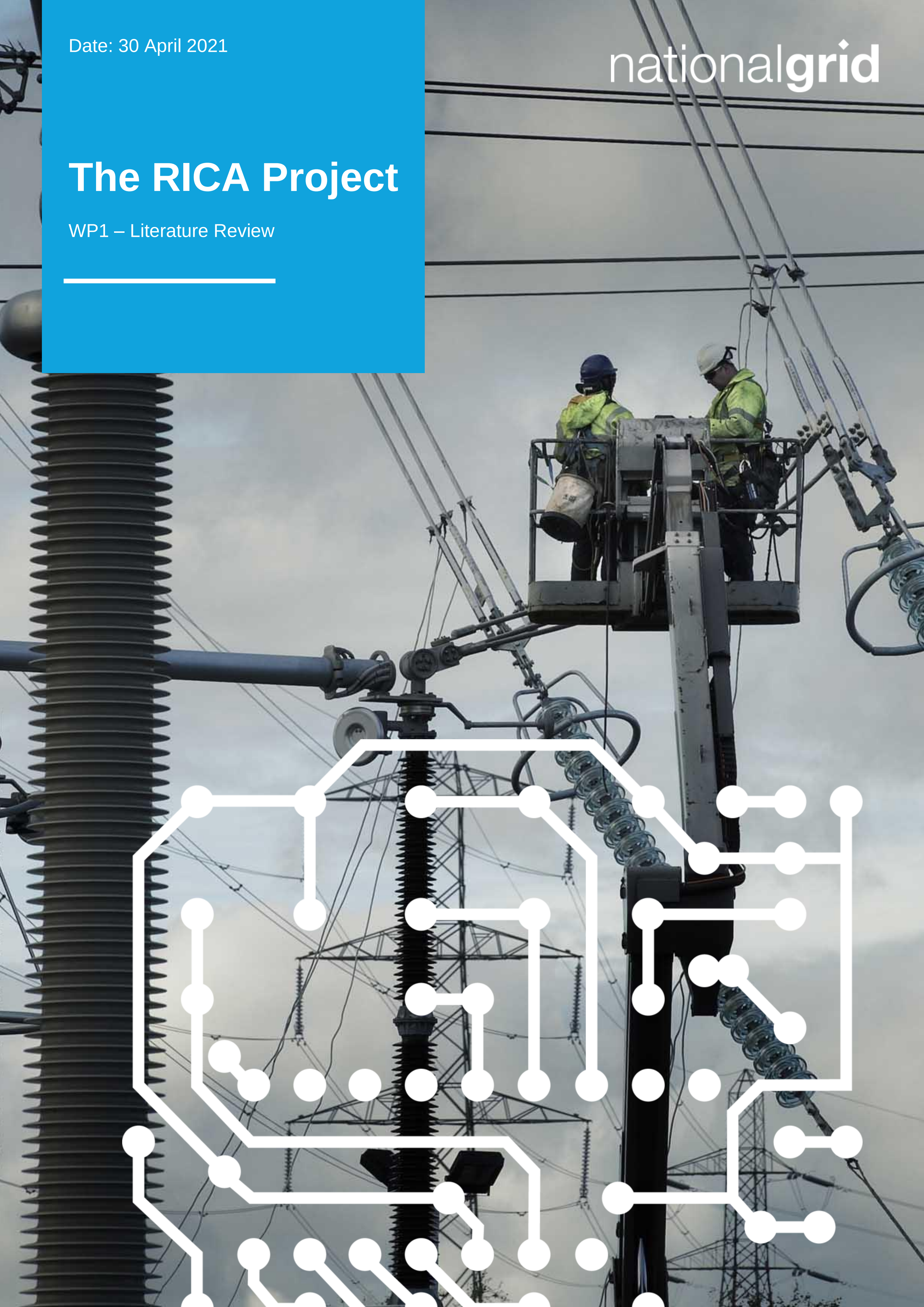
Date: 30 April 2021

The RICA Project

WP1 – Literature Review



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List of Abbreviations

Abbreviation	Term
AAAC	All Aluminium Alloy Conductor
ACSR	Aluminium Conductor Steel-Reinforced
EMF	Electromagnetic Field
HSIL	High Surge Impedance Loading
HTLS	High-Temperature Low-Sag
HV	High Voltage
ICA	Insulating Cross-arm
LSA	Line Surge Arrester
NNA	National Normative Aspects
OHL	Overhead Line
RICA	Retrofit Insulating Cross-arm
ROW	Right of Way
SIL	Surge Impedance Loading
SML	Specified Mechanical Load
SVU	Series Varistor Unit
TSO	Transmission System Operator

Executive Summary

This report is the first of a series of five work packages to provide insight into the full range of implications associated with the introduction of Retrofit Insulated Cross-arms (RICAs) on the 400kV National Grid Network. Work Packages 1 to 4 deliver reports covering the following RICA aspects. The second WP report presents a discussion around existing National Grid Technical Specifications and existing RICA related gaps that will need to be filled prior to business as usual (BaU) adoption on the NG network. The third WP report addresses design considerations associated with the development of the RICA concept into a robust tool for network adoption. Report 4 provides and overview of the NG asset design and development process (ADD) and associated testing that will be required to ensure that RICAs can operate safely and reliably on the UK ET network. Finally, this report summarises the existing literature on ICA technology for both new and existing transmission lines, emphasising on the latter. The fifth work package is a functional specification that outlines all RICA specific requirements that are not covered within existing NG Technical Specifications.

ICAs offer several benefits such as the compaction of transmission line dimensions which minimises the right-of-way requirement, reduces visual impact and electromagnetic radiation at ground level. More importantly, ICAs allow the uprating existing overhead transmission lines to higher voltages improving their power transfer capabilities and therefore reducing the costs, disruption, and environmental impact associated the erection of new lines.

The ICA technology has been used successfully for uprating as well as compaction of transmission lines. Case studies from around the world are presented demonstrating the application of ICAs on conventional lattice structures, monopoles and other non-conventional arrangements.

A review of policies and standards that apply to ICAs is conducted with regards to the mechanical, electrical and materials performance, electric field management, radio interference and EMF. While at the moment there are no specific regulations governing ICA applications, the technology must comply with the regime that applies to conventional insulators and overhead transmission lines.

Factors that can potentially affect successful implementation of the ICA technology are discussed. These include the implications for line stability with rigid and pivoting cross-arms, the impact of the reduction in phase spacing as a result of line compaction and the changes in corona activity, audible noise and EMF. Also, the effects of reduced clearance to insulation coordination are discussed as well as environmental and outage availability aspects that might delay retrofit works.

Technologies and solutions that can be used in conjunction with ICAs to increase potential benefits are summarised. These include methods for increasing the conductor attachment

point and changes to conductor systems such as adding conductors to the bundle, increasing conductor tension, and use of HTLS conductors. The use of line surge arresters and the increase of the surge impedance loading are also discussed.

Lastly an overview of the available technology is provided. It covers commercially available solutions and experimental solutions that have resulted in full-scale prototypes, testing and/or trials.

1 Introduction

In order to satisfy the continuously increasing demand for electrical energy, connect new methods of generation, and account for the changing power flows due to the adoption of new technologies, such as microgeneration and electric transport, the transmission network will have to expand. Constructing new overhead lines (OHLs) can in theory be one of the fastest and most financially attractive solutions to facilitate this. However, the environmental, social and economic impact associated with the erection and operation of OHLs has led to increased public scrutiny. It is not uncommon for residents and local land owners to have developed strong, negative attitudes towards the construction of new lines.

The size and scale of OHLs can have a dramatic impact to the surrounding landscape. The routeing of OHLs through or near areas of outstanding natural beauty, sites of nature conservation and archaeological sites has been of particular concern [1]. Because of the opposition of the public due to the aforementioned environmental, social and economic impact to the local communities, significant problems and delays can arise in obtaining planning permission for new OHLs. As a result, the power industry has been seeking solutions to improve the power transfer capabilities of existing infrastructure. One of the most attractive propositions for increasing the power transfer capabilities of OHLs is the replacement of the steel lattice tower cross-arms with ones made out of insulating materials.

The insulating cross-arm (ICA) concept is not new. Designs featuring two or four insulators were conceived from the 1960s. Early designs relied on the ceramic insulators that were available at the time but this made the cross-arms too heavy for practical applications [2]. In recent years, advances in materials technology have resulted in ICAs emerging as a financially viable alternative for upgrading existing OHLs or constructing new compact OHLs. The products available in the market have primarily been used on monopole structures rather than on traditional lattice towers. In the industry are more commonly known as braced insulators, braced posts or horizontal-V insulators.

With regards to upgrading existing OHLs, ICAs can be retrofitted on lattice towers replacing the steel cross-arms. Since the cross-arms themselves are insulating, the need for additional insulators disappears. This allows for increased clearance between the conductor and the tower body since there is no suspension insulator that can swing towards the tower under the force of wind. Also, the conductor can be raised higher providing additional clearance from the ground. With the increased phase-to-earth clearances allowed by Retrofit Insulating Cross-arms (RICAs) an existing OHL can be upgraded to a higher voltage. Additionally, the increased clearance from ground can potentially be used to increase the current carrying capacity of the conductors by allowing for increased conductor sag. An example of a 275 kV tower converted to a 400 kV tower using RICAs is shown in Figure 1.1. Contrary to other solutions, the deployment of RICAs can be achieved with relatively minor modifications to the existing towers. In addition to the increased power rating, other benefits of the technology include a narrower right-of-way (ROW) requirement, the reduction of electromagnetic radiation at ground level and reduction of the visual impact of OHLs due to the compaction of tower dimensions [3].

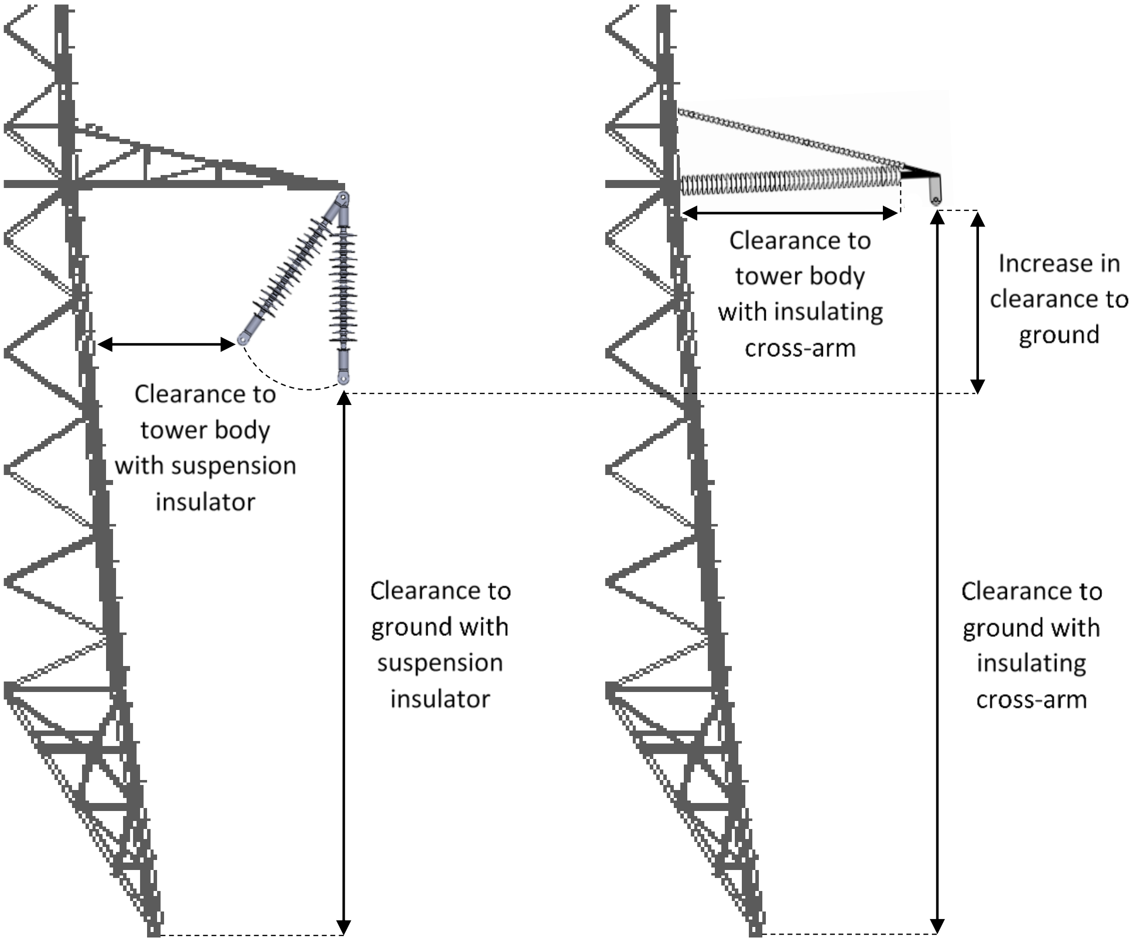


Figure 1.1 - Comparison of phase-to-tower body and phase-to-ground clearances between a tower employing suspension insulators (a) and insulating cross-arms (b) [4]

The report provides a comprehensive literature review of ICA technology, aiming to highlight its capabilities and inform the decision-making process regarding future applications. Various cases where ICAs have been installed around the world are explored. Also, the policies and standards governing the application of ICAs are briefly outlined. Furthermore, the factors that can potentially affect the successful implementation of the technology are considered as well as potential alternatives that in some cases can be used together with ICAs to further increase their benefits. Finally, an overview of commercially available as well as experimental ICA solutions is provided.

The report covers ICAs for transmission applications from 110 kV and above. Fully-composite structures and distribution applications, such as line posts and composite cross-arms for wooden poles, are beyond the scope of this report.

2 Applications

2.1 Uprating

OHL uprating refers to the increase of the electrical characteristics of a transmission line with main aim to improve its power transfer capabilities. This can be achieved either with a thermal rating increase or a voltage rating increase, or in some cases by a combination of the two mechanisms. There are various methods and techniques that have been used to implement either mechanism but this report focuses on the ones that involve ICAs. ICAs can be used to facilitate thermal uprating by increasing the conductor attachment height, hence allowing for higher conductor temperatures and increased sag while maintain the same clearance to ground. Similarly, by increasing electrical clearances while maintain the same right-of-way (ROW), ICAs can allow for voltage uprating. The uprating of an OHL can be achieved either by converting the existing towers to use ICA or by replacing the towers with new designs that incorporate ICAs.

