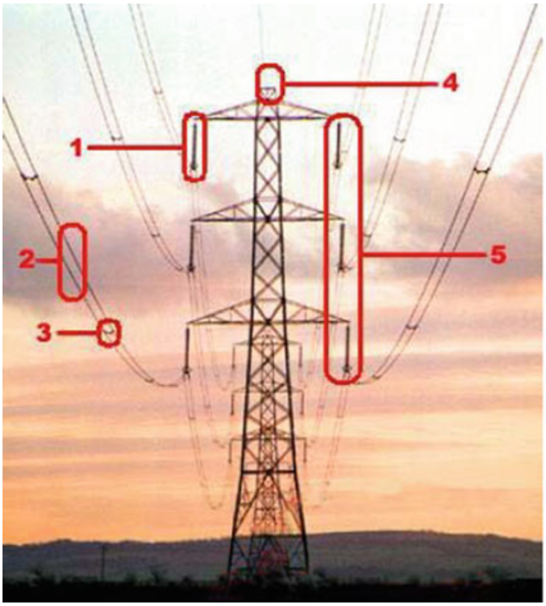
Study Committee B2 deals with overhead lines. The field of activities covers design, construction and operation of, including the mechanical and electrical design of line components (conductors, ground wires, insulators, accessories, supports and their foundations), validation tests, the study of in-service performance, the assessment of the state of line components and elements, maintenance, refurbishment and life extension as well as upgrading and uprating of overhead lines.

The basic methodology to design and build OHL has been established since decades and is improving continuously. Electrical conductors must be insulated from the earth potential and against themselves. OHL use air for insulation. The conductors are fixed by clamps and are mounted on insulators made of porcelain, glass or composite materials. Picture 2 shows a typical transmission tower with two electrical systems (three phases each) and its components.

Existing OHL of the transmission grid have been designed to build up a network or to strengthen it—as it was seen at that time. Due to the liberalization of the electricity market in the last years, the demand for production and consumption of electricity has changed. Also, more and more renewable energy sources need to be integrated into the exiting transmission grid. Overloads of the lines must be prevented. Several ways to overcome these problems exist. Among them are:



Picture 1 Development of OHL voltages, from 1891 to 1990 [1]



(1) Insulator
(2) Phase conductor low-power lines often have a single conductor; higher power lines may use multiple sub-conductors.
(3) Spacer to hold the two sub-conductors apart
(4) Earth wire at the top of the tower or pylon
(5) The three phase conductors on one side of the tower make up one electrical circuit. Most lines have two circuits, one on each side.

Picture 2 Lattice steel tower with two 400 kV electrical circuits (5), Fig. 3.1 from CIGRE publication 338 "Statistics of AC underground cables in power networks". *Remark: typical thermal capacity with two subconductors aluminium 800 mm*^{2} *app.* 2×1500 *MVA, with 3 subconductors app* 2×2250 *MVA*

- build new lines
- change of components on existing lines (e.g. other conductors with higher current capacity)
- increase the line voltage on existing lines (e.g. from 220 to 380 kV)
- application of thermal rating and dynamic line rating on existing lines

The present chapter gives an overview about achieved methods and approaches for the solutions mentioned above. It strongly refers to publications of CIGRE.

2 State of the Art

The configuration of an OHL follows several preconditions. The principle design parameters are:

- **destination of the line**: (city) feeder, transmission grid, distribution grid, feeder from a power plant, merchant line
- **environment, topography**: urban, rural, flat/hilly/alpine, climate, wind and ice, soil conditions, possibilities for access
- **reliability, lifetime**

- **technical requirements**: ampacity, lifetime, voltage, AC/DC, number of electric circuits, route length
- **standards**: design standards, material standards, limits for EMF, radio interference and audible noise
- **structures, supports**: tower configuration, number of circuits per tower, optimized average span
- **tower material**: lattice steel, tubular steel, concrete, wood, compound
- **conductors**: cross section, number of subconductors per phase, material
- **corrosion protection**: galvanized, coating, wood protection
- **maintenance, repair**: live-line work or not, access to the line, fault finding and repair

2.1 Standardization

International and national standards for the design and operation of OHL are helping with achieving a high degree of design and quality of materials [4].

Regulations and standards prescribe minimum values, e.g. for levels of reliability. Higher levels can become necessary depending on the desired function of the line or on the environment along the route. The decision must be taken for each project separately on a case-by-case basis. Keeping in mind that OHL can live 80 to 120 years—if designed for this period—an estimation of the environmental conditions for this period shall be considered (e.g. for wind, rain, ice). Especially natural disasters in the past may give reasons for reliable line design. It is of course not easy to look into the future. Responsible design should provide margins for these uncertainties, even though cost may increase.

2.2 Environmental Changes

The environment is changing in many countries or regions. Tremendous efforts are being made to estimate the environmental conditions and to minimize negative effects from and on overhead lines. The emphasis put on use of land, visual impact of lines, pollution, energy efficiency, global warming aspects and various hazards (like noise, electromagnetic fields) is continuously increasing. Requirements on minimum environmental impact during the life of the equipment will necessitate life cycle assessment, including recycling of older equipment. Assessment of the impact on the environment has become a necessary part of the investigation done prior to obtaining permissions for new lines, which is for many projects carried out in an environmental impact assessment procedure.

