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Client :

Project : **MINEZ - 380kV Intercon Doetinchem-Wesel**

Subject : Feasibility of technical alternatives for the 380 kV interconnection Doetinchem-Wesel

Comments:

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1. INTRODUCTION

The present document refers to the consultancy study ordered by the Ministry of Economic Affairs (MINEZ) from Tractebel Engineering (TE) relative to the feasibility of technical alternatives for the 380 kV interconnection Doetinchem-Wesel.

The scope of the consultancy is, at this point, limited to the technical aspects of the alternatives to be considered, with explicit exclusion of cost and environmental aspects.

The overall technical and economical justification of the Doetinchem-Wesel interconnection of the Transmission Systems Operators (TSO) TenneT and Amprion is not at stake in this report. The need for an interconnection of ~5200 MVA (in N condition) and ~2600MVA (in N-1 condition) is at this point considered as given.

Besides the proposed 380 kV AC (Alternating Current) interconnection technology, questions were raised whether the interconnection could be implemented with other technologies. From outside, suggestions have been put forward to use HVDC (High Voltage Direct Current) in relation with underground cables.

In order to compare comparable things, the DC alternative should cope with the same network constraints and contingencies, and up to the same planning horizon as the AC solution. This implies a full rating (N condition) of ~5000 MW and a single outage (N-1 condition) rating greater than or equal to 2500 MW.

2. ORIGIN

The Dutch Transmission System Operator (TSO) TenneT and its German counterpart Amprion (formerly RWE Transportnetz Strom) intend to implement a new 380 kV interconnection between Doetinchem in The Netherlands and Wesel in Germany. The total length of this connection will be about 55 km, of which 22 km on Dutch and 33 km on German territory.

As both the TenneT and Amprion networks are embedded in the same West-European continental grid, based on AC technology, and the respective points to be connected are both at 380 kV level in a synchronous grid configuration, the choice for a 380 kV AC interconnection seems straightforward.

Network planning studies have been performed by Tennet and Amprion, according to the rules set forth in the Dutch Netcode and respective codes for the German counterpart (Refer: TenneT TSO and RWE TSO, Joint study for a new interconnection between Germany and the Netherlands, Final Report, Dec.2006). These planning criteria involve quite classical N-1 rules, as applicable in most European countries.

As outcome of these studies the link Doetinchem-Niederrhein (Wesel) showed up as the best option for extending the interconnection capacity between The Netherlands and Germany. This conclusion outcome was cast in a MOU by the two TSO involved, pertaining to the construction of this interconnection on short term.

The implementation of these planned circuits on Dutch territory goes through a route decision process conducted by MINEZ, within the legal framework of SEV III (Structuurschema Elektriciteits-Voorziening).

This SEV III favours (whenever possible and useful):

- to combine new circuits with existing circuits on new towers using the same corridor;
- or to bundle new circuits in a line running parallel in the same line corridor with an existing line;
- to bundle new circuits with other (super) regional infrastructure (railroad, canal, highways etc.).

For the Doetinchem - Wesel interconnection on Dutch territory, most of the proposed route can be achieved by combination, i.e. without new cuts through undisturbed landscape.

On a shorter stretch such a new cut is to be achieved.

In order to avoid this new cut, suggestions have been made from outside to investigate a solution with (underground) DC connection.

3. TECHNOLOGIES TO BE COMPARED

Given the clear outline by MINEZ about the consultancy, the comparison has to be made between 3 design configurations:

- Conventional AC line with two circuits per support.
- DC interconnection with same (N condition) transmission capacity and the same (or better) N-1 facilities, with the use of DC overhead line.
- DC interconnection with same (N condition) transmission capacity and the same (or better) N-1 facilities, with the use of DC underground cable.

The solution of 380 kV AC underground circuits is at present used/planned on a limited scale in the TenneT system, with a restricted number of km installed and in operation. Further implementation of 380 kV AC cable in the TenneT system is subject to satisfactory operational and maintenance experience combined with the positive outcome of an ongoing long term research program.

As regards the configurations involving DC, Amprion has made a clear position statement as follows:

- The intended link Doetinchem-Wesel is explicitly included and defined in Federal German law (Bundesgesetz) as conventional AC and in overhead line technology. This same Federal German law has also defined particular cases where new technologies (read: AC 380 kV cables, or DC links) may be applied for gaining experience.
- As Amprion is convinced on technical grounds that DC is neither useful nor justified for an interconnection such as Doetinchem-Wesel, no attempts will be made to change this legal position.
- Application of DC on Doetinchem-Wesel, if strictly restricted to Dutch territory, is however acceptable to Amprion, provided that the agreed dimensioning is maintained. All extra costs related to such a mixed interconnection are then to be borne by TenneT.

This means that any scope for application of DC technique on the Doetinchem-Wesel connection will be limited to Dutch territory.

4. FUNCTIONALITY REQUIREMENTS

4.1. Required functionality of the proposed link Doetinchem-Wesel

4.1.1. The functionality of interconnections in AC power distribution/transmission

For a recall on AC and DC technology, in support to the reading of the present document, refer to Attachment 1.

At the very dawn of the development of electricity distribution, the precursor DC technology (proponent Th. A. Edison) was quickly surpassed by its AC cadet brother (invented by N. Tesla), and this for the following technological aspects:

- AC allows construction of large size, reliable and low maintenance generators as needed for a massive scale electrification.
- AC allows easy change of voltage along the transmission path (by a purely stationary device, the transformer). This allows to choose the most appropriate voltage level at the production centre, along the transmission path, and at the user's premises.
- AC current, by principle, shows 50 cycles, i.e. 100 alternances (change of direction) and 100 zero crossings per second. These zero crossings allow easy interruption of the current by relatively simple and standardized devices (Circuit Breakers).

- AC allows simple measuring transducers for voltage and current and fault detecting devices. This ease and reliability of current interruption, combined with simple fault detection devices has been the key in the development of reliable power supply to large communities.

The first AC electrifications were on a very local basis, but interconnection developed continuously for the following reasons:

- Scale effect for lowering production costs.
- Flattening of load diagram and production allocation costs.
- Lower overall, because shared reserve capacity.
- Better reliability due to mutual support during incidents.

More recently the international interconnections are further spurred by:

- Further peak shaving opportunities, particularly for areas covering different longitudes (and time zones).
- Opportunities between areas with different production mix and (pumped) storage potential.
- The EC wish to create and promote regional electricity markets, beyond country borders.
- The integration of highly variable and unpredictable RES (Renewable Energy Sources).

However, AC transmission and interconnection (at a given voltage level) may reach its limits in the following situations:

- The synchronism limit (see Attachment 1, Item 3.7.2.) sets a maximum on the transmitted power on a given transmission path. This maximum is inversely proportional to the series reactance of the transmission path. The series reactance of the path is itself essentially proportional to the length of the path. In the classic evolution of AC electrification, this hurdle was taken by introducing a higher voltage level, i.e. an AC supergrid with respect to the existing grid.
- The weak link case (see Attachment 1, Item 3.7.2) is a particular case of the synchronism limit. If a weak (high series impedance, low rated power) AC link is installed between large production-load centres, it should allow for keeping synchronism, even in the worst incident expected in either of the production-load centres. If the power limit of the weak link (see Item 3.7.2. of Attachment 1) cannot maintain synchronism, the AC interconnection is tripped due to out-of-step conditions. The interconnection so fails when it is mostly needed, and its usefulness becomes marginal.

- Interconnections add additional generation (short-circuit current sources) and establish additional paths for short-circuit current (see Attachment 1, Item 3.7.4). Progressive interconnection increases the short-circuit current levels in the interconnected grid. The design features of grid elements (e.g. mechanical withstand of busbars, thermal withstand of cables, make and break duty of switchgear) put an upper limit to the short-circuit level. When this limit is reached, further interconnection in AC at the same voltage level is no longer possible. In the classic evolution of AC electrification, this hurdle was taken by switching to a higher voltage level, i.e. an AC supergrid, combined with partial decoupling at the lower voltage level.

- Interconnections contribute to (useful) power transit depending on their location with respect to the gravity centres of production and load of the interconnected networks and inversely depending on their series impedance. In case the load sharing between multiple interconnections is disproportional, the interconnection is poorly used. In conventional AC technology, a phase shifting transformer may be added in series in order to control the power flow.