Various case studies have been performed to estimate the potential benefits from uprating an OHL using ICAs. In [3], calculations have shown that by replacing the steel cross-arms with ICAs on a 275 kV OHL route while maintaining the same voltage and the same conductor, the power transfer capability of the line can be increased by 20% to 30%. If the cross-arm replacement is combined with the replacement of the existing conductor by a novel conductor and the simultaneous voltage uprate from 275 kV to 400 kV, the capacity increase can reach 150%.

In [5] two cases are explored: Case 1: 132 kV to 220 kV and Case 2: 220 kV to 400 kV (Figure 2.1). The cross-arm retrofit is accompanied by conductor replacement. Specifically, for Case 1 the single Panther conductor is replaced by single Casablanca conductor, while for Case 2 the twin Zebra conductor is replaced by a twin Moose conductor. PLS-Tower computations indicate that the towers can withstand the additional loads after the uprating. To maintain the ground clearance for Case 2 it was calculated the ICA for the lower phase would have to be inclined by approximately 3°. The study reports on various parameter changes resulting from the uprating. In summary, it is concluded that the ROW is not only maintained but it is actually reduced slightly, by 8.42% for Case 1 and by 4.34% for Case 2. Radio interference and audible noise levels continue to meet the statutory limits after the uprate in both cases. The calculated transmission capacity improvement is 257.8% and 309.4% for Case 1 and Case 2 respectively.

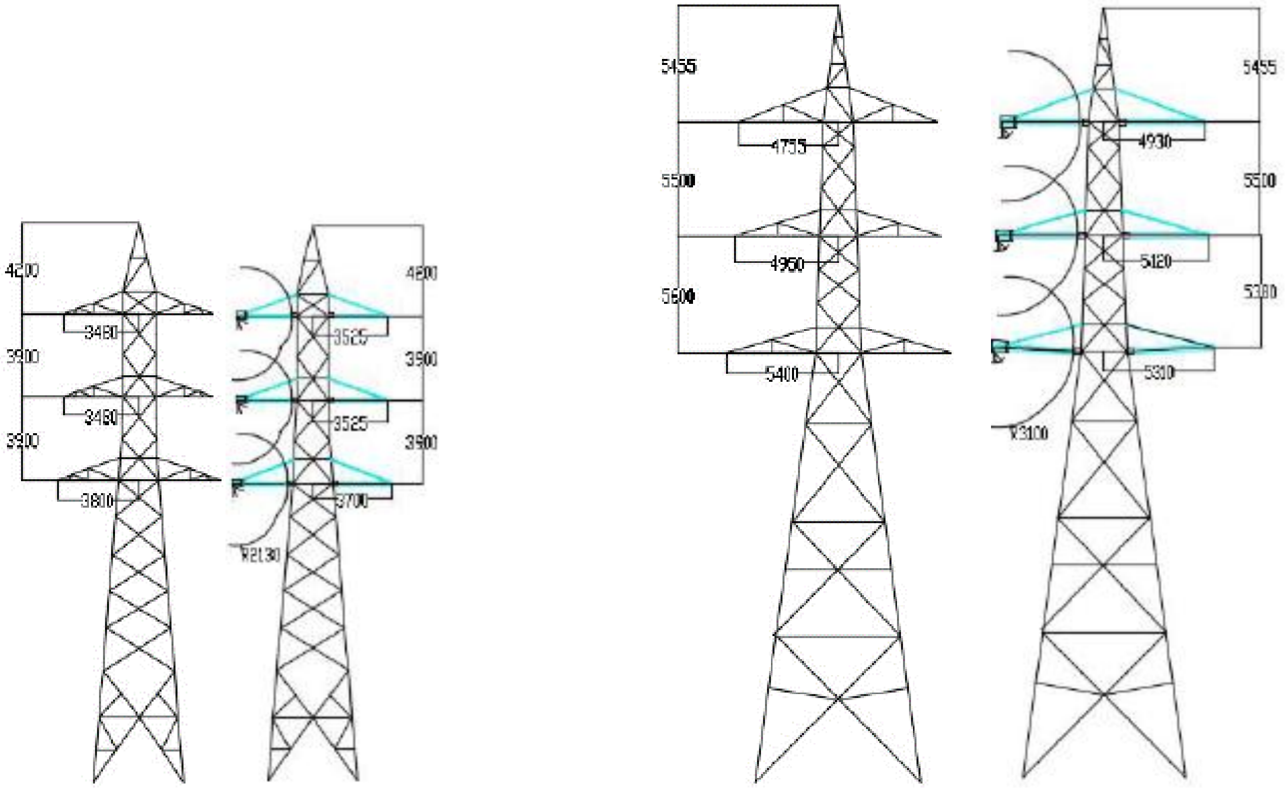


Figure 2.1 - Case 1: 132 kV to 220 kV, Case 2: 220 kV to 400 kV [5]

2.1.1 Spain: Tambre – Santiago II line uprate from 66 kV to 220 kV

Union Fenosa (UF) conducted a line uprating of the Tambre – Santiago II line (operational in January 2000) to support the expansion of the generation capacity, mainly from wind, in the Spanish province of La Coruña. The voltage uprate from 66 kV to 220 kV was estimated to increase the capacity of the line by 233% and result to financial savings of 40% when compared to a new line. The uprated line uses the existing transmission corridor which avoids the construction of an additional OHL hence minimising the environmental impact that would have been caused and avoiding delays in obtaining permissions. 54 of the existing towers were deemed to be satisfactory for the uprate while 24 towers required modifications to satisfy the new ground clearance and mechanical specifications. New 220 kV compact superstructures fitted with ICAs (braced line posts with articulated system) were assembled in the 66 kV tower body. The existing ACSR Condor conductor was maintained. Uprating activities were carried out during weekends with 8-hour interruptions in supply [6].

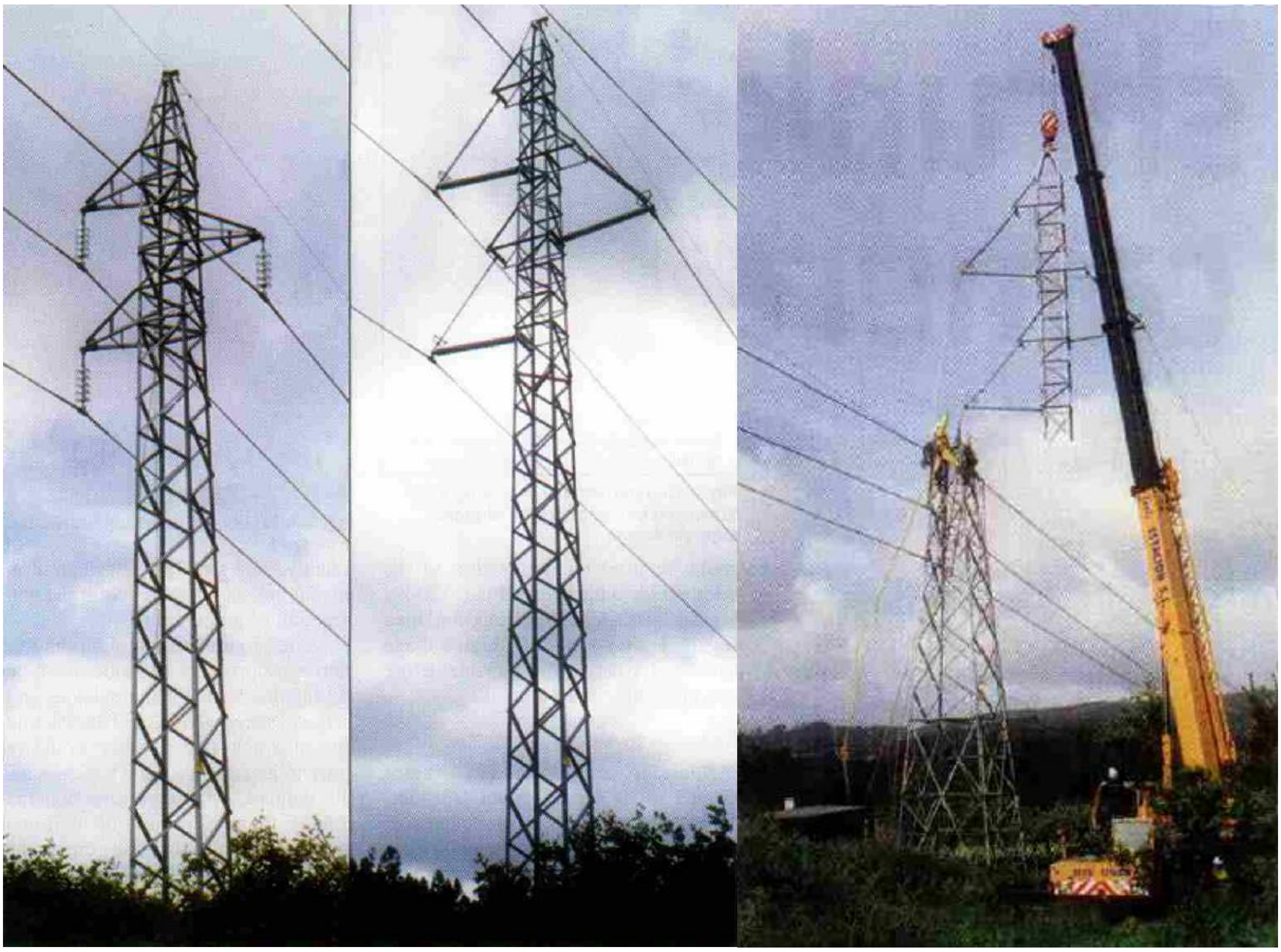


Figure 2.2 - Existing 66 kV tower (left), 220 kV compact tower (middle), and assembly of the new 220 kV compact superstructure (right) [6]

2.1.2 Austria: line uprate from 245 kV to 420 kV

In [7] an OHL uprating from 245 kV to 420 kV is reported. The voltage uprating was facilitated by replacing the steel lattice cross-arms on the existing towers with ICAs (Figure 2.3). To increase the power transfer capabilities of the line even more through better conductor thermal performance, new conductors with larger diameter albeit with the same amount of aluminium were used to replace the existing ACSR conductors.

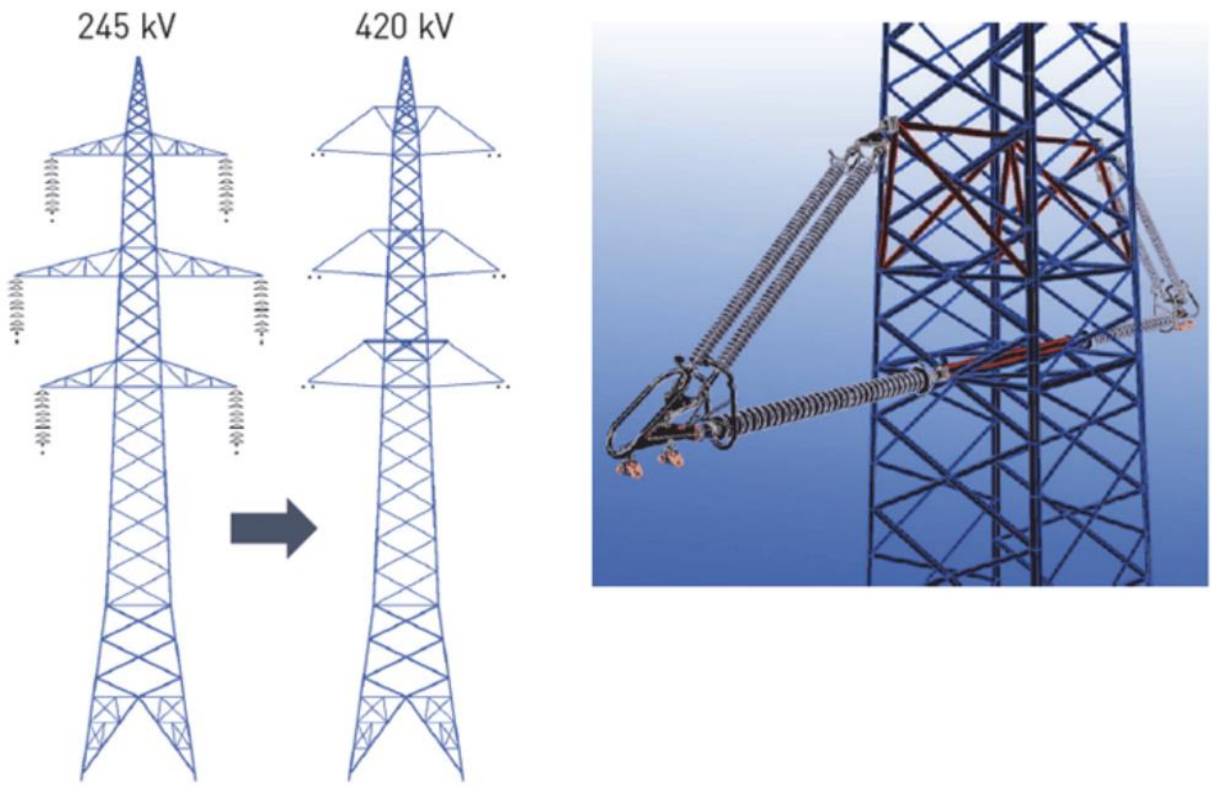


Figure 2.3 - Uprating of 245 kV to 420 kV using composite insulating cross-arms

2.1.3 USA: line uprate from 230 kV to 345 kV

PacifiCorp – Utah – Salt Lake City (limited information).

Figure 2.4 – Existing 230 kV OHL (left), uprated 345 kV OHL with ICAs (right)

2.1.4 Slovenia: Jesenice – Kranjska Gora line uprate from 35 kV to 110 kV

The Elektro Gorenjska d.d. power distribution company conducted an uprating of existing 35 kV OHL in the Kranjska Gora region to 110 kV. The line is passing through the Triglav National Park and therefore it was essential for the uprated line to minimise the visual and environmental impact. The old line was utilising wooden poles and as a result erection of steel lattice towers was deemed unacceptable. The uprated line uses steel monopoles with very similar dimension to the wood poles they are replacing (Figure 2.5), maintaining the special envelop of the line. The line is using 120/20 ACSR conductors supported by horizontal post insulators. Theoretically power transfer capability of the line can be further improved if required in the future by replacing the conductor with 240/40 ACSR. For higher loading cases the cross-arms can be mechanically reinforced with an additional tension insulator forming braced posts [8].