In industrialized countries and in metropolitan areas of developing and developed countries, it is increasingly difficult to get new right-of-way for overhead lines. Asset owners and operators are therefore often tied to existing line routes with increasing need to operate existing facilities closer to the limits, implying use of more sophisticated control, monitoring, and data processing equipment. The pressure for going underground has increased and must be expected to increase more. Underground cables and overhead lines should be seen as complementary rather than alternative solutions to build new links. Both are technical solutions and have their advantages and disadvantages. Each project must be considered on a case-to-case basis.

Other environmental trends of importance are increased emphasis on energy efficiency and use of renewable energy sources, and an increasing intolerance in the society necessitating the use of measures to ensure adequate security of supply.

In many countries exists an increasing demand for strict rules on preserving environment and reducing negative impacts from overhead lines.

OHL can be camouflaged by appropriate coating of towers and even conductors or can be "hidden" if the landscape allows this. Picture 3 shows a "camouflage line" in the Austrian Alps with dark green coated towers and dark green coated conductors.

Picture 3 Two OHL towers with two systems 400 kV each can be seen. Left: galvanized steel tower, clearly visible: right "camouflage line" with dark green coated tower and conductors, nearly invisible [1]

2.3 Changing Social Requirements

Consumers and manufacturers are relying on guaranteed electricity supply. It is more and more difficult to de-energize OHL for maintenance, and the resilience of the electric system needs to be higher and higher. The local communities are claiming for more authority in decision-making related to energy management including development of renewable energy systems, generation–consumption balance, energy mix, considering it may be an attractive strength of their territory. All these reasons lead to asset owners and operators having to get more out of existing lines in terms of life expectancy as well as power transfer.

Many stakeholders will be expecting maximizing utilization of the existing assets to maintain electricity rates at reasonable level. Also, various requirements from not only conventional stakeholders such as inhabitants, but other parties such as system users, are increasing.

Public authorities, regulators, consumers, all these target groups ask the designers of OHL and of electric power systems

- to build OHL which design principles are focused on a very low probability of failures, damages, human accidents and economic disadvantages
- to develop an electric power system which guarantees a high level of continuity of service.

2.4 Audible Noise, Electric and Magnetic Fields, Impact on Other Services

OHL may produce audible noise under unfavourable weather conditions. Methods are available to reduce this (e.g. multiple subconductors, phase arrangement, conductor arrangement and surface treatment) [1].

OHL produce electric and magnetic fields (EMF). Their permissible values are defined in international and national regulations. Impacts on sensitive facilities may come from OHL, from EMF. This can lead to shielding measures or to greater clearances to objects.

3 New Grid Requirements

The changes in the power sector include the unbundling of the generation, transmission and distribution activities, the abolishment of institutional barriers for independent power producers, changes in the financial structure of asset owners and operators and an increased emphasis on competition. Third-party access to the transmission system and the fast installation of wind and solar power plants lead to a more intensive and unplanned use of the system and will enforce an improved power flow control increasing the demand for power transfer of the electric grid. This is happening at the European scale changing flows on EHV grid and at the regional scale changing the flows on the HV grid.

The increasing competition in the energy market is changing the traditional roles in the power industry. The access to grid gives rise to short time horizons for planners as well as situations whereby lines will be operated at the maximum thermal load.

The consequences of environmental events such as wind, floods, fire and ice storms can be more severe than ever before due to the reduced network redundancy. New technologies can help to overcome bottlenecks for a certain period of time. Due to increased opposition against new line projects in many countries, the design process and the authorization phase need more time than before. The shutdown of an OHL for maintenance is harder to achieve than before.

To summarize, the transmission line business has become more challenging; however, new techniques allow for new solutions and approaches to overcome obstacles and objections.

3.1 New Needs of Public, Authorities, Regulators, Consumers

The demands and needs lead to cost-efficient designs involving new design tools and new materials. The design of towers can help to achieve public acceptance (i.e. aesthetically pleasing). Another aspect is the effective management of the existing assets.

The following aspects are often raised from these target groups:

- Are the standards adequate as far as public safety and continuity of service are concerned?
- Are representative climatic data available and are the weather assumptions valid, how can climate change be considered?
- Assessment of the reliability of existing overhead lines. Effect of aged components on the OHL reliability.
- Develop emergency response plans with appropriate manpower, material and equipment resources to address (identified) OHL emergency situations. Improve preparedness.
- Find the optimum balance between the costs of reinforcing (upgrading) OHL to a higher reliability level and the costs of preparedness including restoration actions and revenue lost after possible OHL failure events.

3.2 New Needs of Technical and Asset

From these target groups, the main aspects raised concern maintenance, vegetation management, power transfer capability and other uses of supports

- Diagnosis methods to know precisely the reliability of the line (failure mode and probability)
- Estimation of the remaining life of insulators, supports, foundations, conductors and accessories and how to manage all technical data
- Management of line-related data in information systems (condition of components, maintenance plans, corridor management, etc.)
- Use of geographic information systems (GIS) to integrate environmental, climatic and other data related to the line situation.
- Increase the power transfer capability of existing OHL (e.g. change AC to DC, new conductor materials, high temperature conductors, thermal rating, increase voltage)
- How to manage the risks due to load flow capacity increases in existing overhead lines
- Use of OHL lines for other functions (e.g. for communication data with optical fibres in the ground wire, antennas for mobile data technologies)
- OHL with high transfer capability over very long distances (DC, extra high voltage)
- Reduced life cycle cost.