- The shunt capacitance of AC interconnections generates reactive power (Mvar), which is to be absorbed by the interconnected networks, and which "consumes" transit capacity of the interconnecting link itself (see Attachment 1, Item 3.7.3). This effect goes with the square of system voltage. This puts a limit on interconnector length by underground cables in AC (see 3.7.3. in Attachment 1).

In those cases where additional transmission or interconnection is desirable, but where the limits of pure AC technology are exceeded, asynchronous interconnection may come into the picture. An asynchronous interconnection involves essentially:

- Conversion from AC power (3-Phase) to DC power (2 pole) at one end.
- DC link with 2 conductors.
- Conversion from DC power (2-pole) to AC power (3-Phase) at the other end.

Typical examples are:

- Long subsea transmission cables (NorNed 580 km, 700 MW, ± 450 kV).
- Interconnection of asynchronous AC grids (UK - Continental Europe).
- Weak link between extended grids (Spain-France).

4.1.2. Doetinchem-Wesel as a part of the European interconnected AC grid

The Doetinchem-Wesel connection has shown up in grid studies as the most effective interconnection to achieve increased exchange capacity between The Netherlands and Germany.

In line with long term planning practice in the TenneT grid, the link is dimensioned as double circuit overhead line 380 kV, 2 x 2635 MVA.

By virtue of already existing interconnections between the Netherlands - Germany, the Netherlands - Belgium, Belgium - France and finally France - Germany, the West-European grid is strongly interconnected in closed loop, and there is no risk that the new link becomes outstressed by synchronizing transients.

Both the TenneT and Amprion 380 kV grids have ample short-circuit margins with respect to the expected increase in fault level due to an additional AC interconnection.

The particular location of the Doetinchem-Wesel connection in the Dutch and German grid, with the load and production patterns as forecasted on both sides, ensures effective participation of the new link in the transit of power, both in normal and degraded network conditions. This is achieved by natural effect of Ohm's and Kirchhoff's law (see Attachment 1, Item 2) without any control mechanism needed from outside.

The length of the Doetinchem-Wesel connection (circa 55 km) is considered as short in 380 kV overhead technology, and puts no constraints whatsoever as regards shunt Mvar produced by the line.

4.2. AC interconnection to achieve the functionality

Following conclusions can be drawn from 4.1.1 and 4.1.2:

Given the need and justification of additional cross-border transit capacity between the Netherlands and Germany through an additional interconnection Doetinchem-Wesel:

- Interconnection with 2 x 2635 MVA overhead AC lines fits with the standard planning step-stones of both TSO TenneT and Amprion.
- The new interconnection, if implemented as 2 x 2635 MVA overhead AC line, is embedded in a strongly synchronous grid and not subject to extreme synchronizing or asynchronous events.
- The new interconnection, if implemented as 2 x 2635 MVA overhead AC line, does not pose constraints of short-circuit nature on either side.
- The new interconnection, if implemented as 2 x 2635 MVA overhead AC line, effectively participates in transit sharing, without any additional control feature.
- The new interconnection, if implemented as 2 x 2635 MVA overhead AC line, does not create Mvar related problems, nor in the line itself nor in the adjacent networks.

Therefore, from the pure technical point of view, AC interconnection by overhead line satisfies fully the required functionality. As shown further on in this report it is also the simplest (passive) and therefore most robust and reliable solution.

4.3. DC interconnection to achieve the functionality

Whatever the technology, overhead line or underground cable, the performance of a DC interconnection is defined by the double decoupling AC to DC and then again DC to AC at the extremities of the interconnection (see Attachment 1, Item 4).

We consider that for inland DC links earth return currents are strictly excluded.

Referring to the desired functionality, we may conclude the following:

- The overall link should comprise at least two bi-poles DC, so as to allow N-1 operation without earth return.
- DC is of course immune against asynchronous events, but this is not a requirement for the application Doetinchem-Wesel.
- DC does not increase short circuit levels, but this is not a requirement for the application Doetinchem-Wesel.
- DC offers power flow control and modulation, but this is not a requirement for the application Doetinchem-Wesel.
- As regards Mvar related problems, and assuming the use of Voltage Source Convertors (VSC) DC provides free control of Mvar injected in both the AC sides. This feature is however not required for the application Doetinchem-Wesel.

Therefore, from the pure technical point of view, DC interconnection also satisfies the required functionality. However, the passive (predictable) nature of AC is here replaced by a need for continuous active control of both converter stations. This has also less desirable consequences which will be discussed later in this report.

5. IMPLEMENTATION ASPECTS

5.1. AC Transmission by OH line 380 kV

5.1.1. Transmission line right of way

The typical cross-section of right of way of double circuit line 380 kV in WINTRACK design is shown in Attachment 2.

5.1.2. Line ends and interfaces

The link extremities are in principle standard outdoor or GIS (Gas Insulated Substation) indoor 380 kV bays added in existing 380 kV substations. Outdoor type bay dimensions are typically 22 m x ~80 m for double busbar 380 kV schemes.

5.1.3. Complexity

Complexity of operation: minimal, standard practice of TenneT.

Most maintenance and repair actions can be undertaken by TSO staff.

5.2. DC Transmission by OH line

5.2.1. Transmission line right of way

The typical cross-section of right of way of double bipole line ± 500 kV in a standard design is shown in Attachment 3.

Data are taken from similar projects included in the IEEE compendium, see document in Attachment 3.

5.2.2. Transmission link extremities

Hereby we consider that the conversion equipment of VSC technology is assembled in four 1320 MW units at ± 500 kV DC (Typical size now being commissioned 1100 MW at ± by 320 kV DC), two units operating in parallel per bi-pole, two bi-poles making up the interconnection link. The convertor technology is modular, the actual stacking of modules for higher voltage might result in modified building dimensions (rather longer than wider).

The (simplified) SLD (single line diagram) is also comprised in Attachment 3.

Without making detailed lay-outs, but using typical figures from recent projects we arrive at a convertor station footprint of ~320m x ~300m.

This area comprises a total of ~130m x ~300m reserved for 380 kV outdoor bays (2 incoming AC lines, 2 for bus-coupler, 4 for converters AC side (each with 2 converter transformers in block).

Each converter is housed in a building with estimated ~100m L, ~50m W, ~25m H.

The DC connection yard makes up for the remaining 90m x 300m.

A visual impression (bird view) is also included in Attachment 3.

5.2.3. Complexity

The active control of the converter stations gives rise to specific operational questions and requirement (further detailed in Item 6). Converter stations as such imply substantial extra infrastructure with respect to the AC alternative. This has a negative impact on the reliability of the overall interconnection (see also Item 6).

Maintenance and repair of converter related equipment is almost exclusively reserved to manufacturer staff and probably governed by expensive service contracts.

Owing to fast evolution in power electronics, the risk of short technical life due to orphan technology is real.

5.3. DC Transmission by underground cable

5.3.1. Transmission cable right of way

The typical cross-section of a cable trench for 10 cables arranged in 5 bi-poles ± 320 kV is given in Attachment 4.

Using standard XLPE cable designs now being marketed, 1000 MW can be transmitted per bipole, which is easily extrapolated to 1054 MW (e.g. by controlled backfill of the cable trench).

5.3.2. Transmission link extremities

Per cable bi-pole we consider one converter with VSC technology, in total five 1054 MW units (typical size now being commissioned 1100 MW).

The (simplified) SLD is also comprised in Attachment 4.

Also here the convertor station footprint will de approximately ~280m x ~345m.

This area comprises a total of ~130m x ~345m reserved for 380 kV outdoor bays (2 incoming AC lines, 2 for bus-coupler, 5 for converters AC side (each with 2 converter transformers in block).

Each converter is housed in a building ~90m L, ~45m W, ~25m H.

The DC connection yard makes up for the remaining 60m x 345m.

A visual impression (bird view) is also included in Attachment 4.

5.3.3. Complexity

Same as 5.2.3.

6. LOSSES

6.1. AC Transmission by OH line 380 kV

Considering:

- 2 AC circuits, each with 4 conductor bundle 620 AMS, only losses on Dutch territory considered.
- Lifetime average load transit 1500 MVA.

Transmission losses (TenneT part) are evaluated at ~2.2 MW

6.2. DC Transmission by OH line

Considering:

- 2 DC bipole lines, each pole with 4 conductor bundle 620 AMS, only part on Dutch territory considered.
- Lifetime average load transit 1500 MVA.