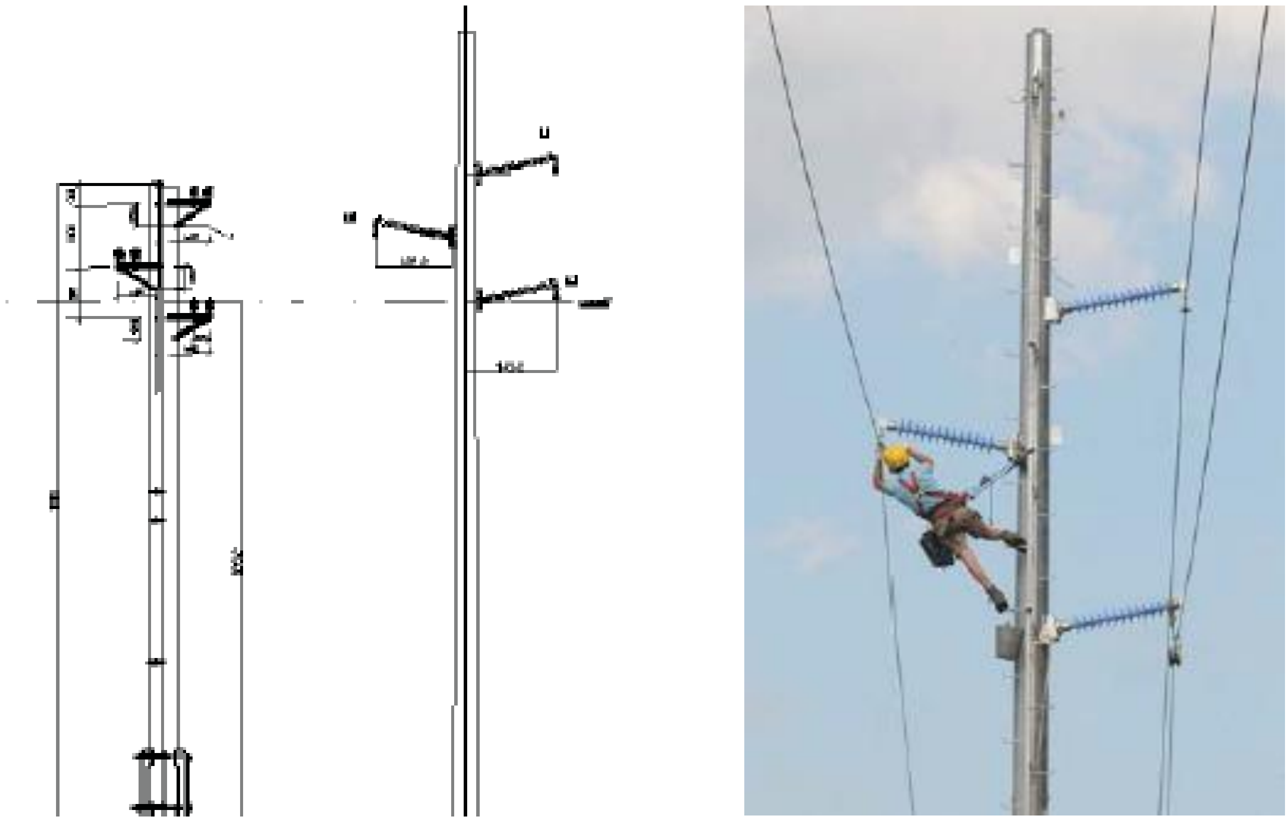


Figure 2.5 – Comparison between the 35 kV existing line and the new 110 kV uprated line [8]

2.1.5 Switzerland: Geneva – Lausanne line uprate from 125 kV to 400 kV

In 1998 a compact HV transmission line utilising ICAs was constructed in West Switzerland between Geneva and Lausanne by Energie Ouest Suisse (EOS). The line uprated the existing 125 kV 3-phase double circuit line to 400 kV while maintaining the same ROW. Additionally, two single-phase 132 kV circuits for the Swiss federal railways (SBB) were suspended from the same towers. To facilitate the uprating, new towers were employed using bidimensional frames [9]. A comparison between the old and uprated line is shown in Figure 2.6. The uprating did not only increase the power transfer capacity of the transmission corridor but also improved the visual appearance of the line and resulted in reduced electric and magnetic field peak values (Figure 2.7). The ICAs for this project used hollow core post insulators to deal with the high compression loads [10].

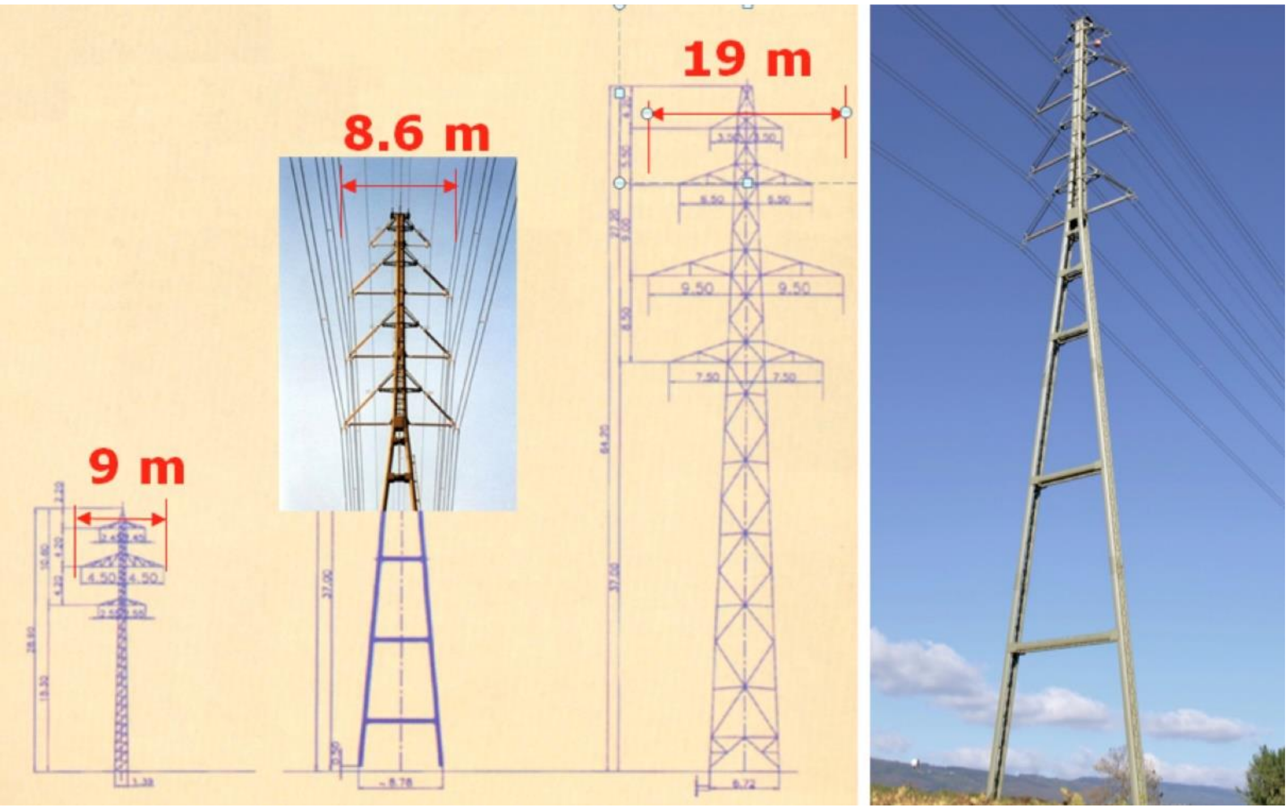


Figure 2.6 - Steel lattice tower of 125 kV line, a Swiss compact tower for 400 kV/132 kV line and a 400 kV lattice tower (left), compact tower with ICAs (right) [7]

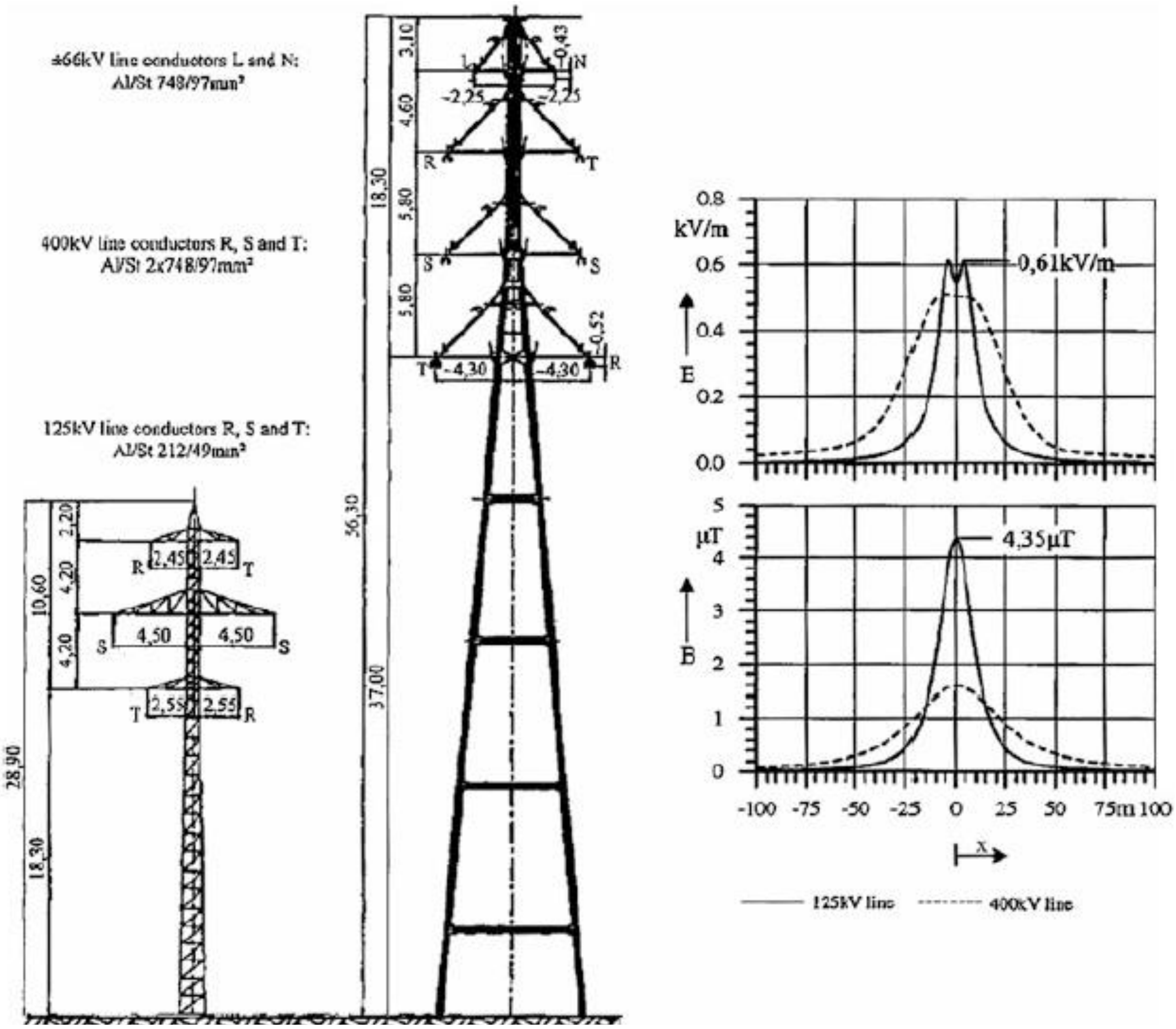


Figure 2.7 - Comparison between the existing 125 kV line and the new 400 kV compact line. Left: comparison of size and row right: comparison of the E and B fields [10]

2.1.6 Belgium: Bévercé, Amel, Bütgenbach line uprate from 70 kV to 110 kV

Elia, the Belgian transmission system operator (TSO), uprated the existing East Loop single-circuit 70-kV OHL to a 110 kV double-circuit compact line (commissioned in December 2016) with the possibility of further uprate to 150 kV in the future [11]. The uprated line maintains the same ROW and the same ground clearance as the old obsolete line. The old 70-kV rectangular-section concrete poles were mainly replaced by new concrete monopoles. Additionally, three composite gantry poles with ICAs were erected near the Bütgenbach substation. This gantry bipolar structure with a connection between the poles used together with ICAs (Figure 2.8) was found to result in a shorter overall line while still meeting relevant standards. The three-section poles were installed on concrete foundations.

Figure 2.8 - Composite gantry poles with ICAs (left) and tower foundations (right) [11]

2.2 Compact Transmission Lines

Constructing new OHLs is becoming increasingly more difficult. One of the main hurdles that needs to be overcome is securing the necessary ROW. This can create friction between land owners and OHL operators, potentially resulting in lengthy delays. Compaction of lines, which entails reduced phase-to-phase distances compared to conventional lines, can provide a solution and it can be achieved with the use of special insulators and/or the reduction of interphase overvoltage levels [12]. Compact OHLs are not only designed to minimise the ROW but in many cases to also reduce the overall visual impact of the OHL to the surrounding landscape. In addition to new routes, compact OHLs have been successfully employed to reuse existing ROWs while increasing the power transfer capability of the transmission corridor previously occupied by an older or decommissioned line. The space saving offered by compact lines can be realised with the use of ICAs on conventional lattice structures, on space-saving lattice structures, or on monopoles.

2.2.1 Belgium: 380 kV Eeklo Noord – Van Maerlandt compact line

Elia, the Belgian TSO, constructed a new 380 kV compact OHL mainly to facilitate the connection to offshore wind generation in the North Sea as well as interconnection with the U.K [13]. One of the aims of the project was to try and maintain the tower silhouettes of the existing 150 kV line which the new compact line was partially upgrading as part of the Stevin project. The compact line utilises ICA on steel lattice towers (Figure 2.9), specifically pivoting Vees (PV) for tangent towers (up to 3 gon running angle) and a non-pivoting Vee (NPV) design for small running angles (< 10 gon).