3.3 New Needs of Operators

The major concern of this target group is the technical performance of OHL in all conditions

- New methods for maintenance (robots, drones, live-line maintenance)
- Right of way management (ecologic right of way management, vegetation, access)
- Line performance under dynamic mechanical loading
- Line reliability under normal and specific climatic conditions.
- In time tracking methods (vegetation control, fire tracking, clearances).

3.4 Future Needs of Science, Education and International Organizations

SC B2 defined the main subjects of concern and research that science and universities can work on. They are:

- information for the update of standards (IEC, CENELEC, national standards, etc.)
- Support the involvement of students and young engineers in work of CIGRE Working Groups
- Get information about new developments in the field of materials and equipment
- Basic research to better understand mechanical and electrical phenomenon affecting OHL.

3.5 Lifetime, Life Cycle

OHL have a lifetime of 80–120 years, if designed for this and if well maintained, though some components may need to be replaced (e.g. conductors and fittings after 40–60 years, corrosion protection 25–45 years). With modern methods, the condition of components and the remaining lifetime can be estimated.

- Lattice steel structures: Maintenance coatings for corrosion protection can be extended if e.g. the "In factory Duplex-system" is applied during the production of the tower. It has been experienced in many countries in the world, that the quality of air has improved (less pollution), which can lead to intervals for maintenance coatings of up to 45 years.
- Transmission tubular metallic poles: Thick layers of coating material can prevent maintenance coatings during the lifetime of the structure. Recently, a promising new method has been presented in Japan for protecting tubular bracings of towers [3].
- Small-size metallic poles can be galvanized and coated which allows in general a lifetime without additional coatings
- Concrete tubular poles live for decades without greater maintenance efforts.
- Composite towers are a new development for transmission lines. Experiences from lower voltage lines lead to expect long-lasting structures
- Wooden poles are used for voltages up to 110 kV. The protection of the wood material is a remarkable effort for maintenance.

Various survey techniques and sensors help with improving life cycle management of assets. A need for better, more accurate methods for managing life cycle of the existing assets is seen. A better knowledge of the condition of existing assets helps to assess their end of life.

4 New Technologies and Materials

System expansion planners and OHL planners are confronted with uncertainties in modern power systems, coming from changed power production, renewable generation, energy storage, shifting political goals, and the continuing difficulty in building new overhead lines, demand, economic preconditions and in addition with uncertainties from future climatic conditions. This unpredictability of power flow and environment means that predictions of normal load and losses over the life of a new line (up to 80 or 120 years if designed, built and maintained for such a lifetime) need to be taken seriously when choosing the main design parameters, e.g. conductor size and number and many others.

Recent advances in new materials and technologies have provided transmission utilities and operators with multiple options for better designs, more efficient operation and maintenance of assets.

Overhead lines offer the possibility of flexible design in a certain range. The motivation for flexible design is that, due to such unpredictable shifts, overhead lines can be adapted to the new situation to gain maximum opportunities. The simplest examples for such flexibility involve, e.g. the use of high temperature conductors, which give the possibility to increase the power flow of existing lines with no or small changes on towers. Conductor phase spacing and bundle designs that allow future increases in AC current. The flexible design of OHL is an important advantage, e.g. to support renewables.

Further improvements of the line utilization may also result from real-time monitoring of the conductor temperature considering the weather conditions prevailing at the time (thermal rating). Another way is to change AC circuits to DC circuits on existing lines, with no or minor changes on the towers. Lines can also be uprated by increasing the voltage.

All such considerations must be made case by case, as not each line can be uprated and measures to increase the ampacity may need no, little, much efforts, or can even be impossible

A large number of topics of concern and/or interest for the future grid can be grouped as follows:

Operation and Maintenance

- Condition assessment and estimating remaining asset life
- Online monitoring
- Maximizing use of existing ROWs while minimizing outages of existing lines
- Methods and tools for diagnostic and maintenance
- Extending transmission line life
- Risk management of OHLs

Design

- Increase capacity and reliability of existing lines
- New materials for use with OHL
- DC line design
- Capacity increase and reduction of active and reactive losses

- Risk assessment of structures and foundations
- Design criteria for ice conditions
- Finding qualified and experienced design staff.

Construction

- Improved assembly and erection of structures
- Work safety, linesmen training
- Live work
- New construction techniques

Weather and Environment

- Weather impacts
- Climate change and atmospheric hazards
- Public acceptance
- Access and environmental constraints
- Environmental impacts
- Overhead lines and underground cables.

OHL can be uprated, uprated and refurbished and their asset can be extended. These expressions are often misunderstood or unclear. CIGRE publication 353 "Guidelines for increased Utilization of existing Overhead Transmission Lines" gives clear definitions [11]:

- **Uprating** is defined as increasing the electrical characteristics of a line due to, for example, a requirement for: higher electrical capacity or larger electrical clearances.
- **Upgrading** is defined as increasing the original mechanical strength and or electrical for increased applied loads such as wind, ice and any load case combination or increasing electrical performance such as pollution or lightning performance.
- **Refurbishment** is defined as being the extensive renovation or repair of an item to restore the intended design working life. Life extension is an option of refurbishment which does not result in the complete restoration of the original design working life.
- **Asset Expansion** is defined as increasing the functionality of transmission lines.