Transmission line losses are evaluated at ~0.7 MW.

VSC Converter losses are evaluated at 2 x ~26.5 MW

Total link losses (TenneT part) amount to ~ 53.7 MW

6.3. DC Transmission by underground cable

Considering:

- 5 DC cable bipoles (10 cables in total), each pole 1 x 2500 Cu XLPE, only part on Dutch territory considered.
- Lifetime average load transit 1500 MVA.

Cable link losses are evaluated at ~0.37 MW.

VSC Converter losses are evaluated at 2 x ~28.2 MW

Total link losses (TenneT part) amount to ~ 56.8 MW.

6.4. Interpretation

Although transmission losses proper are lower in DC, the overall link losses are substantially higher due to the double AC/DC an DC/AC conversion (both converters at TenneT's charge).

The extra losses due to DC over one year amount at least 51.5 MW x 8760 h or 451 000 000 kWh/year.

Assuming average household annual consumption of 3000 kWh/year, the above figure corresponds to the pure waste of energy corresponding to the needs of ~150 000 households.

The above mentioned figure also compares to the expected annual energy output of an off-shore windfarm of say 130 MW (43 turbines 3MW, annual utilization 40 %) ~ 455 000 MWh.

In other words, the extra losses due to DC on Doetinchem-Wesel (TenneT part) would almost completely wipe out the renewable electricity production of such a wind farm.

7. RELIABILITY ASPECTS IN MORE DETAIL

7.1. External events and effects

- Weather - Thunderstorms and lightning.
- Weather - General (wide area) storm conditions.
- Weather - Local tornados and wind swirls.
- Weather - Ice loading induced failures.
- Digging, hoisting, exceptional transport.
- Fire and fire fighting.
- Flying objects, large and small, fast and slow.
- Vegetation induced faults.
- Other and unknown.

7.1.1. Overhead line corridor with two-circuit AC line

The most frequent phenomenon (lightning stroke) results mainly in electrical faults, which in most cases are cleared by single phase trip and reclosing, without any disturbance at all.

The other causes may result in more or less mechanical damage to the line, but even in case of damage to several towers, service may in general be re-established within 2 to 3 weeks by an emergency line set-up (TenneT current practice).

7.1.2. Overhead line corridor with two bipole DC lines

The effects on DC lines are expected to be fairly similar to those on AC lines.

The most frequent phenomenon (lightning stroke) results mainly in electrical faults, but in the case of VSC HVDC, the clearing of DC faults necessitates full de-energizing of all converters feeding into the fault, even on their AC side. In the configuration as foreseen this will result in systematic cut of 50 % of transit capacity during one or two hours (the time needed for fault diagnostics and the re-energizing procedure).

The other causes may result in more or less mechanical damage to the line, but even in case of damage to several towers, service may in general be re-established within a few weeks by an emergency line set-up. Care must be taken for sufficient spare equipment, as the DC line technology is not the standard TenneT practice.

A special case is insulator pollution in DC lines. Normally, for long transmission line projects, special measuring campaigns are set up before construction so as to establish evidence about specific pollutants and their deposit on insulator surfaces. The final line design then takes these parameters into account in the design of line armature and insulator strings. Again here insulator flash-over during adverse weather conditions will result in complete bi-pole clearing as explained above.

7.1.3. Underground trace with DC cables

Only digging or landslides are to be considered as possibly dangerous external events.

Cable fault location and repair may typically put a bi-pole out of operation for 3 to 4 weeks. Key point is the skilled personnel from the supplier, as well as availability of spare lengths of cable and suitable junction boxes.

7.1.4. Outdoor end bays for AC transmission

The only realistic risks, besides intentional human destructive act, are local tornados or flying objects destroying (part of) the outdoor bay.

The probability is low, considering the limited surface involved.

The effects are essentially damaged or destroyed HV hardware, in a limited number.

Repair using spares out of stock is in general possible within 1 to 2 weeks.

7.1.5. AC to DC converter stations for DC transmission

The outdoor 380 kV bays are exposed to the same risks as in the AC case, but the probability is greater due to the greater number of bays involved.

Far more consequential is damage to the converter halls and content (exposed target ~100m x ~300m x 25m). Repair is exclusively possible by the OEM (Original Equipment Manufacturer) and may take several months, provided that sufficient spare is kept to replace complete valves etc.. This may extend to more than a year (if vital equipment is to be re-ordered).

7.2. Internal origin events and effects

- Complexity.
- Equipment track record.
- Staff experience with maintenance.
- Other internal failure cases.

7.2.1. Overhead line corridor with two-circuit AC line

OH AC lines are among the most common assets in the TSO business:

- Complexity: Risks due to human error are very limited:
  - Status: fixed parameters 100 % observable.
  - Purely passive and predictable behaviour in grid operation.
- Equipment track record for the established design is impressive (km x years operation).
- Management of spares, inspection and maintenance are based on sound experience.
- Staff is highly experienced for the established design. Maintenance related outages are minimal.

7.2.2. Overhead line corridor with two bipole DC lines

Though components of DC lines are essentially similar to those of AC lines, the lack of practical experience with DC will adversely affect the availability:

- Complexity: Risks due to human error are very limited (almost as for AC overhead lines).
- But no definite equipment track record in the company.
- Staff experience to be established.
- The unknown factor of pollution and associated maintenance activities.

7.2.3. Underground tracé with DC cables

Little risks of internal origin are expected wit DC cables, nevertheless:

- Complexity: Risks due to human error are very limited.
- No definite equipment track record in the company and very limited experience worldwide yet with DC cables of this rating.
- Staff experience to be established.
- Cable fault location and repair may typically put a bi-pole out of operation for 3 to 4 weeks. Key point is the skilled personnel from the supplier, as well as availability of spare lengths of cable and suitable junction boxes.

7.2.4. Outdoor end bays for AC transmission

Outdoor AC bays are among the most common assets in the TSO business:

- Complexity: Risks due to human error are very limited:
    - Status: fixed parameters 100 % observable, except maybe online protection setting status.
    - Purely passive and highly predictable behaviour in grid operation.
- Equipment track record for the established design is impressive (number of bays x years operation).
- Management of spares, inspection and maintenance are based on sound experience.
- Staff is highly experienced for the established design. Maintenance related outages are minimal.

7.2.5. AC to DC converter stations for DC transmission

7.2.5.1. COMPLEXITY

Whereas a straight AC link is a purely passive device (it will conduct current, depending on voltage phasors at the extremities), the DC link inherently requires active control of the converter stations.

Given the requirements of the proposed interconnection Doetinchem-Wesel and the structure of the respective 380 kV AC networks at both ends, active power control is not needed and is thus not asked for.

On the contrary, the principle of active control implies deep interference with the "natural" behaviour of the AC grid. The specific complexity aspects of this are detailed below.

These aspects can be classified as follows:

- Static aspects.
- Dynamic aspects;.
- Interference or disturbance effects.

7.2.5.1.1. Static control features

The control of flow overriding the pure laws of Ohm and Kichhoff may result in specific operational effects as follows:

- The effect is not strictly local, but propagates more or less in the entire AC network at both extremities. It is as if besides the natural flow in the AC network, without the controllable link, an extra flow is superposed by one extra generator at the receiving end and one extra load at the sending end of the controllable link.
- Several of these controllable links in operation together may interfere and "in fine" even counteract. This puts an extra constraint on SCADA management of the AC network as a whole. The key point is knowledge of all settings and setting programs at the system observatory. Without exact data, even the most sophisticated network calculation and management programs just produce rubbish.

7.2.5.1.2. Dynamic control features

The pure AC system has its proper dynamics associated with rotating masses in generators on one hand and "elastic" links ("equivalent springs") provided by the AC network series components (lines, transformers, ..). Local feedback control systems such as generator voltage regulators and turbine governor systems already further complicate the dynamic response of the whole. As a result, the AC system has potentially a high number of dynamic "eigenvalues", which need all positive damping in order to maintain a stable operation of the whole. These dynamic equivalents are not stable in time, as e.g. generator may be running or not running, network elements may be out of operation, load patterns are shifting over the day; ...

Any additional control feature such as from one or more controllable links (like DC-connections) influences the overall system dynamics, and may inadvertently favour oscillations by introducing negative damping on an unexpected oscillation mode. Again:

- The effect is not strictly local, as the whole AC network dynamics play a role.
- The cumulative effect of several controllable links is even more pronounced than for the steady state issue.
- An overall view at the power system observatory is almost impossible: the real control system block diagrams and parameter settings are hidden in obscure parameter tables which manufacturers tend to keep secret for possible competitors.