Figure 2.9 - Pre-existing 150 kV line (left) and new 380 kV compact line with ICAs (right) [13]

For the installation of the ICAs a flexible mounting platform was developed to raise them in place (Figure 2.10). This method was preferred to the alternative of preassembling sections of the tower at ground level, albeit slightly less efficient. The reasoning was due to the increased requirements for safety and coordination at ground level as well as due to the higher risk of damaging the ICAs. With the chosen installation method, it was possible to install three cross-arms per hour or finish one structure per half a day.

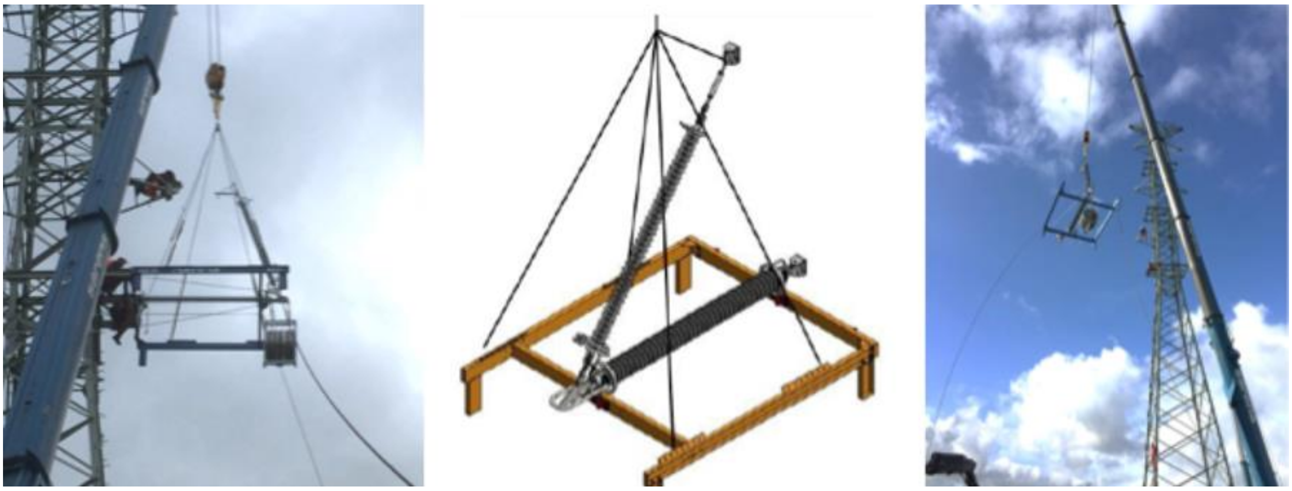


Figure 2.10 – ICA installation using flexible mounting platform [13]

For maintenance purposes it was deemed necessary to develop a suitable access workbench (Figure 2.11) to facilitate access to the ends of the ICAs without the need for heavy trucks or cranes since many of the towers do not have road access.

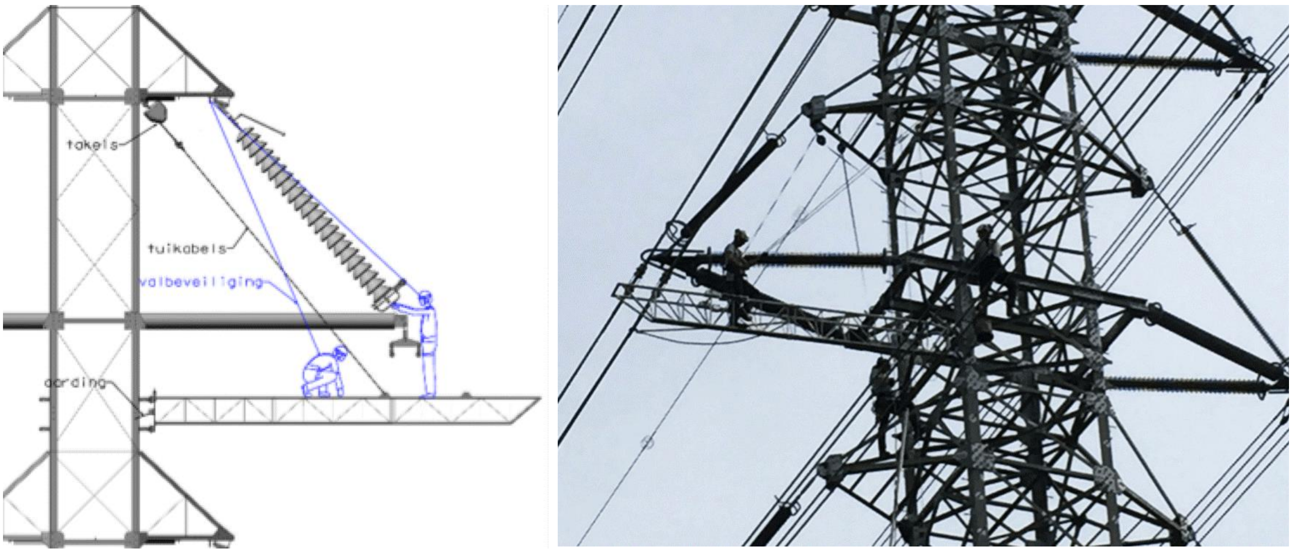


Figure 2.11 - Access workbench [13]

2.2.2 Spain: 220 kV Mudarra – La Olma compact line

Red Eléctrica de España constructed a new 220 kV single-circuit compact OHL near Valladolid. The line employs ICAs (horizontal Vees) on lattice structures. Typical tower height is 26 m and conductor separation (left from right) is approximately 6 m. There is one conductor per phase and the structure are designed to support a second circuit. The line is running through mostly flat agricultural terrain. It essentially replaced an old decommissioned (in 1985) 132 kV line with the new compact line fitting within the existing ROW.

Figure 2.12 - Horizontal Vee ICAs (left) and compact line running through agricultural land (right) [14]

2.2.3 Italy: 380 kV Villanova – Gissi compact line

Terna Rete Italia developed a new structure, the “Vitruvio” tower, that can be equipped with ICAs for the construction of compact OHLs with 10 towers, tension and suspension (Figure 2.13), installed on the 380kV double-circuit “Villanova – Gissi” OHL in 2016 [15]. The structure is composed of two standard lattice steel structures, one inside the other, to form a composite octagonal section with the same dimensions of a steel monopole. The lattice structure can be covered with thin steel plates to give the impression of a monopole. Specially designed glass and porcelain “anti-torsional” ICAs have been employed together with special axisymmetric suspension clamps. The clamp is connected to the porcelain post insulator with a ball joint to minimise the risk of insulator damage in case of broken conductor or unbalanced conductor bundle load (Figure 2.14). The cross-arms connections are reinforced to optimise the internal shear load distribution and to avoid local bending on angles. The line is using triple-bundle ACSR 31.5 mm conductors and a 17.9 mm ground wire.

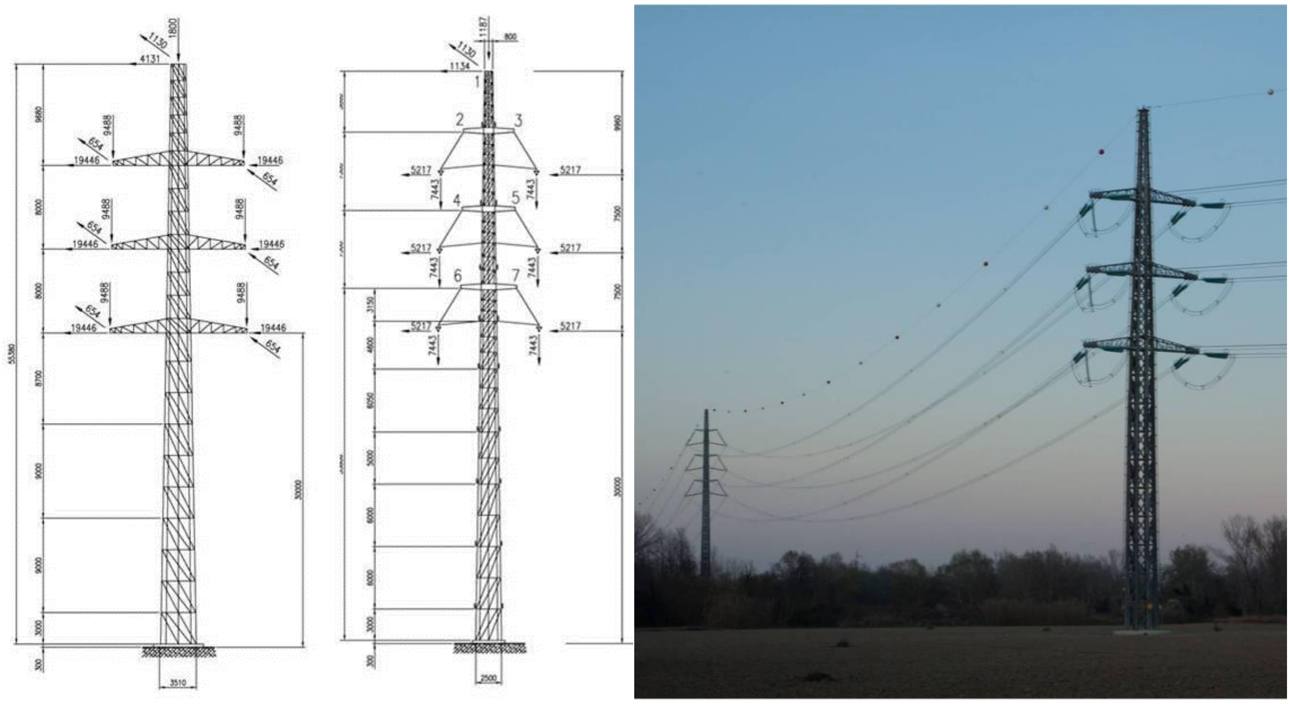


Figure 2.13 - Tension and suspension "Vitruvio" towers [15]

Figure 2.14 - Vitruvio tower main members connections and internal view (left), assembled tower with and without external cover (middle), suspension clamp and ball joint (right). [15]

2.2.4 Netherlands: 380 kV Wateringen – Bleiswijk compact line

TenneT, the Dutch national TSO constructed a compact 380 kV OHL comprising 33 "Wintrack" towers [16]. These towers are steel bi-poles with 16 metres, pole-to-pole separation, with typical height of 54 m consisting of two sections. Typical span lengths can reach 350 m to 400 m. The line is using silicone rubber composite ICAs (braced posts) with the post insulator having a diameter of 100 mm supporting a 620 mm quad-bundle AAAC conductor arrangement. The line is capable of carrying up to 1000 A per circuit.

Figure 2.15 - Wintrak ICA (left) and Wintrak towers (right) [16]

2.2.5 Dubai: 420 kV Mushrif – Nahda compact line

The Dubai Electricity & Water Authority (DEWA) constructed a new compact 420 kV double-circuit OHL in 2007 running in parallel with a conventional OHL of the same voltage [10]. The line employs steel monopole structures and ICAs to achieve a much narrower ROW than the conventional line (Figure 2.16). It is using quad-bundle AAAC Yew conductors with 450 mm spacing (vertical and horizontal) to reduce audible corona noise compared to a twin-bundle configuration.

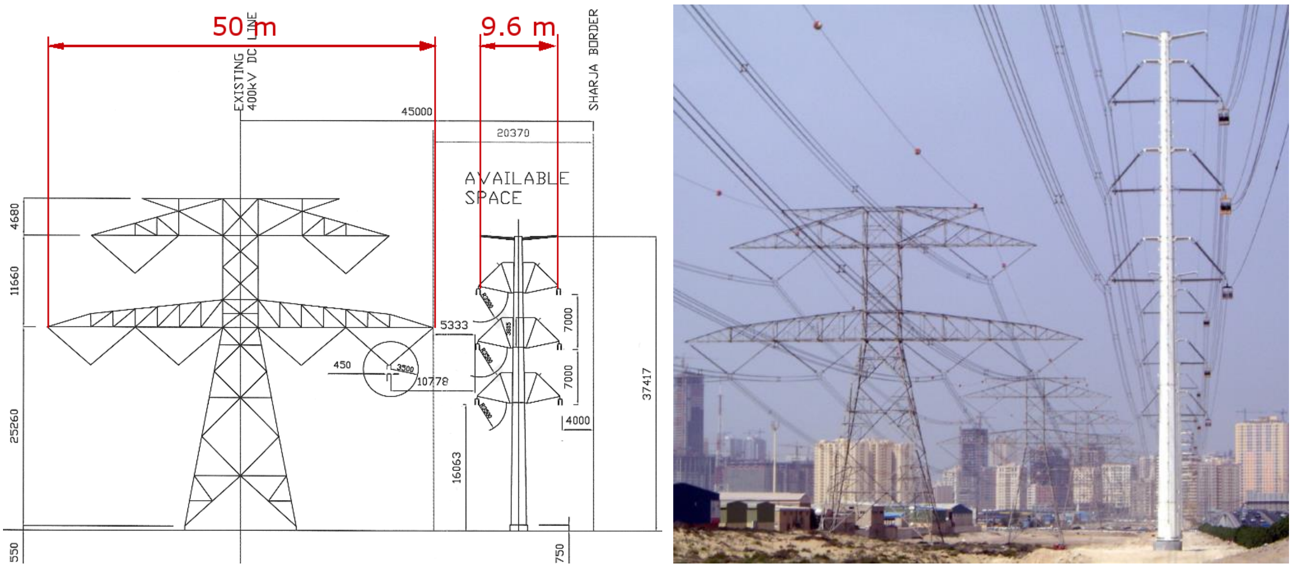


Figure 2.16 - 420 kV compact next to the existing conventional 420 kV line [10]

2.2.6 Sweden: 400 kV compact line test span at STRI

A short test span of a new compact OHL concept was trailed in 2001-2002 [17]. The single circuit line consists of steel monopole structures with height of 19 m. Hollow-core post insulators filled with special foam are used to support the twin-bundle conductor configuration. There is one vertical insulator with rated at 148 kN and creepage of 8600 mm and two horizontal insulators rated at 50 kN and circa 8000 mm creepage. The design required one of the ROW compared to a conventional 400 kV line. This concept was considered as a solution for spans up to 250 m over relatively short distances e.g. urban areas with narrow transmission corridors or environmentally sensitive routes due to the reduced visual impact. The electromagnetic fields for this line were found to be 40% of those of a comparable conventional OHL. Additionally, the installation using pre-assembled superstructures was found to provide additional savings.