In the following, examples for new materials and new methods are given. The above-mentioned aspects are covered.

4.1 *Uprating of Existing Overhead Lines*

4.1.1 High Temperature Low-Sag Conductors

CIGRE Technical Brochure TB 763 "Conductors for the Uprating of Existing Overhead Lines" [10] explains the main methods for OHL uprating, among them for: ***Reconductoring with High-Temperature, Low-Sag (HTLS) conductors****—Replacement of the original line conductor with an HTLS conductor, allows a substantial increase in the line rating by going to a higher maximum thermal capacity without changing the structure loads or requiring physical structure modifications to increase clearances.*

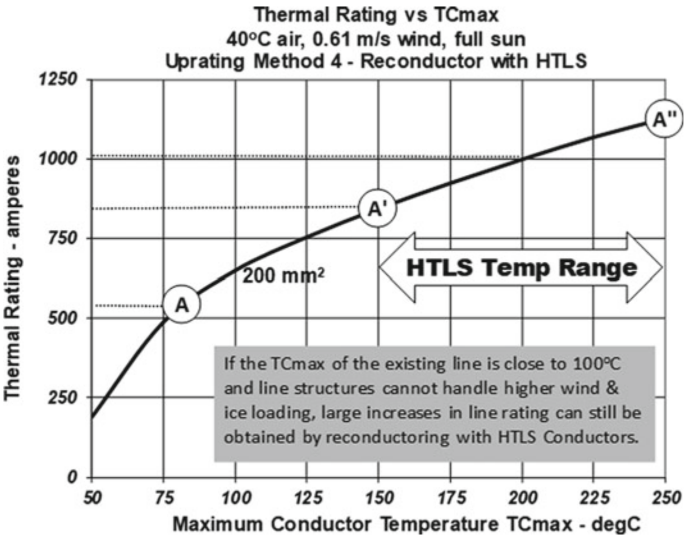
High temperature low-sag conductors (HTLS) are made of special alloys and can be used at temperatures of up to 210 °C. Such conductors can carry more electric current than standard conductors with an allowable temperature of 80–90 °C. The new materials limit the sag and conductor pull to prevent respective minimize adaptions of towers including preventing replacements by higher towers. HTLS conductors are used for reconductoring for the uprating of existing lines as well as for new lines. Different conductor designs are shown in Picture 4.

The new conductors brought a wide range of new types and abbreviations. A not complete overview on conductor types is:

- AAAC All aluminium alloy conductor
- ACSR Aluminium conductor steel reinforced
- TACSR Thermal-resistant aluminium conductor steel reinforced
- G(Z)TACSR Gap-type (Super) thermal-resistant aluminium alloy conductor steel reinforced
- (Z)TACIR (Super) Thermal-resistant aluminium alloy conductor invar reinforced
- ACAR Aluminium conductor alloy reinforced
- ACSS Aluminium conductor steel supported
- ACCC Aluminium conductor composite core
- ACCR Aluminium conductor composite reinforced.

Such conductors can increase the thermal capacity of an OHL remarkably. Depending on the permissible conductor temperature, the increase can be up to

Picture 4 Different types of high temperature low-sag conductors (from left: 3 M, CTC, Lumpi-Berndorf) [1]



Picture 5 Increase of capacity (amperes) depending on the conductor temperature for a certain project [10]

200%. This needs of course the investigation of clearances to ground and obstacles prior to the installation of such conductors. Also, the mechanical loads from the new conductors on the existing towers need to be evaluated. Picture 5 shows an example of the increase of capacity depending on the conductor temperature for a certain project.

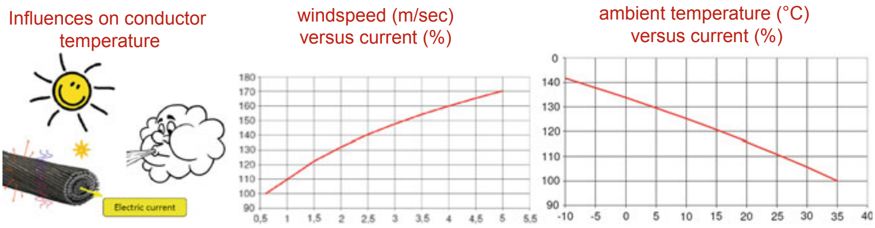
Each project must be investigated on a case-to-case basis. HTS are often "tailor made" for a project. The higher the load, the higher the current, the higher the losses. This must also be considered.

4.1.2 Thermal Rating and Dynamic Line Rating

CIGRE Technical Brochure TB 763 "Conductors for the Uprating of Existing Overhead Lines" [10] explains the main methods for OHL uprating, among them for: ***Dynamic Line Rating****—Line monitors and weather measurement devices can be used to determine the rating of the line in real-time. Such ratings are typically higher than static line ratings but are more complex to implement in system operations.*

Dynamic line rating uses the actual temperature of the conductor and the actual environmental parameters to determine the permissible electric load in order not to violate clearances or other restrictions. The ampacity of an overhead line depends on several factors which need to be considered:

- clearances to ground, buildings, obstacles
- maximum allowable conductor temperature (mechanical aspect)



Picture 6 Principles of thermal rating, high wind and low temperature allow higher permissible current in the conductors

Table 1 Correlation between ambient temperature, wind speed and current capacity

Ambient temperature (°C)	Wind speed (rectangular) (m/s)	Current capacity (%)
30	0.6	100
20	0.6	115
20	2	150

- substations must be prepared for higher current
- load flow considerations of the grid
- legal situation (permission) to run the line with the desired current.