- Even if block diagrams and parameters might theoretically predict the performance of a device, the actual physical response is still subject to uncertainty. The final check (as e.g. in classic AC protection) is an independent test set-up which tests the expected output values against the predicted performance from block diagrams and settings. Such an independent evaluation (without contribution of the manufacturer) is almost not feasible in the present stage of development and standards of HVDC equipment.

7.2.5.1.3. Undesired interference and power quality issues

As long as AC-DC conversion remains an isolated issue in a, for the rest, predominant AC grid, the interference by current switching patterns is relatively easily mastered by adequate filtering circuits.

When AC-DC conversion equipment becomes predominant, more complicated interference patterns are to be expected, with associated power quality problems. Cases have been signalled with the first off-shore HVDC Hubs for wind power collection in the German North Sea.

7.2.5.1.4. Summary on complexity

The introduction of active power control implies drawbacks which need to be mastered before large scale and repetitive implementation.

In essence the static and dynamic effects of power control may interfere locally, but also with the performance of the AC network as a whole.

These effects are also cumulative with the relative weight of actively controlled power in the overall AC system power.

This consideration suggests that controllable DC links should be applied with caution and essentially be reserved for those cases where their technical advantages over AC compensate the potential drawbacks. An unordered proliferation of DC links embedded in AC networks may be a source of overall grid instability and is to be avoided on technical grounds.

7.2.5.2. EQUIPMENT TRACK RECORD / MANAGEMENT OF SPARES

The VSC AC-to-DC converters are presently in a rush of evolution with components (IGBT wafer performance), architectures (level structures) and associated control hardware and software. In this light every installation is in some sense a prototype.

This brings an inherent dependency on the manufacturer, with possibly expensive service and maintenance contracts.

7.2.5.3. STAFF EXPERIENCE

As explained under Item 7.2.5.1, AC-DC conversion can in certain cases be a useful tool, but may conduct to degraded conditions if not properly coordinated at the level of the interconnected grid as a whole.

This will require additional effort from the TSO operation for coordination at TSO and inter-TSO level of procedures and operational settings.

Given the complexity of DC, it will also take time before staff will have acquired the same level of skill and confidence as for the well known AC.

7.2.5.4. SPECIFIC "COMMON MODE" RISKS

As for particular equipment risks one should mention:

- Common mode causes of failure, particularly the cooling systems, control equipment, ...
- Fire propagation in convertor structures, between branches of one converter and finally between converters.
- Availability of spares of critical components for the worst expected outage (e.g. all tiers of one converter branch destroyed in one event).
- The orphan technology trap (due to fast evolution) and difficulty to maintain an adequate service level for ageing equipment, upgrading and revamping costs.

8. RESEARCH AND OTHER INTERNATIONAL PROJECTS

8.1. European research

The technical limits of the 400 kV AC transmission (See 4.1.1) may be reached in a number of locations the European interconnected grid in a foreseeable future.

The introduction of a massive AC supergrid (750 kV to 1100 kV) seems difficult and not justified in mature markets with moderate load growth.

Judicious and selective introduction of major properly situated DC links (technology available) or even DC supergrids (not yet feasible) may offer an alternative solution.

International learned societies (CIGRE) are actively studying this possibility (e.g. CIGRE Working Group JWG C4/B4/C1.604, which is expected to submit his findings shortly). Such basic work is normally to be followed by development of adequate standards (IEC, IEEE) before really entering "industrial" application.

Also the EU has recognized the importance of this issue and supports a number of initiatives with funding:

- Development of HVDC related grid code by ENTSO-E. The purpose is to develop the rules and conditions of application and operation of HVDC embedded in AC networks, in order to guarantee the performance and safety of the network as a whole.

- Development of the HVDC breaker, which is needed to apply DC in meshed (in contrast with point-to-point) grids. This research is conducted with manufacturers. At present prototypes of the basic switching circuit have been tested in laboratory conditions.
- Funding of interconnection application France-Spain INELFE (2000 MW, 320 kV), and of the interconnection application Germany - Belgium ALEGRO (1000 MW, 320 kV). These projects are specifically dealt with at more length in the paragraph below.

In general, before a massive introduction of DC technology on vital power links such as Doetinchem-Wesel can take place reliably, the following considerations must be taken into account:

- HVDC links may have a vital role to play in the future European grid, but should be judiciously planned in this respect. Hastily and erratic application in situations where they are not technically needed may hamper the future of the overall European grid.
- Ongoing research and standard development, among others, has to be accomplished successfully in order to master the negative side effect of DC conversion on AC grid performance.
- Pilot projects now planned or under construction must have rendered hands-on experience on how to deal with the retro-action of DC on AC grid operation and reliability issues.

8.2. International projects

Within Europe at present two other interconnection projects using an underground DC direct current cable are either envisaged or already under construction. These projects are the INELFE project between France and Spain and the ALEGrO project between Belgium and Germany. In this paragraph these projects are briefly described and compared to the Doetinchem-Wesel interconnection.

8.2.1. The INELFE project

The INELFE project is already in construction as a 320 kV underground direct connection between Baixas in France (Perpignan region) and Santa Llogaia in Spain (Gerona region). The project provides a new direct connection between two regions which have at present only a weak connection crossing the Pyrenees mountain region. The new connection will be about 60 km long and will have a capacity of 2 x 1000 MW.

Although the overall interconnection capacity is almost tripled by the addition of the new link, it remains very small with respect to the generation-load clusters on either side. In that sense INELFE is a showcase of weak link between AC systems (refer Attachment 1, Item 3.7.2) with all associated symptoms of poor system stability.

In this context the choice for DC offered the following real technical advantages:

- Better stability and continuity thanks to the elimination of out-of-step conditions.
- Voltage support by the reactive power control capability of the VSC technology.

Given the EU interest in new interconnection technology, and the opportunity to test DC interconnections at their real potential in this type of application, the project was granted EU funding as pilot project.

As for comparison with the Doetinchem-Wesel case, the following distinction is to be made:

- The INELFE case is a prototype of weak link, whereas Doetinchem-Wesel is just an additional strong link in an already strongly interconnected synchronous network. Application of DC has a real technical advantage in the former, but none in the latter.
- The size of the INELFE interconnector remains altogether moderate, at least with respect to the generation-load clusters in which it will be embedded. The advantages of DC outweigh the associated risks. Doetinchem-Wesel on the other hand is a massive interconnection link which does not require the functionalities of DC. The introduction of DC brings only additional risks, losses and extra costs, without a compensating advantage.
- The size of INELFE is still compatible with a pilot application, whereas Doetinchem-Wesel size is definitely not.

8.2.2. The ALEGrO project

The ALEGrO project is a new 320 kV direct current connection between Lixhe (Liège region in Belgium) and Oberzier (Aachen region in Germany). This project caters for a direct electricity connection between Belgium and Germany where at present no such direct connection exists. The proposed connection will be circa 75 km long an will be laid underground. Its capacity will amount to about 1000 MW.

Due to its East-West orientation, ALEGrO is an economically interesting interconnection. However, by virtue of existing grid structure and the predominant North - South load flow patterns, an AC link without extra control would not be effective in load sharing. Conventional AC phase shift transformers would even not be sufficient. Hence the choice for DC, with the associated load flow control facilities.

Given the EU interest in new interconnection technology, and the opportunity to test DC interconnections at their real potential in this type of application, the project was granted EU funding as pilot project.

As for comparison with the Doetinchem-Wesel case, the following distinction is to be made:

- The ALEGrO case is a prototype of unfavourable load sharing in AC networks, where additional control, as offered by DC, is a must. Doetinchem-Wesel allows as AC connection already adequate load sharing. Application of DC has a real technical advantage in the former, but none in the latter.

- The size of the ALEGrO remains moderate, at least with respect to the grid in which it is embedded. The real advantages of DC outweigh the associated risks. Doetinchem-Wesel on the other hand is a massive interconnection link which does not require the functionalities of DC. The introduction of DC brings only additional risks, losses and extra costs, without a compensating advantage.
- The size of ALEGrO is still compatible with a pilot application, whereas Doetinchem-Wesel size is definitely not.

9. COMPARISON OF ALTERNATIVES FOR DOETINCHEM-WESEL

This comparison is restricted to the purely technical aspects of functionality and reliability.