Figure 2.17 - 400 kV compact OHL test span at STRI using foam-filled hollow core post insulators

2.2.7 Brazil: 230 kV compact line experimental span

COPEL transmission has constructed a test span in 2003 consisting of 4 towers for a compact 230 kV OHL for urban environments. The line is using concrete post with average height of 22 m and phase separation of 3 m [18]. The ICAs consist of silicone rubber insulators with minimum dry arcing distance of 1800 mm and minimum creepage distance of 4600 mm. The line employs twin-bundle ACSR Ibis conductors and two shield wires (4/0 AWG) one above and the other below the phase conductors. The latter is for providing protection against accidental contact with the bottom phase conductor and for reducing short-circuit currents and ground level EMF [19].

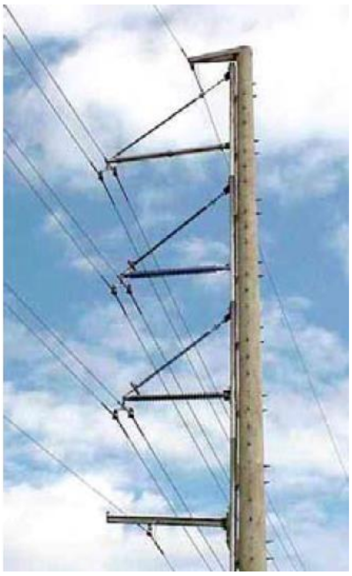


Figure 2.18 – ICA (left) and suspension structure (right)

2.3 Novel Structures, Visual Impact and Environmental Considerations

2.3.1 Italy: 380 kV Trino – Lacchiarella line

Terna Rete Italia constructed a line section using six “Germoglio” towers [20]. The main aim was to minimise the visual impact of the line by using structures that resemble trees. The line is using triple-bundle ACSR conductors with 31,5 mm diameter and two separate ground wires on each arm with 17.9 mm diameter. To suspend the conductors different composite insulator arrangements are used for each phase as follows:

- the higher phase is connected to the top of the tower with a composite insulator and to the main body with porcelain post insulators
- the middle phase is connected to the main body with porcelain post insulators
- the lower phase is connected to the main body with porcelain post insulators and to the bottom of the tower with a composite insulator through the counterweights system which regulates the load applied by the insulating equipment on the top of the tower

To ensure the structural stability of the line section extra deep foundations were used. To allow for maintenance operations, each tower is equipped with an external rail, which replaces the common climbing devices and allows the use of a semi-automatic lifter. Additionally, special devices for the maintenance tool connections were welded on the upper part of tower arms for climbing.

Figure 2.19 - Trino – Lacchiarella "Germoglio" towers in operation [20]

2.3.2 South Africa: 400 kV Palmiet – Stikland line

A new 400 kV compact transmission line was constructed by Eskom in the Cape Town area. The line provides an additional route connecting the Palmiet pumped storage generation site with the substation in Stikland. The line is routed through pristine properties and nature conservation zones. Aiming for the construction of an environmentally friendly line utilising limited ROW and foundation space, the line utilises steel monopole towers fitted with ICAs, among other compact tower designs. Specifically, braced double solid core post insulator assemblies were utilised on the 531 A (Suspension) and B (0 – 10 degrees angle deviation) towers (Figure 2.20). The line is using a triple Kingbird conductor with a 380 mm sub-conductor spacing [21].

Figure 2.20 - 531A single pole suspension steel mast and double braced post insulator [21]

2.4 Right of Way (ROW) and Clearances

2.4.1 Greece: 150 kV compact line

The Public Power Corporation constructed single and double-circuit 150 kV compact lines in the Athens area [22]. The lines utilise polygonal tapered steel poles and ICAs (pivoting Vees). The lines were primarily designed to minimise the ROW, reduce the impact to properties from the construction of foundations and reduce the visual impact since the line is passing through residential areas. The double circuit line has a 25 m ROW, reduced substantially from the 40 m required for a conventional line. The poles have a maximum height of 33 m and the foundation depth does not exceed 3 m. The line employs a Grosbeak ACSR conductor with diameter of 25.1 mm. The ICA consists of a 10-unit cap-and-pin insulator and a post insulator (Figure 2.21).

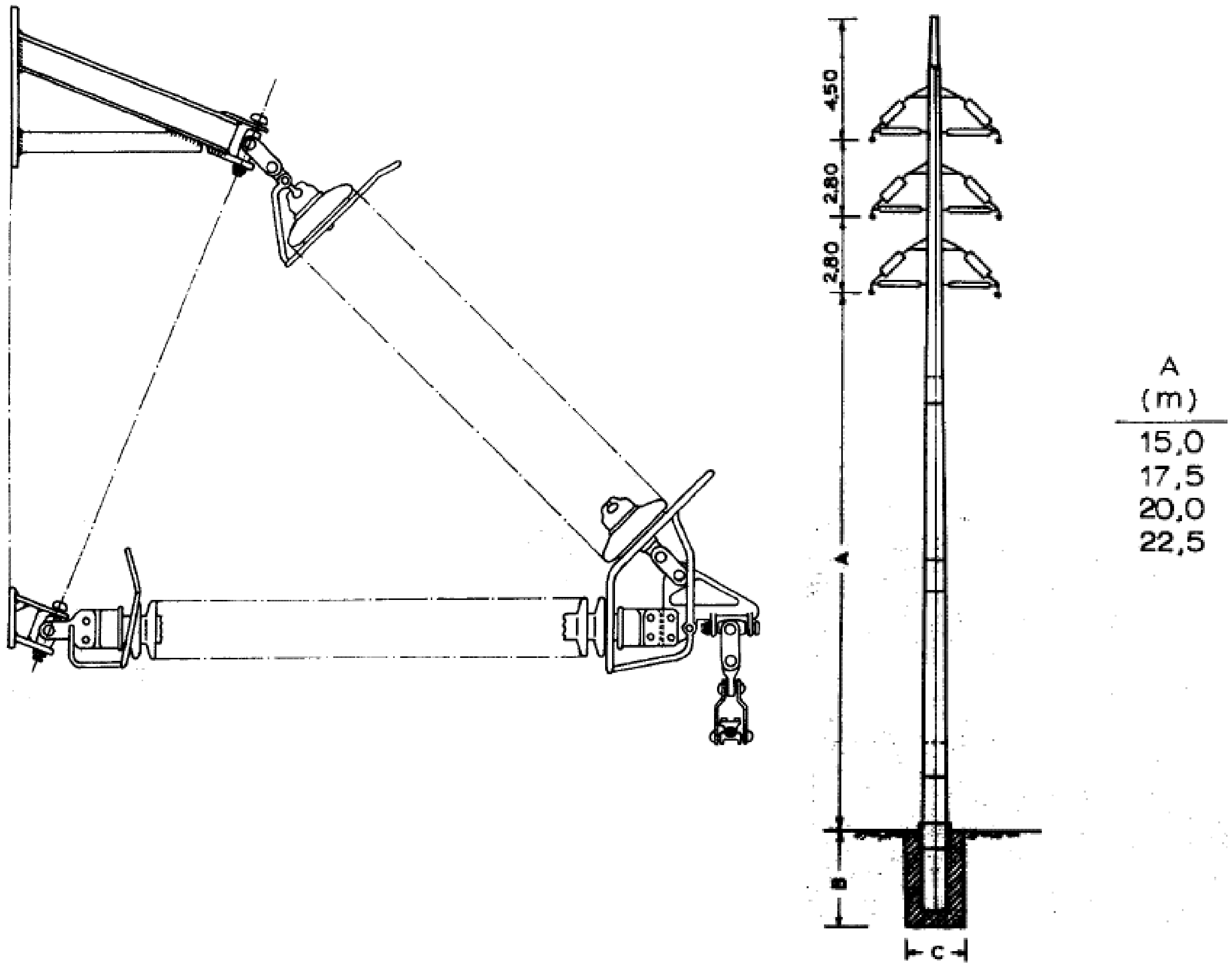


Figure 2.21 - ICA (left) and double-circuit compact line (right) [22]

2.4.2 India: 132 kV Imlibun – Bandlaguda line

TSTRANSCO, Hyderabad performed a replacement of the steel lattice cross-arms on a 132 kV DC OHL with ICAs in 2019 to improve the ground clearance of the line passing through an urban area (Figure 2.22). By using UCAs the conductor to ground clearance was increased by 2 m. Additionally, the ROW was reduced by 4.1 m.

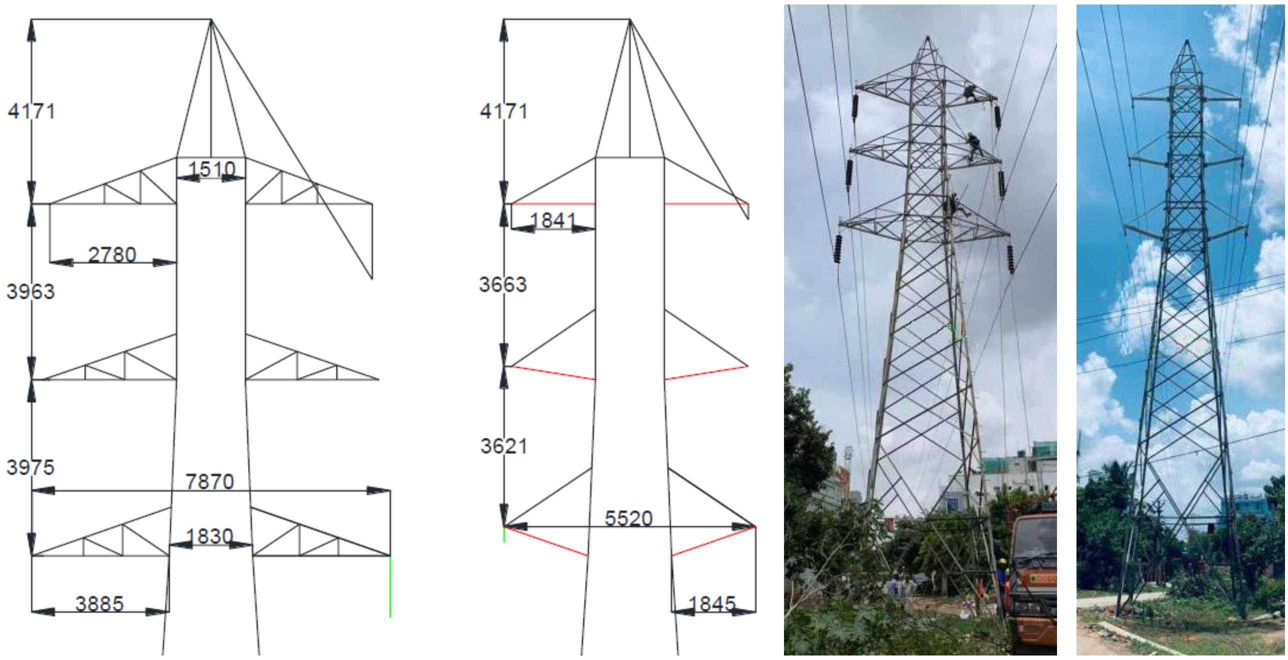


Figure 2.22 – OHL before and after the ICA replacement

2.5 Summary

Table 2.1 – Table of transmission lines utilising ICAs sorted by operating voltage

Country	Line	Operator	Voltage (kV)
Belgium	Bévercé, Amel, Bütgenbach	Elia	110
Slovenia	Jesenice – Kranjska Gora	Elektro Gorenjska	110
India	Imlibun – Bandlaguda	TSTRANSCO	132
Greece	N/A	Public Power Corporation	150
Spain	Tambre – Santiago II	Union Fenosa	220
Spain	Mudarra – La Olma	Red Eléctrica de España	220
Brazil	Experimental span	COPEL	230
USA	N/A	PacifiCorp	345
Belgium	Eeklo Noord – Vanmaerlandt	Elia	380
Italy	Villanova – Gissi	Terna Rete Italia	380
Italy	Trino – Lacchiarella	Terna Rete Italia	380
Netherlands	Wateringen – Bleiswijk	TenneT	380
South Africa	Palmiet – Stikland	Eskom	400
Sweden	Test span at STRI	N/A	400
Switzerland	Geneva – Lausanne	Energie Ouest Suisse	400
Austria	N/A	N/A	420
Dubai	Mushrif – Nahda	N/A	420

3 Policy and Standards

3.1 Mechanical performance

The majority of OHL insulators are designed to be able to withstand tensile forces while line post and braced post insulators are subjected to cantilever or compression forces, or a combination of the two. The maximum occurring mechanical load, also known as specified mechanical load (SML), is calculated for a number of load cases that take into consideration the following parameters:

- conductor weight
- wind load
- ice load
- construction and maintenance loads
- security loads (failure containment, broken wire)

The design load of an insulator for each load case is determined by multiplying the SML by a partial factor which ranges between 1.0 and 2.0 [23]. The National Normative Aspects (NNA) for each country, for example the BS EN 50341-2-9 [24] for the UK, specify methods for calculating the parameters mentioned above and recommend partial factors for specific load cases. Some of them that depend on specific project requirements can be changed accordingly but they cannot infringe the minimum limit set by the NNA.

To assess the long-term mechanical performance and establish the rating of composite insulators, the damage limit concept is used, which was originally introduced by Dumora and Feldmann [25] and later adopted by the IEC 61109 [26]. The damage limit is the critical load limit after which the core starts showing plastic behaviour as the weaker fibres start breaking.

ICAs are not covered explicitly by NNAs and while aspects of the load calculation methodologies described within them might apply, this is not always the case. ICAs in many cases consist of more than one insulating member and these members can be of different type i.e. tension and compression (brace and post). Also, ICA assemblies can be rigidly attached to the tower or attached through an articulated fitting which allows the assembly to swing. IEEE Task Force 15.09.09.07 [27] has provided recommendations on how to calculate the mechanical loads on Braced Insulator Assemblies. Furthermore, due to the bending loads that rigidly attached assemblies are likely to be subjected to in service, it is not recommended to use ceramic post insulators for such applications.

3.2 Electrical performance

The operating voltage is the primary parameter that determines the creepage distance of an insulator; this is the shortest distance along the surface of the insulator. The lightning and switching impulse levels are considered when determining the dry arc distance, the shortest distance in air between the HV and ground-end fittings. The withstand voltage levels are specified in the NNA for each country. Table 3.1 shows the relationship between operating voltage, impulse levels and minimum clearance distances for UK transmission.