Picture 6 shows the principle: the higher the ambient temperature—the lower the permissible electric load; the higher the windspeed—the higher the permissible electric load. The optimum for a high current capacity of an OHL are cold winter nights (no solar radiation) and wind at high speed perpendicular to the line direction.

Wind blowing on the conductors has a very high influence on the current capacity. Table 1 shows the correlation. The values are examples under optimized conditions, not a general statement.

Several systems for DLR exist, using thermal sensors directly on the conductor, sensors for the conductor pull, or calculating methods from the environmental data and many others.

A recent comparison shows that methods using sensors on the conductors and methods using weather data and historical data correspond very well. One method can confirm the other and eases the decision for the most appropriate approach for a certain application. Paper [2] explains the deviation is approximately 1% only when comparing the two ways of DLR.

Thermal rating and dynamic line rating have become common practice for many TSOs worldwide. The gained additional capacity depends on the actual climatic conditions and cannot be seen as a general approach. Each project must be considered on a case-by-case basis.

4.1.3 Voltage Uprating

Voltage uprating means to increase the operating voltage of an existing OHL to increase its capacity. Necessary measures on structures, insulators and conductors must all be checked for the envisaged purpose and mostly need to be modified more extensively than would be required for thermal uprating. This must be counterbalanced with the costs and the gained additional capacity. The increase of capacity for voltage uprating with unchanged conductors is in the range of 70% when changing from 220 to 380 kV.

The basic voltage design technical considerations are [11]:

- Clearances to ground, to support structures, to over crossings of other power lines, roads and railway lines and clearances to adjacent structures and vegetation;
- Conductor motion and electrical phase-to-phase clearance between conductors
- Clearance between earth wires and conductors
- Insulation requirements for power frequency, switching and lightning surges;
- Clearance for live-line maintenance
- Conductor surface voltage gradient, corona onset voltage and radio interference voltages which are influenced by conductor diameter and conductor bundle diameter
- Audible noise.

With higher voltages, the electric field increases and probability of audible noise will increase, if a certain limit is exceeded. This may lead to the increase of internal phase-to-phase clearances and the installation of additional subconductors or conductors with larger diameters. Additional mechanical loads form wind and ice due to bigger or more conductors must be considered. This all needs to be investigated; see Table 2. In addition, the legal possibilities shall be checked.

4.1.4 Conversion AC to DC

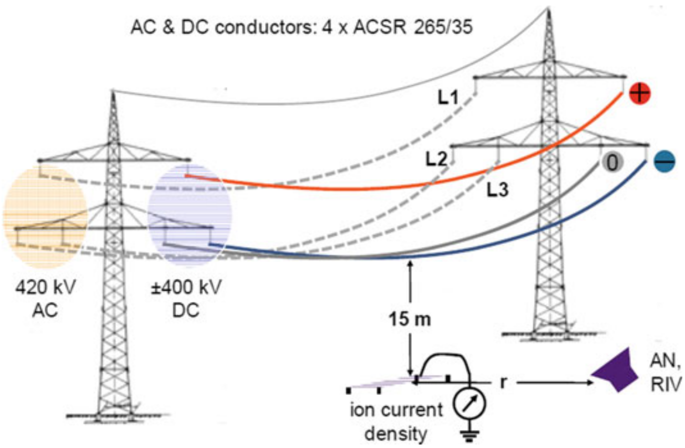
The conversion of an existing AC overhead line to DC can increase its ampacity. The big advantage in general is the better control of the grid with a DC line. The efforts for adaptions on the line, the new built AC/DC- and DC/AC-converter stations at the ends of the line must be counterbalanced with the gained advantages. In general, DC lines are used to transport large quantities of energy over long distances (typically exceeding 600 km) as point-to-point connections. For shorter lengths AC lines are usually more economic.

A pilot project with the so-called hybrid line (one circuit at an existing OHL shall be changed to DC, the other one remains AC) is being constructed in Germany to check technical possibilities and electrical influences. Picture 7 shows the principles of such a line.

Table 2 Influence of parameters for voltage uprating [11]

Parameter		Electric fields	Magnetic fields	Radio interference	Audible noise
Phase to phase distance	↑	↑	↑	↘	↓
Conductor height above ground	↑	↓	↓	↘	↘
Number of sub-conductors (for a given total cross-section)	↑	↑	=	↓	↓
Sub-conductor spacing	↑	↗	=	↗	↗
Total conductor cross-section	↑	↗	=	↘	↘

↑ Strong increase
↗ Slight increase
↓ Strong decrease
↘ Slight decrease
= No significant effect



Picture 7 Line configuration for AC–DC conversion, one system AC, the other one DC (*Source* B2 Session 2013 Auckland, Symposium papers 141, 142) [1]

4.2 New Tower Design

Over the decades of OHL business typical standard tower configurations have been developed and are in use, which are optimized in terms of material, transportation, erection, maintenance, costs and lifetime. Many utilities started considerations for a new tower design to get—or to increase—the acceptance for new OHL. Several towers in alternative design are known from countries all over the world. Most of them are single solutions; some even have the function as eye-catchers. CIGRE publication 416 shows examples. Five of them are in Picture 8 [5].