Cost aspects and environmental aspects are outside the scope of this consultancy.

9.1. Required functionality performance

All three alternatives:

- AC overhead line.
- DC overhead line.
- DC underground cable.

Satisfy the functional requirements for the Doetinchem-Wesel interconnection.

The DC alternatives offer additional functionalities, but these are not part of the basic functionality requirement.

9.2. "Local" reliability aspects

9.2.1. Short duration forced outages

The AC line is by far the most reliable solution, with fault rates of ~1/(100 km circuit x year), of which ~90 % are fugitive and automatically cleared without service interruption.

Typically FEU (Forced Energy Outage) of 0.077 %.

DC systems on average come to FEU of 3.1 % (CIGRE paper 2012-B4-113 on reported performance of existing HVDC installations worldwide).

Even if one assumes that the latest technology performs twice as good, the FEU rate of DC is 20 x the rate of the AC solution.

9.2.2. Long duration severe events

As shown above, total outage times of the AC link is in any condition limited to a few weeks (set-up of emergency line or revamp a bay 380 kV).

For DC one has to care for a major event in either of the two end stations. Outage times can vary from several months up to more than a year. The only solution to this is a physical separation and independence of the four (or five) converters making up the converter station so that total loss in a single event is excluded.

9.3. "System wide" reliability aspects

9.3.1. AC solution

The AC line is the standard solution, which does not introduce new or unexpected system wide implications. Furthermore it is well integrated in the future development of the pan-european grid.

9.3.2. Solutions with AC-DC conversion

As detailed in chapter 7.2.5 the introduction of AC-DC conversion may result in a number of negative operational effects that may endanger not only the interconnection proper but also the performance of the AC surrounding network as a whole.

The "non-planned" introduction of DC in Doetinchem-Wesel for a local non-technical problem will disturb a coordinated European approach which intends to reserve DC in the future for coping with the real technical necessities of the European grid.

Without return of experience on smaller scale demonstration projects (now planned or in construction), this remains a heavy argument in decisions for large scale project in a vital sector such as electric power supply.

10. CONCLUSIONS

The building blocks (cables, AC-DC VSC conversion modules) available on the market may allow modular assembly of a DC interconnection at the rating considered for Doetinchem-Wesel. This would be the largest DC VSC application in the world today.

Bearing in mind however:

- The lower reliability of the DC link itself (compared to AC) and the effect of this on the reliability of the overall grid in which the DC link is embedded.
- The unasserted risks related to non-coordinated interaction of multiple DC installations in the same AC grid, which may be source of instability in this overall grid.
- The considerably higher losses of DC on this short link.
- The lack of return yet on ongoing research, standardisation and ongoing pilot projects in the field of embedded DC.
- The negative impact on the orderly and planned implementation of DC techniques to solve the problems of European transmission grid of the future;

we consider it not wise to implement DC today on the Doetinchem-Wesel link, just in order to solve a local non-technical problem.

11. ATTACHMENTS

- Attachment 1 : AC versus DC in electric power transmission
- Attachment 2 : AC Line solution - Right of way
- Attachment 3 : DC Line solution - Right of way - End stations
- Attachment 4 : DC Line solution - Right of way - End stations

ATTACHMENT 1

AC versus DC in electric power transmission

Feasibility of technical alternatives for the 380 kV interconnection Doetinchem-Wesel
AC versus DC power transmission

TABLE OF CONTENTS

1. INTRODUCTION

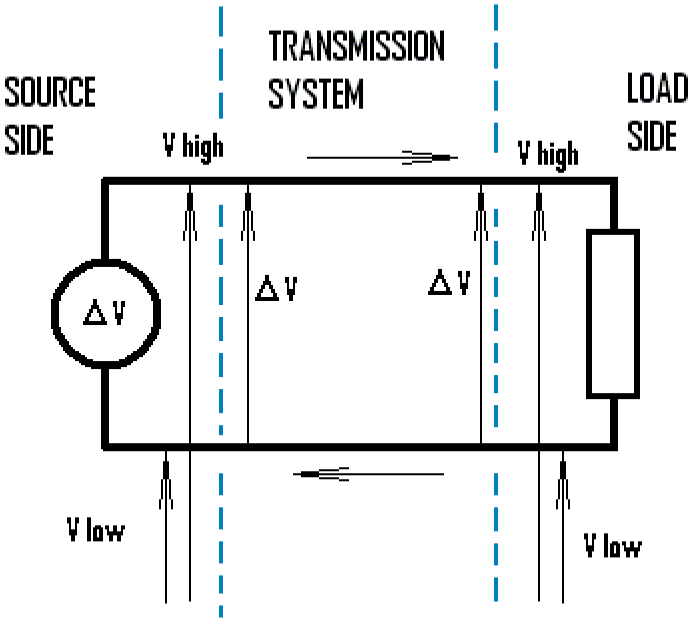
The present document refers to the consultancy study ordered by MINEZ from Tractebel Engineering (TE) relative to the feasibility of technical alternatives for the 380 kV interconnection Doetinchem-Wesel.

The aim of this document is to give a brief recall on the fundamentals of electric power transmission, and in particular on the comparison of the AC (Alternating Current) and DC (Direct Current).

2. THE FUNDAMENTALS OF ELECTRIC POWER TRANSMISSION

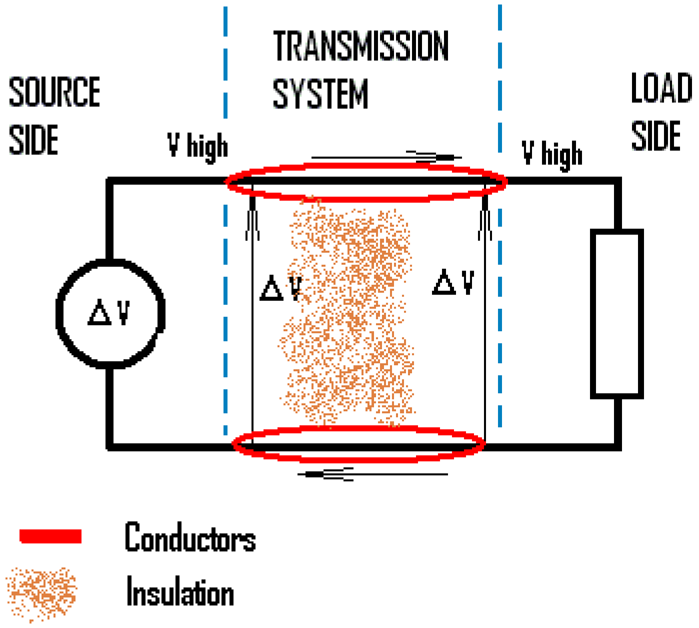
The electric power transmission is fundamentally based on the physics principle of the flow of electric current (expressed in Amps, whereby 1 A = an electric charge of 1 Coulomb flowing per second) under a potential difference (expressed in Volts, whereby 1 V represents a potential energy of 1 Joule for an electric charge of 1 Coulomb at that same location).

The power circuit has a source side and a load side, connected by the transmission system.



On the source side, the electric charges flowing get a boost in potential energy. They then flow through the transmission system, maintaining roughly (see further: losses) their potential energy boost.

Arrived at the load side, the electric charges loose the potential energy while flowing through the load device. They then return to the source to repeat the cycle. The load device converts the electric energy received into the desired application (e.g. motion, light, heat, ...).