Table 3.1 - Withstand voltage levels and clearances for UK transmission [24]

Nominal system voltage (kV)	**132**	**275**	**400**
Lightning impulse level (kV)	550	1050	1425
Switching Impulse Level (kV)	650	850	1050
Phase to earth clearance (m)	1.1	2.1	2.8
Phase to phase clearance (m)	1.4	2.4	3.6

For ICAs the electrical strength of the difference insulators comprising the assembly needs to be coordinated to ensure adequate performance. According to [27], the insulators must be able to individually withstand the aforementioned electrical stresses. A leakage distance for the entire assembly can be specified by considering the shorter leakage distance of the insulator components.

3.3 Insulator housing performance

The IEC/TS 60815-3 [28] provides recommendations for selecting and dimensioning composite insulator profiles based on the expected severity of site pollution. It categorises insulator profile parameters in three classes (none, minor, major deviation) based on how much they can reduce the performance of the insulator. It is advised that none of the parameters should lie in the 'major deviation' category and preferably with only one in the 'minor deviation' category. Table 3.2 shows the recommended values of the parameters for different insulator positions, dimensions and profile types.

Table 3.2 - Recommended values of profile parameters [4] adapted from [28]

			Deviation		
Parameter	**Position / Dimensions**	**Profile**	**None**	**Minor**	**Major**
s/p	Shank diameter ≤ 110 mm	w/ under-ribs	0.85 - 1	0.75 - 0.85	0.4 - 0.75
		w/o under-ribs	0.75 - 1	0.65 - 0.75	0.4 - 0.65
	Shank diameter > 110 mm	w/ under-ribs	0.75 - 1	0.6 - 0.75	0.4 - 0.6
		w/o under-ribs	0.65 - 1	0.5 - 0.65	0.4 - 0.5
c (mm)	All	Uniform	25 - 50	22.5 - 25	20 - 22.5
		Alternating	40 - 50	30 - 40	20 - 30
l/d	All	All	0 - 4.5	4.5 - 5.5	4.5 - 7
α	Vertical	All	5^o - 25^o	0^o - 5^o 25^o - 35^o	35^o - 60^o
	Horizontal c < 30 mm		0^o - 20^o	20^o - 30^o	30^o - 60^o
CF	All	All	2.5 - 4.25	4.25 - 5	5 - 5.5

- c is the minimum distance between adjacent sheds of the same diameter
- d is the straight air distance between two points on the insulating part or between a point on the insulating part and another on a metal part
- l is the part of the creepage distance measured between the above two points
- α is the shed angle
- Creepage factor, CF, is equal to L/A where L is the total creepage distance of the insulator and A is the arcing distance of the insulator

3.4 Materials performance

The quality of materials used for the core and housing of composite insulators helps to maintain their integrity. The core must have a low void percentage to reduce the probability of electrical discharges that result in degradation and reduce its resistance to puncture. These properties of the core material are validated by the dye penetration and water diffusion tests specified in the BS EN 61109 [26].

The housing material must exhibit high resistance to tracking and erosion in the presence of arcing activity [29]. To achieve these properties, the basic material of the housing, SiR or EPDM, is combined with filler materials, the most common of which is Alumina Trihydrate (ATH) [30]. These materials increase the thermal conductivity of the housing, conducting heat generated from discharges away from hot areas of the surface, thus decreasing the rate of erosion [31]. Other additives are used such as UV stabilisers, antioxidants and ionic scavengers, to ensure the longevity of the housing material under service conditions which include exposure to solar radiation, pollutants and biological growth [28]. Of equivalent importance to the long-term electrical performance of insulators is the quality of the interfaces. BS EN 62217 [32] specifies various tests for checking the quality of the housing material and interfaces such as the steep-front impulse voltage test and the water immersion test among others.

3.5 Electric field management

Electric field management on insulators or insulator assemblies is not presently covered by any one specific standard. It is recognised however, that this is of particular importance for composite insulators since high electric field gradients can not only contribute to audible noise and radio interference but can also damage the housing material and/or end-fitting seals [4]. Individual operators generally specify the acceptable limits for electric field magnitude which are based on the recommendations of the IEEE taskforce on Electric Fields and Composite Insulators [33] and the EPRI [34]. For example, in the UK National Grid specifies the following:

- Maximum permissible electric field magnitude on the sheath and sheds measured 0.5 mm from the surface: 4.5 kV_{rms}/cm
- Maximum permissible electric field magnitude at the triple junction: 3.5 kV_{rms}/cm
- Maximum permissible electric field magnitude inside the core and weather-shed material: 30 kV_{rms}/cm
- Maximum permissible electric field magnitude on metallic end-fittings and electric field grading devices: 18 kV_{rms}/cm

Electric field for ICAs can be managed in a similar way to other OHL insulators, i.e. with the use of grading rings. Nevertheless, depending on the voltage level and/or implementation, simplifications or changes can be made to the grading rings. For example, a grading ring for the compression member(s) might not be necessary if one of the tension member(s) is sufficient. On the other hand, single piece bespoke corona rings might be necessary to provide sufficient field grading for the entire ICA assembly [27].

3.6 Radio interference

Corona discharges and the associated transient currents and electromagnetic field can propagate along OHL conductors for significant distances until their amplitude attenuates. They can cause interference in TV and AM-radio receivers in the vicinity of the line [35, 36]. The interference caused by transmission lines attenuates at relatively short distances away from the line since the frequency spectrum of the pulses can extend up to approximately 100 MHz. CISPR TR 18-1 [37] details methods for calculating for determining the radio noise produced by corona on OHL and CISPR TR 18-2 [38] provides details on how to perform the relevant measurement. The latter also lists frequency bands that need to be protected from interference.

3.7 Electromagnetic fields (EMF)

In the UK the Energy Networks Association has agreed to a voluntary code of practice for demonstrating compliance with EMF exposure guidelines [39]. Exposure limits adopted are the ones defined by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for limiting exposure to EMF in the range 100 kHz – 300 GHz which have been updated in 2020 [40]. The restrictions are determined for two scenarios, occupational and general public, and are summarised in Table 3.3 and Table 3.4 for reference. For OHLs at voltage levels of 275 kV and above evidence of compliance might include calculations or measurements of maximum fields directly under the lines or at the location of the closest property. Furthermore, compliance with the Optimum Phasing of high voltage double-circuit Power Lines voluntary code of practice [41] needs to be demonstrated. This is particularly pertinent to ICA applications since phase separation will be different than that of conventional lines and therefore might necessitate a switch from untransposed to transposed phasing or vice versa to ensure compliance with the aforementioned codes of practice.

Table 3.3 - Basic restrictions for electromagnetic field exposure from 100 kHz to 300 GHz, for averaging intervals ≥6 min.[a] [40]

Exposure scenario	Frequency range	Whole-body average SAR ($W\ kg^{-1}$)	Local Head/Torso SAR ($W\ kg^{-1}$)	Local Limb SAR ($W\ kg^{-1}$)	Local S_{ab} ($W\ m^{-2}$)
Occupational	100 kHz to 6 GHz	0.4	10	20	NA
	>6 to 300 GHz	0.4	NA	NA	100
General public	100 kHz to 6 GHz	0.08	2	4	NA
	>6 to 300 GHz	0.08	NA	NA	20

[a]Note:

1. "NA" signifies "not applicable" and does not need to be taken into account when determining compliance.
2. Whole-body average SAR is to be averaged over 30 min.
3. Local SAR and S_{ab} exposures are to be averaged over 6 min.
4. Local SAR is to be averaged over a 10-g cubic mass.
5. Local S_{ab} is to be averaged over a square 4-cm^2 surface area of the body. Above 30 GHz, an additional constraint is imposed, such that exposure averaged over a square 1-cm^2 surface area of the body is restricted to two times that of the 4-cm^2 restriction.

Table 3.4 - Basic restrictions for electromagnetic field exposure from 100 kHz to 300 GHz, for integrating intervals >0 to <6 min.[a] [40]

Exposure scenario	Frequency range	Local Head/Torso SA ($kJ\ kg^{-1}$)	Local Limb SA ($kJ\ kg^{-1}$)	Local U_{ab} ($kJ\ m^{-2}$)
Occupational	100 kHz to 400 MHz	NA	NA	NA
	>400 MHz to 6 GHz	$3.6[0.05+0.95(t/360)^{0.5}]$	$7.2[0.025+0.975(t/360)^{0.5}]$	NA
	>6 to 300 GHz	NA	NA	$36[0.05+0.95(t/360)^{0.5}]$
General public	100 kHz to 400 MHz	NA	NA	NA
	>400 MHz to 6 GHz	$0.72[0.05+0.95(t/360)^{0.5}]$	$1.44[0.025+0.975(t/360)^{0.5}]$	NA
	>6 to 300 GHz	NA	NA	$7.2[0.05+0.95(t/360)^{0.5}]$

[a]Note:

1. "NA" signifies "not applicable" and does not need to be taken into account when determining compliance.
2. t is time in seconds, and restrictions must be satisfied for all values of t between >0 and <360 s, regardless of the temporal characteristics of the exposure itself.
3. Local SA is to be averaged over a 10-g cubic mass.
4. Local U_{ab} is to be averaged over a square 4-cm^2 surface area of the body. Above 30 GHz, an additional constraint is imposed, such that exposure averaged over a square 1-cm^2 surface area of the body is restricted to $72[0.025+0.975(t/360)^{0.5}]$ for occupational and $14.4[0.025+0.975(t/360)^{0.5}]$ for general public exposure.
5. Exposure from any pulse, group of pulses, or subgroup of pulses in a train, as well as from the summation of exposures (including non-pulsed EMFs), delivered in t s, must not exceed these levels.

4 Challenges for Implementation

The use of RICAs can have various techno-economic challenges that will need to be overcome if they are to be used effectively. Many of these are a result of the fact that an OHL using RICAs is essentially compacted when compared with a conventional line of the same voltage. Others are associated with the changes that will need to be made to an existing OHL.

4.1 Line stability

ICAs have substantially different mechanical properties than other OHL insulator arrangements and these can potentially affect the overall stability of the line on which they are installed. Generally, the tension members (braces) of an ICA assembly take the vertical loads while the compression members (posts) take the horizontal loads (Figure 4.1). In the case of rigidly attached ICAs, it is important to avoid a cascade failure if a compression member fails. Depending on the expected loads it might be necessary to use bottom fittings with fail-safe bases and suspend the conductor with load release clamps. Even when a compression member fails, the tension member in most cases will be sufficient to prevent conductor release however if there are concerns regarding this scenario the use of additional tension members might be considered [10]. More information on this is provided in the design considerations report.

Application of pivoting ICAs is accompanied by its own unique challenges. The compression members in this case can be subjected to eccentrically applied loads meaning that the insulators can also be subjected to bending. This has been found to substantially reduce the measured failing load. To alleviate this problem the use of special fittings might need to be considered (Figure 4.1). Certain conditions such as wind gusts, irregular icing, and large variations in span length, can result in temporary differential line tension at the tip of a cross-arm. This can lead to considerable deflections for pivoting ICAs that can compromise the electrical clearance between conductor and tower. While in the majority of cases the ICA will regain stability, if conditions are severe enough, e.g. very high wind load toward the line, the ICA can rotate sufficiently for the conductor to come in contact with the tower [10]. To avoid such occurrences, additional measures might need to be considered that can include increasing the inclination angle of the ICA or the angle between tension and compression members, increasing conductor tension, and using 'stabilising' cross-arms in long line sections [27].

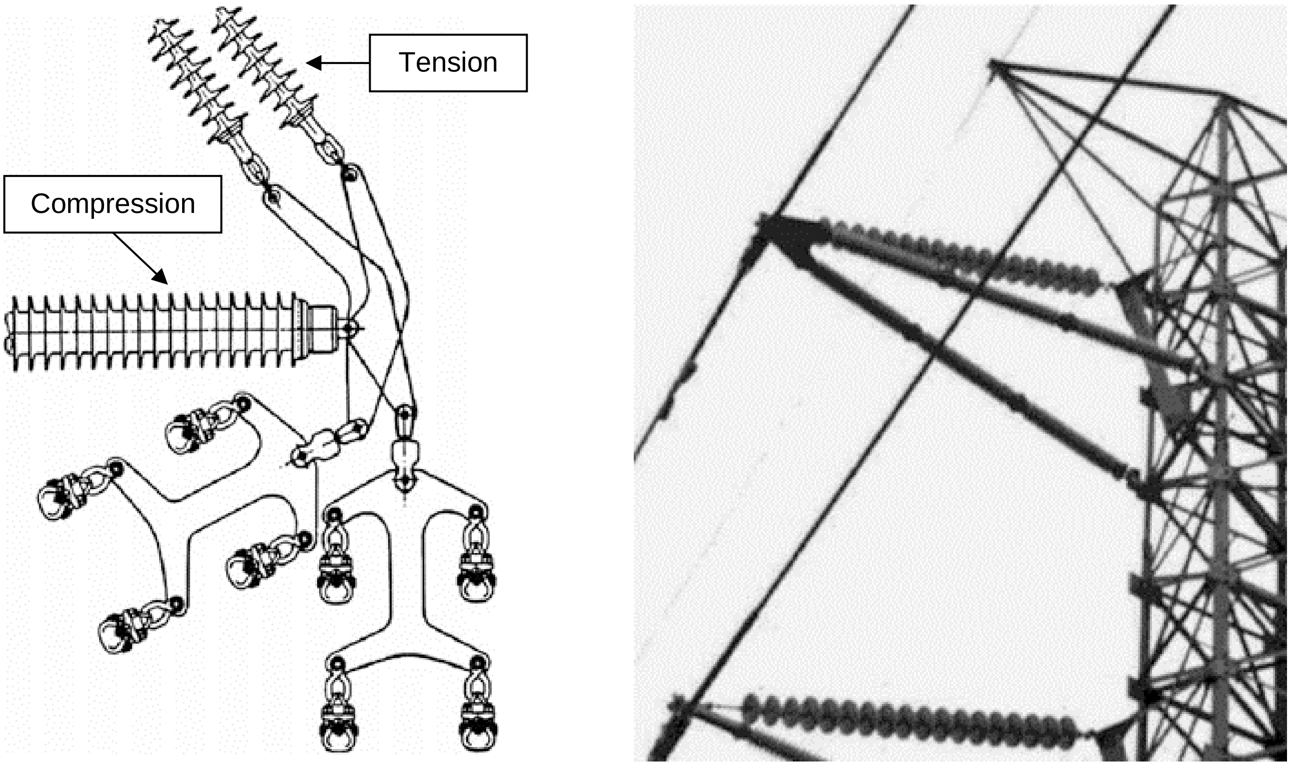


Figure 4.1 – "Boomerang" fitting with quad bundle (left) and stabilising ICA on 345 kV line (right) [10]

4.2 Phase spacing and conductor movement

The use of RICAs results in a reduction of conductor clearances which in many cases brings them close to their minimum allowable values. Since RICAs modify the line structures, conductor galloping behaviour is likely to change. Galloping describes the large amplitude, low frequency, wind-induced oscillation of conductors or conductor bundles and depends not only on aerodynamic characteristics but also on mechanical properties such as damping, stiffness, and mass distribution [42]. Oscillation amplitudes can reach values close to the sag of a span and as a result galloping can cause phase-to-phase flashovers. Furthermore, additional excessive loads can cause damage to the conductors themselves as well as other line equipment including the tower and the insulators. Hence, the conductor or conductor bundle galloping needs to be evaluated to ensure that the reliability of the line is not adversely affected [12]. If the problem is deemed to be severe, the use of galloping control devices, such as interphase spacers, might be necessary.