Only few new designs are suitable as new standard configurations. One of them is being built in The Netherlands where this "wintrack tower" will be erected in hundreds in future. These towers are built as steel poles; two poles are one tower. Other materials, as concrete, were under consideration. Apart from the different visual appearance, the right of way is smaller than with standard towers. Maintenance work needs special tools and facilities. Picture 9 shows a suspension and a tension tower. In the right picture, the transition from a standard lattice steel tension tower to a wintrack tension tower can be seen.

Other examples for new tower design have been installed in Denmark and the UK. Picture 10 presents examples for such double-circuit 400 kV OHL.

The **left** design "eagle" has been built over many kilometres with more than 500 pieces. They consist of tubular steel poles and two crossarms, building the form of

Picture 8 New tower design; from left: Finland, France, USA, Finland, Spain (*Source* CIGRE publication 416)

Picture 9 Wintrack towers in the Netherlands, here as a double-circuit 400 kV line with one system on each pole; left: suspension tower, right: tension tower (*Source* Austrian Power Grid)

Picture 10 New 400kV tower design in Denmark (left) and in UK (right) (*Source* Bystrup architects)

an eagle. An adapted design has lattice steel tower bodies and crossarms, but uses tubes for the bracings.

The **right** design "T-pylon" is based on tubular steel poles and tubular crossarms. The conductors are mounted in the form of a diamond. The towers' height is 35 m above normal ground; this is smaller than standard lattice structures with two or three crossarms. If maintenance work is necessary, it can be done using cranes. The structures are galvanized and coated; it is expected that maintenance coating will become necessary not before 80 years.

It shall be mentioned that the compaction of OHL is a good way to reduce the visibility of the line in the environment. But it is not the solution for every project. Compaction must be considered carefully, as the gained visual advantages may create disadvantages for other aspects. Especially audible noise, electric and magnetic fields must be calculated and calibrated when thinking about compaction.

4.3 New Materials for Structures

New fibre reinforced polymer (FRP) materials show benefits for the electrical utility industry in terms of durability, lightweight, high strength-to-weight ratio, environmentally inert nature, and their electrical non-conductive properties. In the last years, FRP has become more and more common in various industrial applications in aerospace, military, shipping, car, civil engineering and sports gear industries. Such composites can also be used as construction material for OHL structures. First lines in the lower HV range have already been built with such materials [7, 8]. Picture 11 shows examples for such towers.

One of the advantages of FRP is that unlike steel, FRP does not rust or corrode which would be especially beneficial in coastal or industrial areas. There are various resin systems available to the fabricator, which provide long-term resistance to almost every chemical and temperature environment. Properly designed FRP composites

Picture 11 110 kV towers made of composite material. Left: tower in lattice design, right: tower made of tubular poles (*Source* Cigre Working Group B2.61 "Transmission Line Structures with Fibre Reinforced Polymer (FRP) Composites"

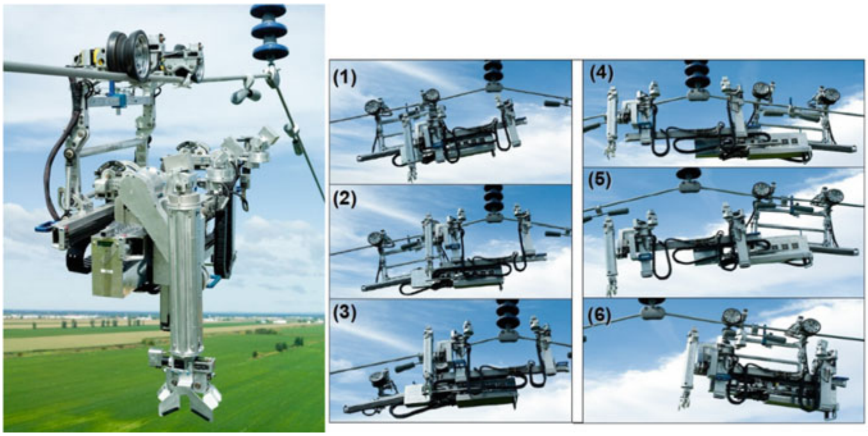
parts have long service life and minimum maintenance as compared to most typical materials used for utility structures.

For LV and MV lines, it is of interest that in comparison with wood poles which can absorb considerable amounts of moisture which affect its electrical conductivity; FRP absorbs less than 1%, so its electrical properties stay relatively consistent. FRP products are resistant to boring by insects and/or woodpeckers. Compared wood treated with preservatives, which cannot be recycled and introduced toxins into the soil, FRP materials exhibit no leaching of chemicals into the environment. The weight of an FRP composite pole is typically 50–70% lesser compared to a wood pole. The low weight reduces transportation costs and enables the use of smaller and lighter vehicles for transportation and installation. At the end of their usable service life, FRP poles can be recycled and used in applications where the initial shape can be used, like fence posts and culverts.

The use of FRP as a material for the manufacture of utility structures is relatively recent. While thoroughly tested, the lack of a long-term use history may be of concern to some prospective users.

4.4 Maintenance with Robots

Robotic in assessment and maintenance of OHL are becoming more and more common at many utilities. Such machines can check conductors and insulators and can climb walls and structures. They assist asset managers in evaluating damages and end of life and are a valuable tool to evaluate damages [6].