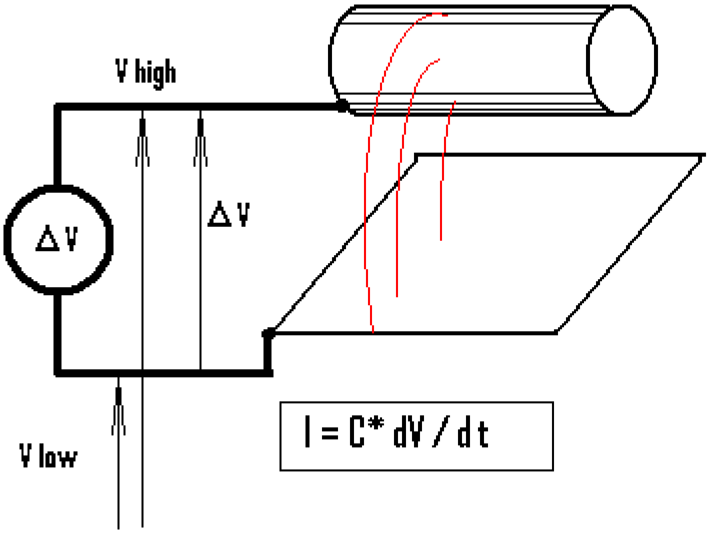


The transmission system:

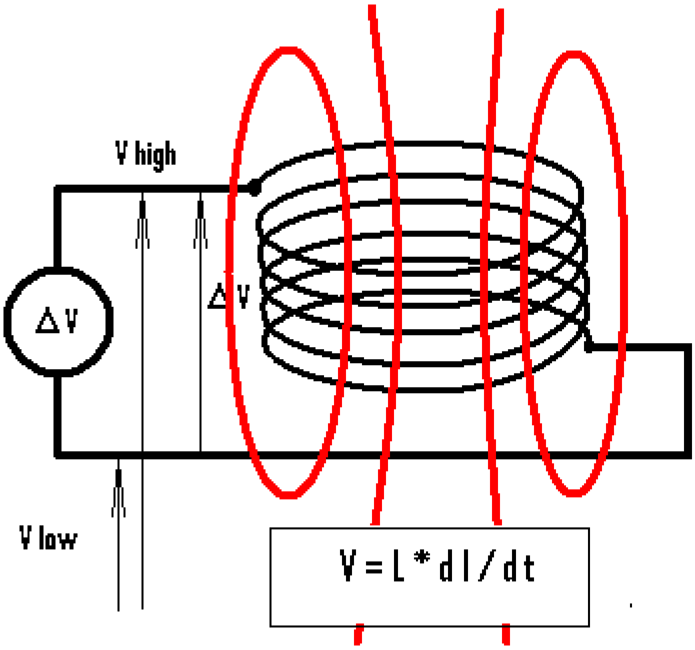
- Comprises (at least) 2 conductors in which the current flows.
- The conductors operate under a potential difference (and need to be insulated from each other).
- In case overhead line: air insulated, large spacing between conductors.
- In case of underground cable: solid (XLPE) insulation of each conductor with respect to ground.

Besides the aspect of energy flow in a closed circuit as shown above, a few other aspects are important:

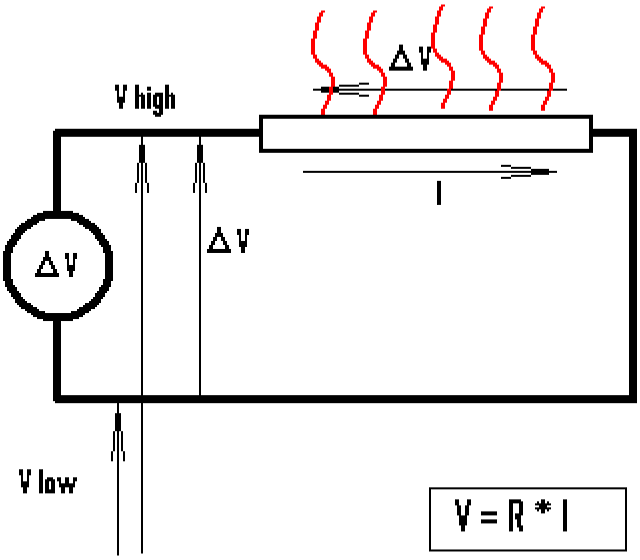
- In order to build up a potential difference between conducting surfaces, some electric charge is stored on these surfaces. This effect is described as Capacitance (C) and is expressed in Coulombs/Volt of potential difference (or 1 Farad = 1 Coulomb/ 1 Volt). In other words, electrostatic energy is stored between conductors at a different voltage. Capacitance is influenced by geometry (e.g. two close-by conductors have higher capacitance than two largely spaced conductors), and also by the medium in between (e.g. Air gives lower capacitance than poly-ethylene). Consequence overhead line shunt capacitance is far lower than capacitance.



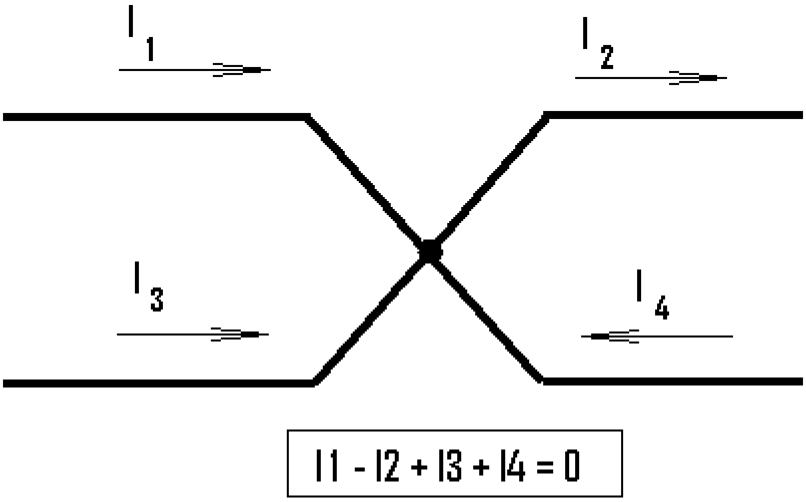
- All flowing currents create a magnetic field, which also stores energy. Any change of current requires increase or decrease of this stored magnetic energy. Therefore any change of current in a conductor creates a voltage which opposes the intended change. In this way, an increase of current stores additional energy in the magnetic field, and in complement, a decreasing current pulls out energy from the magnetic field. This effect is described as circuit Inductance (L) and expressed in Henry (1 Henry = 1 Volt induced for a change of current of 1 Amp per second).



- Any flow of current in a conductor (normal conductor at room temperature) is opposed by an internal friction of the conducting charges (electrons), which is proportional to the current intensity. This friction causes a voltage drop. The electric energy of this voltage drop is converted to heat.



- No accumulation of electric charges is possible in a conductor node, in other words, the sum of currents in a network node equals zero.



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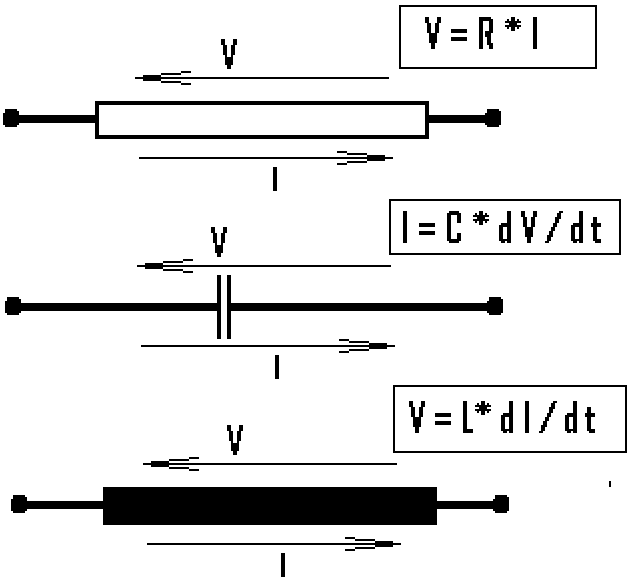
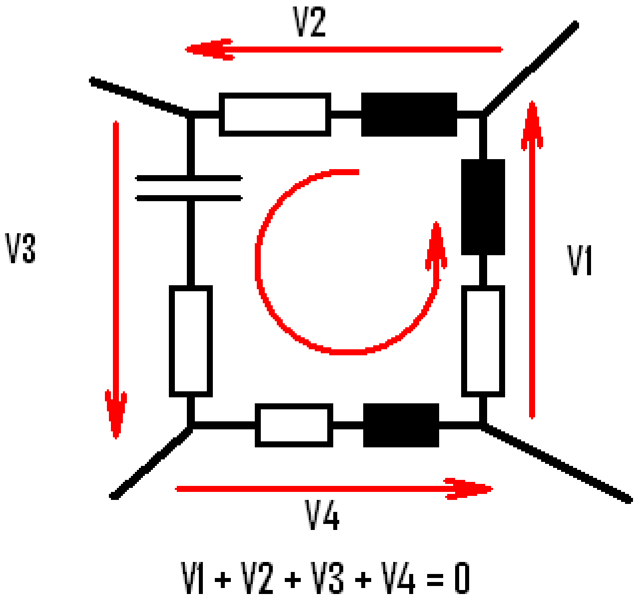
- Circuit symbolism and voltage current relations.