4.3 Corona, EMF, and audible noise

Corona discharge on OHL conductors is a complex phenomenon influenced by various factors including voltage level, conductor diameter, bundle geometry, weather conditions, and phase-to-phase separation. The latter will decrease in cases where RICAs are used for uprating existing lines which will result in increased surface gradients on the conductors. On one hand, this is beneficial since it results in reduction of EMF. On the other hand, corona activity will increase accompanied by increases in radio interference and audible noise. Although noise and acceptable limits can vary between locations, a noise level 7 dB above the background level is considered disturbing. Since corona problems are extremely difficult to address after an OHL is commissioned, it is advisable to be conservative with corona related aspects. Particular attention should be paid to the conductor bundle size and configuration which might accompany RICA applications to ensure it is suitable for all weather possibilities [12].

4.4 Insulation co-ordination

The term insulation co-ordination is defined in BS EN IEC 60071 [43] as the "*selection of the dielectric strength of equipment in relation to the operating voltages and overvoltages which can appear on the system for which the equipment is intended, and taking into account the service environment and the characteristics of the available preventing and protective devices*". Overvoltages on OHLs are generally caused by switching operations, lightning strikes or faults. Rating of equipment and clearances are predominantly determined by the expected magnitude, duration and frequency of these overvoltages. Insulation co-ordination considers the probability of overvoltage occurrence to calculate the risk of insulation failure.

Application of RICAs can affect insulation co-ordination since the position of the phase conductors relative to the tower as well as relative to each other will be different than for a conventional OHL. This can minimise the beneficial effect of certain overvoltage control measures. An example is the shield wire which aims to reduce the probability of direct lightning strikes on phase conductors [44]. With RICA application on existing towers the overvoltage clearance envelope will change since the conductor will be positioned closer to the top of the tower. Another example is the enhancements that might need to made to the towers and their foundations in order to cope with the potentially higher mechanical loads due to RICAs. These can potentially affect the footing resistance which influences the probability of back-flashover. Addressing the aforementioned challenges might necessitate modifications to the tower-top geometry, use of additional shield wires or utilisation of line surge arresters [45]. Hence, insulation coordination will need to be considered carefully in order to ensure the reliability of an OHL using RICAs is not compromised.

4.5 Environmental consideration and outage availability

Retrofitting an OHL with ICAs will inevitably involve construction activities that can affect the environment at the vicinity of the line. Based on the route, an appropriate Environmental Protection Plan might need to be prepared by the operator and approved by the relevant authority before work can commence. Restrictions could be imposed regarding the scheduling as well as the type of activities permitted. These can include the use of specific materials, equipment that can be brought to site, and noise levels among others. Additionally, the plan can contain provisions for the protection of archaeological sites and protection of endangered flora and fauna [46].

Outage availability of the line can also become a challenge when considering RICA application. An OHL being considered for an uprate is likely to be in an already congested corridor and/or being operated close to capacity. Hence, completely removing it from service for extended periods of time might not be an option. At the same time, employing live-line working might also be difficult since, as mentioned previously, use of ICAs results in reduction of clearances compared to conventional lines, which could make the risk of live-line work unacceptable. In such cases, it might be necessary to construct a temporary line by-pass for isolating certain line sections from the live circuit [46].

5 Complementary (and competing) solutions

The primary purpose of RICAs is to increase the power capabilities of existing transmission lines. However, other solutions are available for achieving the same purpose. Their application can be accompanied by different challenges compared to RICAs making them more or less attractive from a technical or financial perspective. More importantly though, some of the alternatives could be used in conjunction with RICAs to achieve even greater improvements to the utilisation of existing OHL structures and corridors.

5.1 Changes to conductor system

Making changes to the conductor system allows for the thermal uprating of an OHL. There are different methods for achieving this. The replacement of existing conductors with larger conductors of bigger cross-sectional area can reduce the electrical resistance and increase the surface area hence increasing the power transfer capability of the line. Alternatively, additional conductors could be used to increase the size of the conductor bundle to achieve a similar effect. However, such changes are associated with substantial costs, increased mechanical loads and complex installation techniques, and as a result tower reinforcements are often necessary [47]. Increasing conductor tension can also be used to increase the rating of an OHL by allowing the conductor to carry more current without infringing ground clearance. This however results in additional loads on towers, insulators and fittings of angle and tension structures in particular. Furthermore, increased conductor tension can increase the likelihood of aeolian vibration and probability of conductor damage [48].

High-Temperature Low-Sag (HTLS) conductors utilise different materials than conventional conductors such as steel or composite cores [49], and annealed aluminium or aluminium alloy strands [50]. These materials limit the thermal elongation of the conductor allowing the conductor to operate at higher temperatures while exhibiting comparable mechanical strength and sag to conventional conductors [51]. The various types of conductors can be found in Appendix A. Generally, application of HTLS conductors can be achieved without substantial modifications to towers, although some will require higher stringing tensions. Hence, reinforcements to terminal and angle structures might be necessary. An example of application of HTLS conductors in conjunction with ICAs is reported in [51] where a 110 kV single-circuit line utilising steel monopoles was uprated from 1092 A to 1879 A, an increase of 72%. The existing ACSR Finch conductor was replaced by a BTACSR conductor. The two conductors have very similar characteristics with the exception of the operating temperature, 80 °C for the former and 150 °C for the latter, hence no modifications to the towers were required.

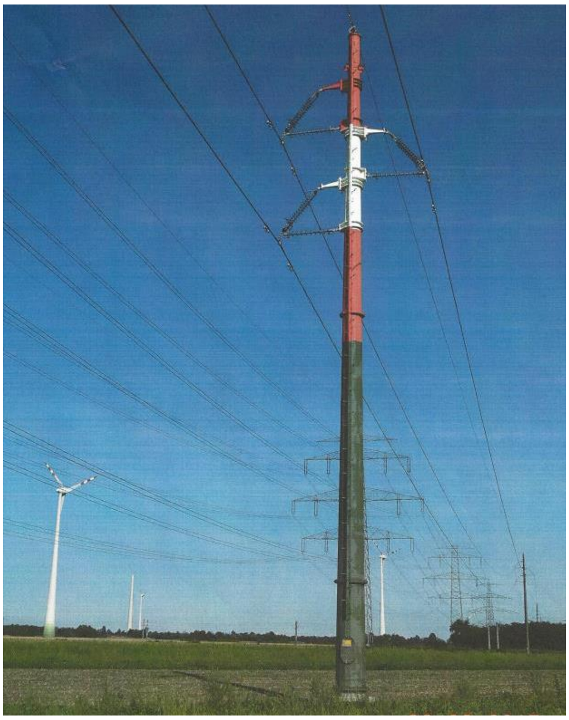


Figure 5.1 – 110 kV compact line with ICAs and HTLS conductor [51]

5.2 Increasing conductor attachement height

The maximum operating temperature of existing conductors can be increased to allow for increased current flow. To maintain the mandated clearances, the conductor attachment height will have to increase and there are several methods with which this can be achieved. ICAs allow for increased sag since the conductor attachment height is raised due to the absence of a suspension insulator. Conductor re-tensioning or the re-purposing of suspension towers as tension towers can be used to allow for additional conductor sag resulting from the increased thermal rating of an uprated line. Provided that the tower foundations are in good condition and can withstand additional loads, another option is to use tower extensions to increase the height of towers, hence increasing conductor ground clearance. Yet another option resulting in the same effect is to install light-duty additional towers at span mid-points, hence reducing the span length which reduces the maximum sag [52]. It is, however, important to keep in mind that additional conductor current and consequent higher temperatures can produce high temperature creep and annealing which alter the physical properties of the conductor resulting in plastic deformation and increased risk of fracture [53].

5.3 High Surge Impedance Loading (HSIL)

The Surge Impedance Loading (SIL) refers to the power that can be delivered by a transmission line to a load equal to its surge impedance, i.e. the characteristic impedance of the line, Z_C:

$$SIL = V^2 / Z_C \tag{1}$$

where V is the voltage.

In such a situation the sending and receiving-end voltages are the same, and all the reactive power demand from the series inductance of the line is supplied by its shunt capacitance. Power transmission above the SIL value results in reactive power consumption from the line which, in addition to the losses, can impact voltage stability and/or necessitate the need for reactive power support [54]. Hence, if the SIL of a line is increased so will its power transfer capability.

The value of SIL is dependent on the conductor bundle characteristics, specifically the number and area of sub-conductors as well as the field intensities on conductor surfaces [55]. Therefore, the SIL value of an OHL can be raised by changing the conductor bundle geometry, a technique known as expanded bundle technology (EXB) [56]. Another technique for increasing the SIL is line compaction, which can be realised with the use of ICAs. The reduction on phase-to-phase spacing increases the coupling between phases and as a result their mutual impedance, Z_m. This in turn reduces the positive sequence impedance, Z_1:

$$Z_1 = Z_s - Z_m \tag{2}$$

where Z_s is the phase self-impedance.

Consequently, the impedance of the line is reduced and as a result, the SIL is increased since it is inversely proportional to the surge impedance. Even after other limiting factors are considered, such as clearances and corona, increases in SIL due to line compaction can reach 20% [54].

Table 5.1 - Comparison of SIL between conventional and HSIL lines of the same voltage [54]

	SIL (MW)	
Voltage (kV)	**Conventional line**	**HSIL line (theoretical)**
69	9-12	up to 36
138	40-50	up to 120
230	120-135	up to 360
500	800-1000	up to 1900

5.4 Line Surge Arresters (LSAs)

The maximum operating voltage of a transmission line is constraint by the clearance requirements relating to overvoltages. Insulation coordination principles defined in BS EN IEC 60071 [43, 57] essentially dictate the sizing of the insulation, and therefore influence the dimensions of the tower, in order to achieve an acceptable level of reliability for the line. By installing line surge arresters (LSAs) not only at the line ends but also at strategic locations along the length of the line switching and/or lightning overvoltage levels can be controlled allowing for reduction in clearances. This in turn can enable the compaction of a new OHL or the voltage uprating of an existing one [58, 59]. There are two types of LSAs, non-gapped line arresters (NGLAs) and externally gapped line arresters (EGLA), each with its benefits and drawbacks. Theoretical studies have demonstrated that the clearances for a conventional 420 kV line can be reduced by as much as 30% with the use of LSAs [60].

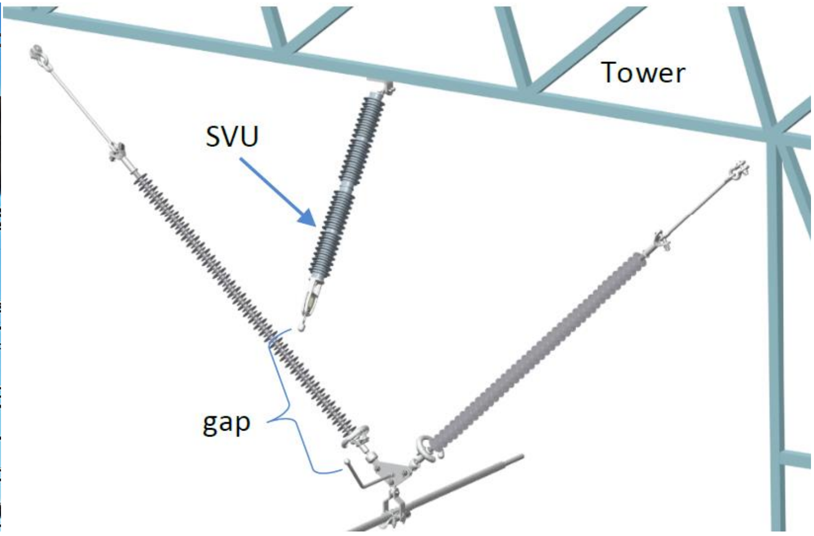


Figure 5.2 - NGLA hanging from the transmission line and grounded to the tower (left) and EGLA mounted inside of a suspension V-string [60]

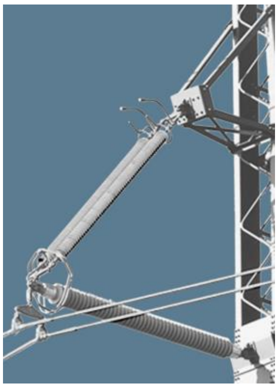
6 Available Technology

6.1 Commerically available solutions

Information regarding commercially available ICA solutions is summarised in Table 6.1. This has been sourced directly from suppliers' product catalogues which are referenced in the Table. The list is not necessarily exhaustive.