Picture 12 LineScout Robot from Hydro-Québec; the robot is designed for live-line work up to 765 kV and can manage obstacles as suspension clamps (left: picture courtesy of Hydro-Québec; right: Pouliot et al. (2009), © 2009 IEEE) [6]

Four robot classifications can principally be identified:

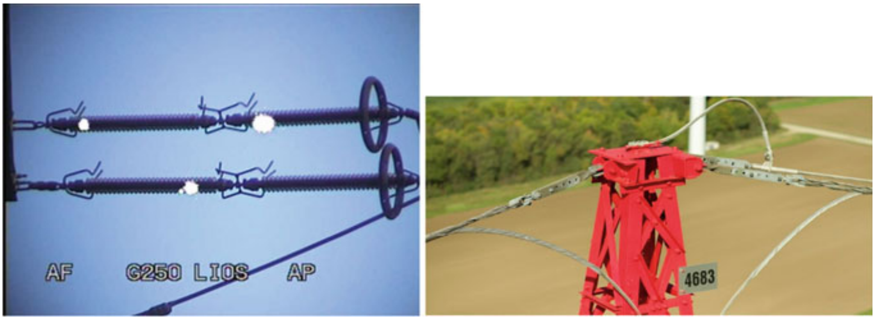
4.4.1 Line-Suspended Robots

They are designed to serve as the extended eyes and arms of the transmission lineman. Their basic design function is to perform visual inspection of transmission lines that cross difficult areas, such as large rivers or mountainous areas. Also, they may detect and locate corrosion pits and locate broken steel core wires of conductors, measure the remaining cross section of such steel wires as well as temporary repair of components.

Such robots are able to travel over the live or ground conductor of OHL, and many of them are able to pass through or cross over different obstacles (clamps, spacers, etc.); see Picture 12. Line-suspended robots are also used to remove ice from conductors in order to release mechanical stress from OHL under severe winter conditions.

4.4.2 Unmanned Aerial Vehicles (UAV)

These are helicopters with trained personnel to capture information for an intended purpose. They give clear images and unique inspection view when they fly close to the transmission lines. In addition to normal images, pictures in the infrared (IR) and ultraviolet (UV) spectrum can be taken. IR images are taken from insulators and conductors. Hot spots due to pollution on the insulator surface or weak connectors on the conductors can be detected (see Picture 13). UV images will reveal corona



Picture 13 Left: corona discharges due to heavy pollution on insulators, detected from an UAV (overlaid UV and visible recording) [6], right: check of earth wire connections

discharges which can originate from damaged conductor strands or from mechanical damage to the insulators.

The technical development for this application is fast and very promising for the future. Such robots have achieved autonomous operation and can wirelessly transmit images and other information to ground. In some countries, before using a UAV, a flight plan approval is required by the authorities. Unmanned aerial vehicles (UAV, multicopter, drones) assist with inspections of OHL also with emergency inspection. Battery life and how to translate images into useful reports need special attention. UAV can be classified as fixed-wing aircraft, helicopter, multicopter (Picture 14). The operating range of these systems varies much in the range of some hundred meters (multicopter) up to autonomous operating time between 1 and 2 h (helicopters). The load they can carry is between some kilos for multicopters and fixed wing aircrafts, and up to 100 kg for helicopters.

Laser scanning of overhead lines is another typical field of application for UAVs. Mostly LIDAR technology is used, for the actualization of existing line documentation, vegetation control in the right-of-way, line routing for new OHL projects, and many others.

Picture 14 Unmanned aerial vehicles for inspection of OHL. Left: Fixed-wing aircraft, middle: multicopter, right: ground system vehicle for helicopter [6]

Picture 15 138 kV double dead-end structure replacement utilizing the LineMaster™—Chicago, IL. © Quanta Services [6]

4.4.3 Ground-Based Robots

Such robots are designed to remotely capture and control energized conductors and execute tasks that are far beyond human capability from a mechanical and electrical stress perspective. This technology has been used for more than 15 years and can be used for line structure repair and replacement, insulator replacement, etc. A big advantage is the reduction of time needed and live-line work; see Picture 15.

4.4.4 Other Types of Robots

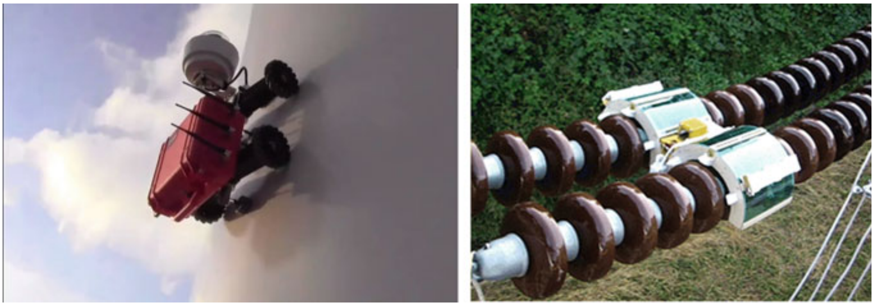
For inspection and maintenance of OHLs, there are still some components that remain mostly off-limits to robots. Towers, insulators, and jumpers may require the use of specialized robots for inspection and maintenance. Therefore, other types of robots have been developed for less-conventional works, such as tower/pole climbing, insulator inspection, and insulator cleaning (Picture 16).