- The sum of all voltage differences around a closed loop equals zero.



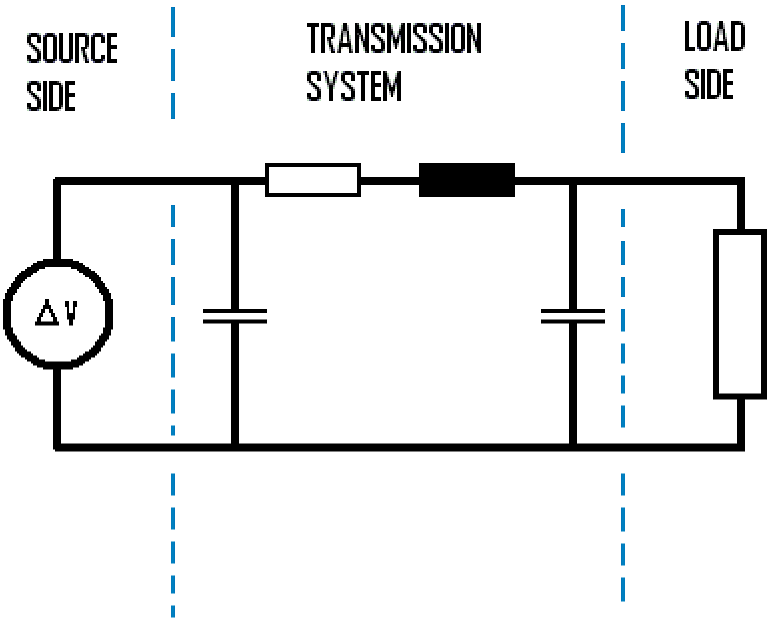
A particular case in power transmission: source voltage equals load voltage plus voltage drop in transmission circuit.

3. TRANSMISSION TECHNOLOGIES DC AND AC

3.1. General

A transmission system is composed of conductors connected in circuits.

Therefore and by principle a transmission system contains series resistance and inductance, as well as shunt capacitance.



3.2. DC transmission

Power transmission can be made with constant voltages and currents, i.e. DC (Direct Current) transmission. In steady state, series inductance and shunt capacitance play no role. The power sent by the source minus the losses dissipated in the series resistance is delivered to the load side.

Main characteristics of DC:

- Very simple steady state relationships.
- L and C only concerned in transients.
- Efficient utilisation of conductors and insulation: lowest cost/(power transmitted x km).
- No easy way to change voltage levels.
- No easy way to interrupt DC current.

Voltage, current, power relationships:

- All steady state currents, voltages and voltage differences are constants which add up algebraically (i.e. with sign according to direction).
- Source power Ps = source voltage Es * source current I.
- Load side power Pl = load side voltage El * load current I.
- Transmission voltage drop = R * I.
- Source power Ps = Load side power Pl + R * I^2.

3.3. AC transmission

Technological evolution showed quickly that AC (alternating current, advocated by N. Tesla) was easier to generate, simply transformable to different voltage levels, and easier applied to motor applications. Main characteristics of AC:

- Steady state is sinusoidal, L and C play a decisive role also in steady state.
- Transmission length limited by L and C effects.
- Less efficient utilisation of conductors and insulation: higher cost/(power transmitted x km) of the transmission circuit itself.
- Simple and efficient change of voltage levels.
- Simple and reliable mechanical circuit breaking thanks to the natural zero crossings of current.

Voltage, current relationships:

- By virtue of the voltage-current relations explained under Item 2, a capacitor draws sinusoidal current with 90° phase shift ahead of the applied voltage.
- By virtue of the voltage-current relations explained under Item 2, a reactance draws sinusoidal current with 90° phase shift lagging the applied voltage.
- By virtue of the voltage-current relations explained under Item 2, a resistor draws sinusoidal current exactly in phase with the applied voltage.
- By the same, a series R-L (resistor-reactor) circuit shows a combined (vectorial added) voltage drop, which is vectorially added to the load side voltage to find the source side voltage.

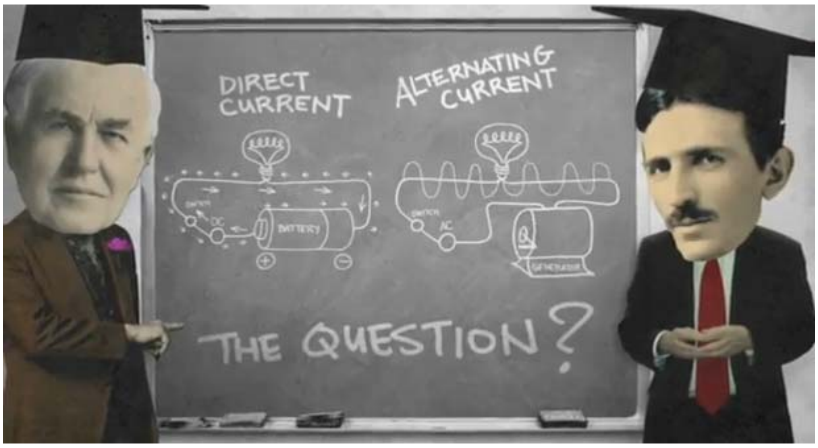
Voltage, current, power relationships:

- Besides the notion of direction, AC needs further to consider the sinusoidal nature of both current and voltage, and the effect of possible phase shift between those two signals.

- In the most general case, when considering that current is shifted (i.e. the signal of current mimics the signal of voltage with a delay (positive or negative) expressed by an angle phi, the following applies (single phase case):
  - $E = \text{Eamp} \times \cos(\Omega t)$.
  - $I = \text{Iamp} \times \cos(\Omega t - \Phi)$.
  - $P = (1/2) \times \text{Eamp} \times \text{Iamp} \times \cos(\Phi)$ + oscillating component at frequency 2x $\Omega/2\pi$ (with average output = 0.
- When considering the vector or phasor notation, it is as if only the current component which is in phase with the voltage ($\text{Iamp} \times \cos(\Phi)$) is active in the power transfer.
- The current component in quadrature with the voltage has itself a phase shift of 90 degrees and provides, with cos (90) being 0:
  - $P = (1/2) \times \text{Eamp} \times \text{Iamp} \times 0$ + oscillating component at frequency 2x $\Omega/2\pi$, thus only an oscillating component with average output = 0.
- Although the quadrature component of current ($\text{Iamp} \times \sin(\Phi)$) has no average effect in power transfer, it is greatly involved in the AC transmission technique.
- The corresponding "Power", though physically only existing as oscillating component at frequency 2x $\Omega/2\pi$ is designated by the symbol Q:
  - $Q = (1/2) \times \text{Eamp} \times \text{Iamp} \times \sin(\Phi)$ is designated as Reactive Power, in contrast with:
  - $P = (1/2) \times \text{Eamp} \times \text{Iamp} \times \cos(\Phi)$, which is termed as Active Power.
- Hereby it should be noted that leading quadrature components and lagging quadrature components give rise to Reactive Power of opposite sign, due to the $\sin(\Phi)$.
- The international convention is "Current lagging Voltage (Quadrant I Vector)" - gives rise to positive reactive power and "Current leading Voltage (Quadrant IV Vector)" - gives rise to negative reactive power.
- Mathematically $S = P + jQ = E \times I^*$
- It should be remembered that power flow is always associated to a direction of measurement of current.
- Using RMS values of voltages and currents $E = E\ \text{rms} = \text{Eamp}/\text{sqrt}(2)$ and $I = I\ \text{rms} = I\ \text{amp}/\text{sqrt}(2)$, the power formulas simplify to $P = E \times I \times \cos(\Phi)$ and $Q = E \times I \times \sin(\Phi)$.

3.4. Consequences for application

The very first power production, transmission, distribution was based on DC, with its proponent Th. A. Edison.



Since the invention of the transformer, AC has quickly become the standard worldwide.