Table 6.1 - Commercially available ICAs for transmission applications

Supplier	Configuration	Max. voltage	Representative image
Hubbell Power Systems [61]	Rigid Pivoting	230 kV	
K-Line Insulators [62]	Rigid Pivoting	230 kV	
NGK-Locke Polymer Insulators [63]	Rigid Pivoting	230 kV	

MacLean Power Systems [64]	Rigid Pivoting	345 kV	
PFISTERER [65]	Rigid Pivoting	420 kV	
Bonomi [66]	Rigid Pivoting	500 kV	
Allied Insulators [67]	Rigid	765 kV	

6.2 Non-commerically available and experimental solutions

6.2.1 The University of Manchester and Arago Technology, UK

The development of an ICA for OHLs up to 400 kV (Figure 6.1), funded through the Network Innovation Allowance mechanism (ref.: NIA_NGET0024 [68]), is reported in [4]. The cross-arm consists of four insulating members, end fittings, field grading devices and a nose connection for the attachment of the conductor. The two main structural elements of the assembly have a unique non-cylindrical geometry which gives them improved mechanical characteristics compared to conventional OHL insulators. The ICA was dimensioned based on the requirement of uprating existing 275 kV OHLs to 400 kV. The insulator profile for the compression members was designed according to [28]. Bespoke electric field grading devices were designed and optimised using Finite Element Analysis (FEA) simulations [69].

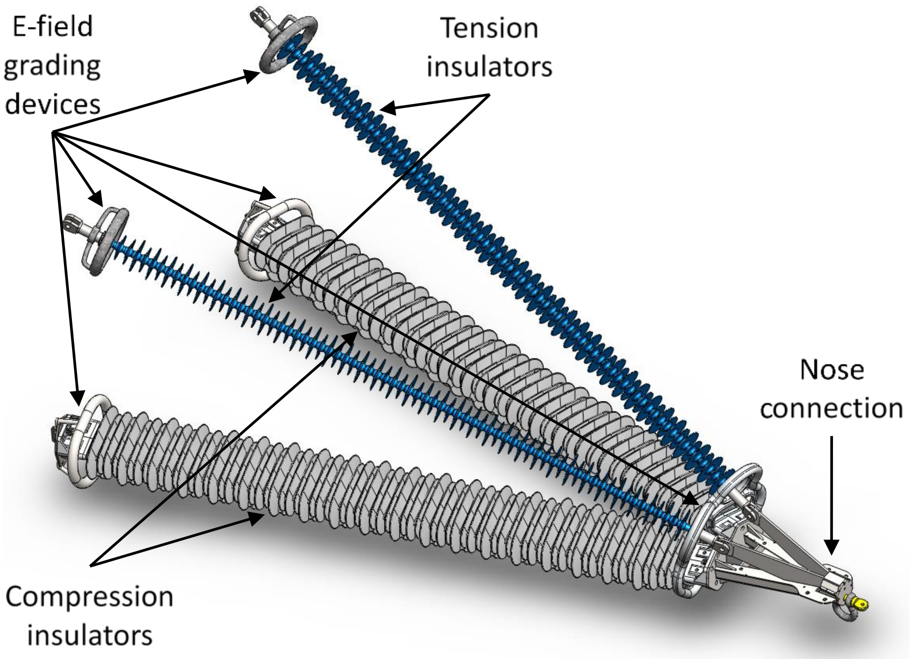


Figure 6.1 – ICA [4]

A type testing regime was drafted based on the standards used for composite OHL insulators, BS EN 61109 [26] and BS EN 62217 [32], and the Technical Specifications of National Grid, TS 3.4.17 [70] and TS 3.4.18 [71]. Extensive testing of the ICA was undertaken at the HV laboratories of the University of Manchester (Figure 6.2).

Figure 6.2 - Wet switching impulse withstand voltage test using bespoke spray system (left) and Corona Extinction test (right)

The ICA technology was field-tested in trials. The first trial saw the installation of four prototype cross-arms on PL16 towers, on a decommissioned 132 kV line in an exposed location of the Scottish Highlands [72]. The trial aimed at evaluating the mechanical capabilities of the cross-arm when exposed to severe weather and to assist with the optimisation of the insulator profile. It also provided the opportunity to test installation procedures (Figure 6.3).

Figure 6.3 - Removing the steel cross-arm (left) and raising the insulating cross-arm (right) [4]

The second trial saw the deployment of two ICAs in a coastal trial facility (Figure 6.4) for a period of six years [73-75]. The cross-arms were energised at 400 kV and monitored with a variety of instruments to evaluate the performance of the compression insulator profile, pollution accretion behaviour over time, and other electrical and material performance aspects.

Figure 6.4 - Live trial site (left) [74] and algae growth on the ICA insulators 35 months (right) [75]

Six 132 kV ICAs were installed on a live OHL in Scotland in 2013. The trial was funded through the Network Innovation Allowance mechanism (ref.:NIA_SHET_0007 [76]). The cross-arms of one circuit of two towers were replaced by ICAs (Figure 6.5). This gave the opportunity to test installation methods as well as evaluate the performance of the ICAs in an operational environment.

Figure 6.5 - 132 kV ICA (left) and three ICA installed on a live OHL (right) [4]

6.2.2 Central Research Institute of Electric Power Industry (CRIEPI), Japan

The development of a 154 kV ICA in Japan is reported in [77]. It consists of three composite insulators, two under compression and one under tension (Figure 6.6). The ICA was designed to withstand a maximum longitudinal load of 40 kN for OHLs using 410 mm^2 ACSR conductors. A full-scale prototype has undergone extensive mechanical and electrical testing, including impulse and power-frequency voltage withstand tests.

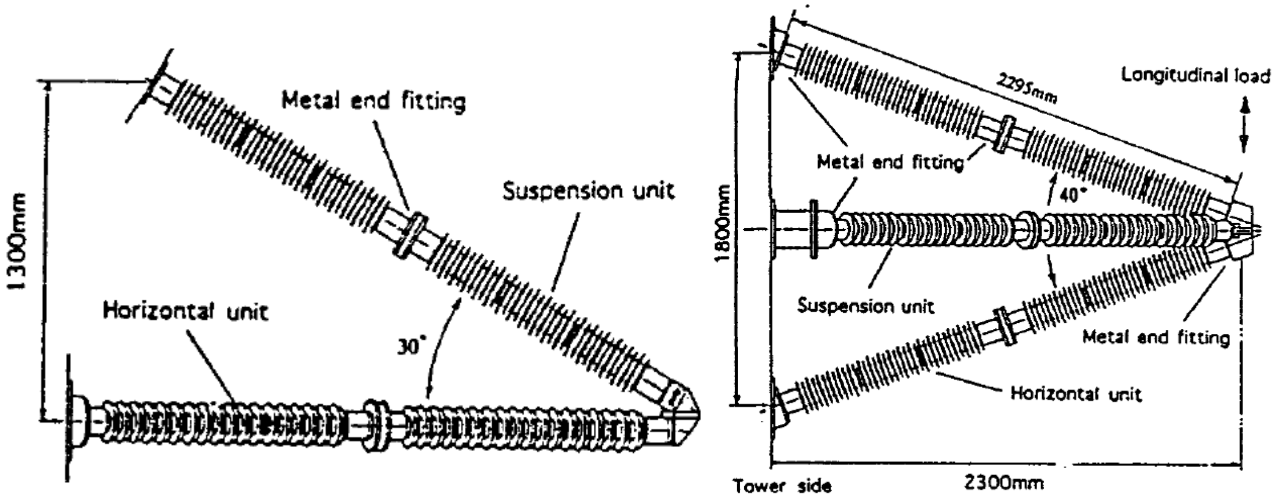


Figure 6.6 - 145 kV ICA side view (left) and upper view (right) [77]

6.2.3 State Key Laboratory of Electrical Insulation and Power Equipment and Xi'an Jiaotong University, China

The optimisation of a 750 kV ICA is reported in [78]. The cross-arm consists of six insulating members. There are two horizontal post insulators with an outer diameter of 320 mm, another two post insulators with an outer diameter of 140 mm connecting the mid-point of the two horizontal members to the tower, and two tension insulators. The ICA is designed to support a sextuple conductor bundle. Bespoke grading rings have been developed for the HV end of the cross-arm. The ICA has undergone electrical and artificial pollution tests and prototypes have been installed on a live transmission line (Figure 6.7).

Figure 6.7 - Switching impulse test (left) and ICAs installed on a live line (right)

6.2.4 Tsinghua University and Electric Power Research Institute of CSG, China

The development of a 500 kV rigid ICA is reported in [79]. It consists of two tension and two compression insulating members. The tension members are conventional suspension insulators (Figure 6.8). The compression members are large-diameter (320 mm), hollow-core post insulators. The core is filled with dielectric foam. Full-scale prototypes of the ICA have undergone mechanical testing, examining various load scenarios including operating loads, installation loads, and failure containment loads.

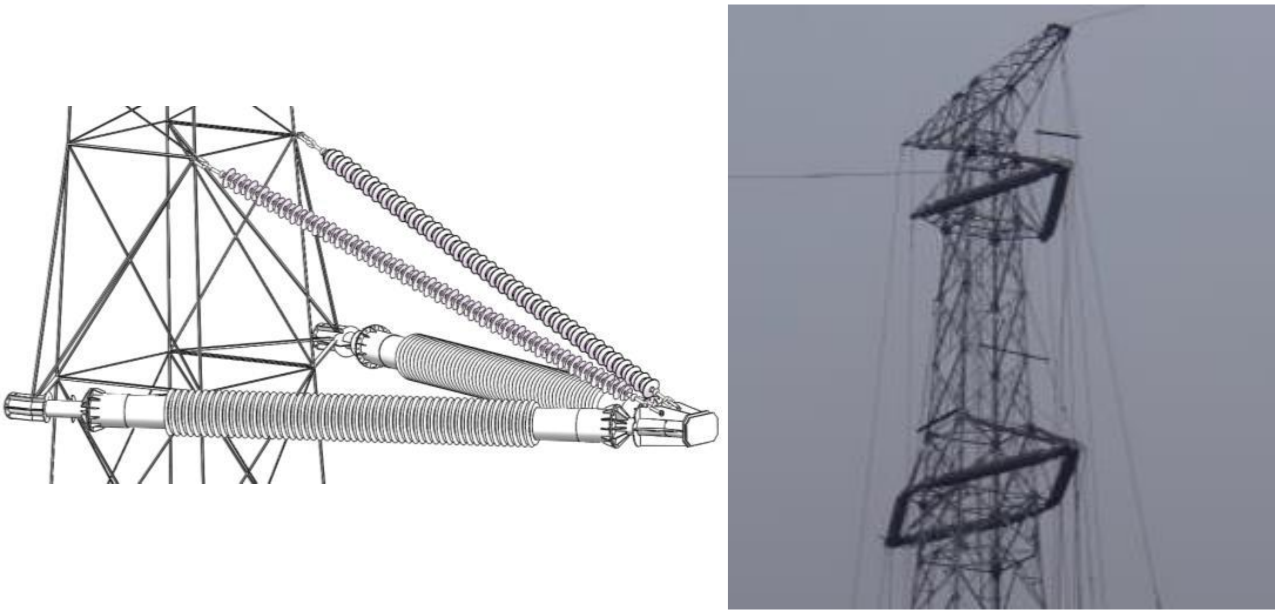


Figure 6.8 - 500 kV ICA assembly (left) and tower with ICAs (right) [79]

7 Conclusions

The literature review has highlighted several cases where ICAs have been successfully employed to uprate existing transmission lines or construct new transmission lines with compacted dimensions. The technology is applicable to lattice towers, monopoles and novel structures which is indicative of its flexibility. Although ICAs are not as widely available as other OHL insulator systems, designs are commercially available from various insulator manufacturers showing signs of maturity. Nevertheless, adoption of the technology is not necessarily straightforward.

ICAs fundamentally change the concept of the overhead transmission line and therefore changes might be required to standards and regulatory frameworks in order for the benefits of the technology to be fully realised. Furthermore, various techno-economic factors will need to be considered to ensure effective implementation. Additionally, it is important to be aware of other technologies that are available for increasing the utilisation of existing structures and transmission corridors. These can potentially be used together with ICAs to further increase the power transfer capabilities of existing infrastructure.

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APPENDICES

Appendix A - Conductors classification

Table 0.1 - Conductors classification [80]

Type	Core	Envelope	Acronym or trademark	Description
0	Galvanized or aluminium clad steel	Hard drawn aluminium and aluminium alloys	ASC, AAC, AASC, AAAC, ACSR, AACSR, ACAR, etc.	Operating at temperature not exceeding 95°C
1	Galvanized, mischmetal or aluminium clad steel	Thermal aluminium AT1 (TAL or 60TAL)	TACSR	Thermal resistant aluminium alloy conductor, steel reinforced
	Invar steel	Thermal aluminium AT1 (TAL or 60TAL)	TACIR	Thermal resistant aluminium alloy conductor, invar reinforced
	Galvanized, mischmetal or aluminium clad steel	Thermal aluminium AT2 (KTAL)	KTACSR	High strength, thermal resistant aluminium alloy conductor, steel reinforced
	Galvanized or mischmetal clad steel	Thermal aluminium AT3 (ZTAL or UTAL)	GZTACSR	Gap type, ultra thermal resistant aluminium alloy conductor, steel reinforced
	Galvanized, mischmetal or aluminium clad steel	Thermal aluminium AT3 (ZTAL or UTAL)	ZTACSR	Ultra thermal resistant aluminium alloy conductor, steel reinforced
	Invar steel or aluminium clad invar steel	Thermal aluminium AT3 (ZTAL or UTAL)	ZTACIR, ZTACIR/HACIN	Ultra thermal resistant aluminium alloy conductor, invar reinforced
	Invar steel or aluminium clad invar steel	Thermal aluminium AT4 (XTAL)	XTACIR, XTACIR/HACIN	Extra thermal resistant aluminium alloy conductor, invar reinforced
2	Galvanized, mischmetal or aluminium clad steel	Annealed aluminium 1350-0	ACSS	Aluminium conductor, steel supported
3	Metal matrix composite	Thermal aluminium AT3 (ZTAL or UTAL)	ACCR, ACMR	Thermal-resistant aluminium alloy conductor, metal matrix composite core reinforced
4	Polymer matrix composite	Thermal aluminium AT1 (TAL or 60TAL)	ACPR	Thermal-resistant aluminium alloy conductor, polymer matrix composite core reinforced
		Thermal aluminium AT3 (ZTAL or UTAL)	ACCFR, ACFR, ACPR	Thermal-resistant aluminium alloy conductor, polymer matrix composite core reinforced
		Annealed aluminium 1350-0	ACCC, ACPS, ACCFR, ACFR, CRAC, HVCRC, C^7	Annealed aluminium conductor, polymer matrix composite core supported