Robots can install and remove aircraft warning spheres mounted on ground wires, provided they are designed for being mounted respective being replaced by robots. The presence of aircraft warning devices is also a problem when conductors or earth wires shall be replaced, as the conductors cannot be pulled out due to the spheres.

4.4.5 Future Vision for the Use of Robots

It is expected that the use of robots will increase. From today's point of view, the following drivers provide the motivation to meet this future vision:

- Safety of both workers and the public



Picture 16 Left: Metallic surface climbing robot from helical robotics; right: live-line insulator cleaning robot (Korea Electric Power Research Institute) [6]

- Effective use of capital and maintenance budgets
- High level of reliability for the transmission system
- Environmental and societal responsibility
- Resilience.

4.5 Asset Expansion of OHL

A typical asset expansion is the use OHLs for telecommunication purposes. Many OHL carry earth wires with integrated optical fibres "Optical Ground Wires—OPGW", and even conductors with fibres have been installed (Picture 17). Such lines can take hundreds of fibres and help to strengthen public and private information grids, together with land cables and radio links. For the same purposes, many OHL towers are equipped with antennas, receivers and amplifiers for telecommunication (Picture 17). With new Internet systems, e.g. 5G, the number of installations of

Picture 17 Left: ground wires of different types with integrated optical fibres (source Lumpi-Berndorf), right: telecommunication antennas mounted on an OHL tower (Austrian Power Grid)

such facilities will increase. Telecom providers in general appreciate the possibilities to use OHL towers for their antennas, and in many countries regulations exist that grid owners have to allow such installations on their structures.

4.6 New Overhead Lines

To build new lines is one of the possibilities to overcome the needs to strengthen the grid. For high voltage, extra-high voltage and ultra-high voltage, the big majority of new lines will be overhead and will especially remain the most used technique to transport electric energy over long distances with high capacity.

The design of new OHL considers all of the relevant aspects which have been explained in the chapters above and combinations of these if appropriate. Good experience exists with this approach. Which method or decision is the optimum for a project must be investigated on a case-by-case basis. General statements cannot be given and make no sense.

5 Conclusions

There is an increasing demand of new lines in many countries. This concerns the replacement of existing lines, the erection of new lines and the increase of the capacity of existing lines. The big majority of those lines will be overhead lines (HV, EHV and UHV).

It is increasing difficult to build and maintain highly reliable overhead lines while keeping cost for the lines low. It is also difficult to provide highly reliable supply of power while optimizing available resources (financial and manpower).

The development of new, advanced technologies and materials in designing and maintaining overhead lines can help to keep the chosen risk level in design and maintenance while keeping reliability level high.

Long-term reliability, long service life, cost efficiency and consideration of environmental aspects are required. Modern approaches, materials, methods and design help to fulfil these requirements.

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56. WG B2.74: Use of Unmanned Aerial Vehicles (UAVs) for Assistance with Inspection of Overhead Power Lines
57. WG B2.59: Forecasting Dynamic Line Ratings
58. WG B2.62: Compact HVDC Overhead Lines."
59. WG B2.63: Compact AC Overhead Lines
60. WG B2.61: Transmission Line Structures with Fibre Reinforced Polymer (FRP) Composites

61. WG B2.65: Detection, Prevention and Repair of Sub surface Corrosion in Overhead Line Supports, Anchors and Foundations
62. WG B2.67: Assessment and Testing of Wood and Alternative Material Type Poles
63. WG B2.66: Safe Handling and Installation Guide for High Temperature Low-sag (HTLS) Conductors
64. WG B2.68: Sustainability of OHL Conductors and Fittings—Conductor Condition Assessment and Life Extension

Lugschitz born 1954 in Vienna, has been working in the field of overhead lines (OHL) for more than 40 years. This covers the complete overhead line business, including technical planning, tower design, calculation and erection of OHL, authorization procedures (Environmental Impact Assessments), alternative tower design and public relations activities. He has been employed as Senior Officer in Asset Management at Austrian Power Grid (APG). In this period, he also participated as technical expert for OHL projects in Africa and Asia for the African Development Bank, European Development Bank, Gesellschaft für Technische Zusammenarbeit GTZ, and UNIDO. He was member in several CIGRE Working Groups of Study Committee SC B2 "Overhead Lines" since the 1980s and was Austrian delegate in B2 from 2004 till 2014 (observer and member). He is chairman of B2 from 2016, and will continue in this function till 2022. He has several functions in standardization bodies. Among them he is Austrian delegate at CENELEC for the establishment of the European Standard EN 50341 "Overhead electrical lines exceeding 1 kV AC" and is chairman of the Technical Committee "Overhead Lines and Embedding of Power Cables" of Austrian Electrotechnical Association—OVE. He was chairman of Association of Austrian Electricity Companies "Österreichs Energie"—section "Grid Matters" for many years.

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Zibby Kieloch has M.Sc., in civil engineering from Warsaw University of Technology. He has been designing overhead transmission lines at voltages up to 500 kV at Manitoba Hydro, Canada for over 25 years. Most recently, he is responsible for one of the largest HVDC projects in North America—Bipole III Transmission Line Project. He has been a CIGRE member and the Canadian Representative on the Study Committee B2 since 2005, making contributions to a number of Working Groups. Since 2012, he has been the Convenor of the SC B2 Customer Advisory Group. He is also an active member of the Canadian Standards Association technical committees responsible for overhead line design and conductor design standards.