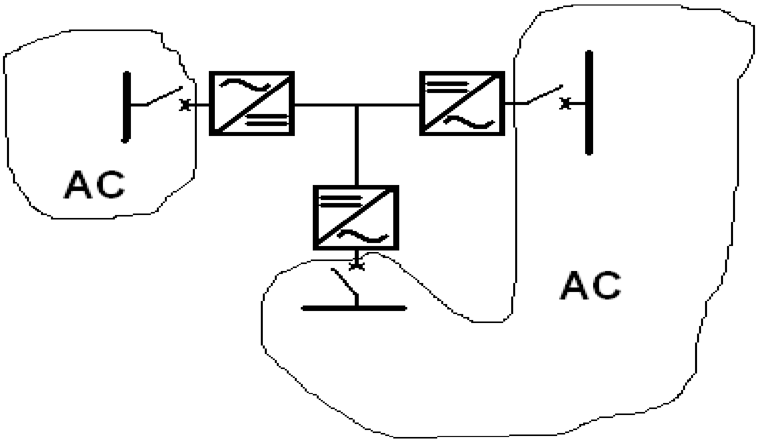
Due to the ease of voltage manipulation and the simple circuit breaker, AC is the technology of choice for large scale electrification.

DC comes only into the picture for:

- Very long distance transmission, thanks to cheaper transmission circuits.
- The cases where AC reaches its technical limits.

3.5. DC is not used on its own, but as a complement of AC:

- There is no production and no consumption at DC level. DC power originates from an AC grid and returns to an AC grid.

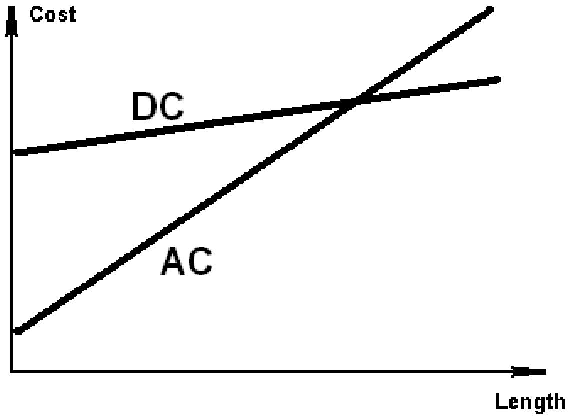


- The principle of AC-DC conversion and vice-versa requires "electronic" controllable switching.
- AC side switching and controlled electronic switching replace the missing DC circuit breaker functionality (DC breaker still far from industrial application).

3.6. Very long distance transmission

DC is characterised by costly conversion equipment, but cheaper transmission infrastructure itself:

- The cheaper DC transport carrier (line, cable) compensates the extra expenses for AC-DC conversion on both sides.

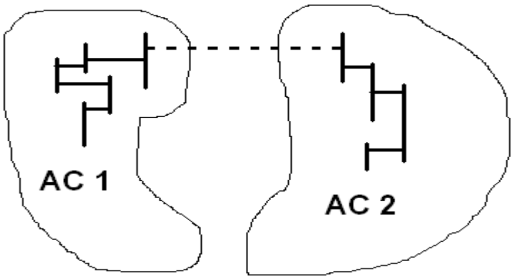


- For overhead line break-even is in the range of 1000 km.
- For cable break-even is in the range well over 100km (depends on voltage).

In most of these cases economy is not the only reason, because AC is also reaching its physical limits on longer transmission.

3.7. Limits of application of AC

3.7.1. Links between grids at different frequency or asynchronous grids at same frequency



An AC link is only possible between grids of the same frequency. Mutual support between grids at different frequency need a decoupling which may be AC - DC and then DC - AC, in other words a DC link.

An AC link (of limited capacity) is between (large) grids is only possible when these grids are synchronous, i.e. interconnected already in AC.

3.7.2. The power transmission limit in AC with in particular the weak links between extended AC networks

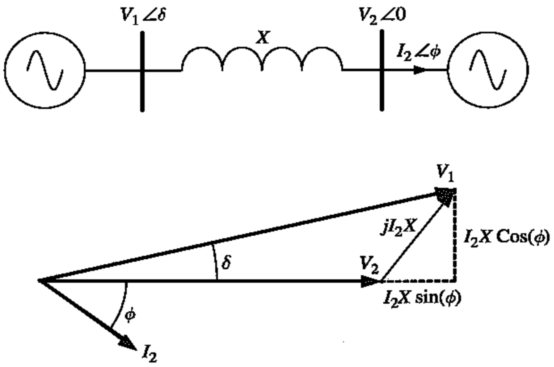
The transmittable power through an AC link has a physical limit, due to series inductance of the circuit. X stands for Reactance of the circuit at the AC frequency (f) in question $X = 2\pi f L$, with L the inductance of the circuit.

This case may happen with massive power transfer over long distances.

Maximum power is inversely proportional to the (total) series reactance, and directly proportional to the square of system voltage.

The classic AC approach is to compensate part of the reactance by a series capacitor, or to select a next higher voltage level for the transmission.

In the DC approach, the reactance of the circuit is not relevant. Transmitted power is only related to the acceptable resistive voltage drop, which reflects directly the efficiency of the transmission (x % voltage drop = (100-x) % efficiency).

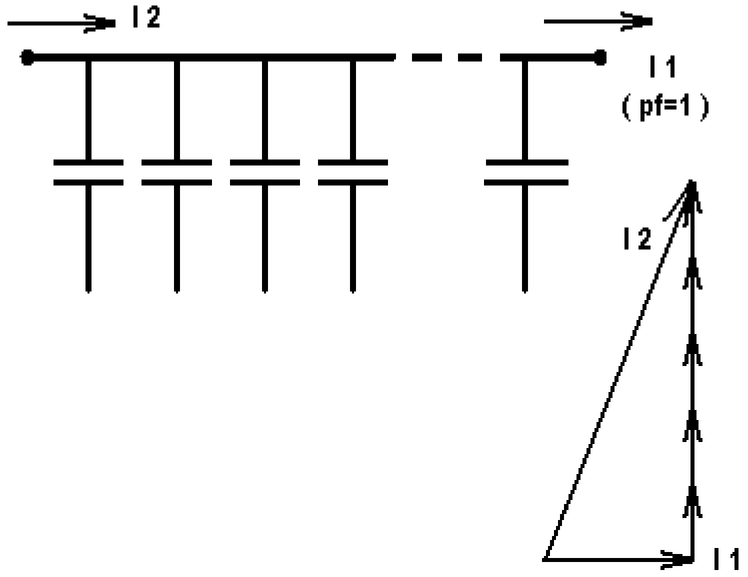


$$P = V_2 I_2 \cos(\phi) = \frac{V_1 V_2 \sin(\delta)}{X}$$

Weak AC links are a special case of the power transmission limit. When a severe unbalance occurs in one of the strong AC sub-grids, the weak AC link tries to maintain synchronism and gets charged beyond its transmission limit, with loss of synchrolism and loss of the interconnection.

3.7.3. Shunt capacitance loading

The capacitive loading currents (mainly in cables) need evacuation to the extremities of the link. They may "consume" part if not all of the current carrying capacity.

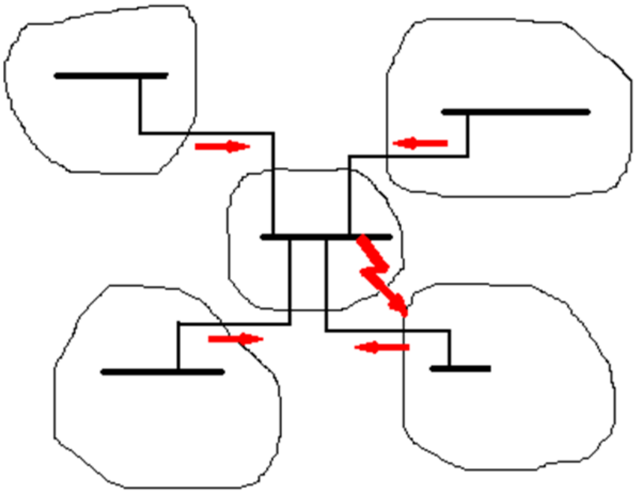


This is well illustrated above with I1 (load side current) purely resistive and in phase with load side voltage. We see that cable capacitive loading currents gradually add up in quadrature with the useful load current.

If the source side current matches the cable ampacity, only a fraction of this ampacity (and thus the investment) is used effectively in useful power transfer.

3.7.4. Limits of short-circuit rating

The more AC networks get interconnected, the more the fault current level rises. Both for mechanical withstand and for current breaking capacity the fault current level is to limited.



When these limits are reached no further AC interconnection is possible at the same voltage level.

The classic AC approach is to select a next higher voltage to create a superposed grid, und to decouple partially the lower voltage grid.

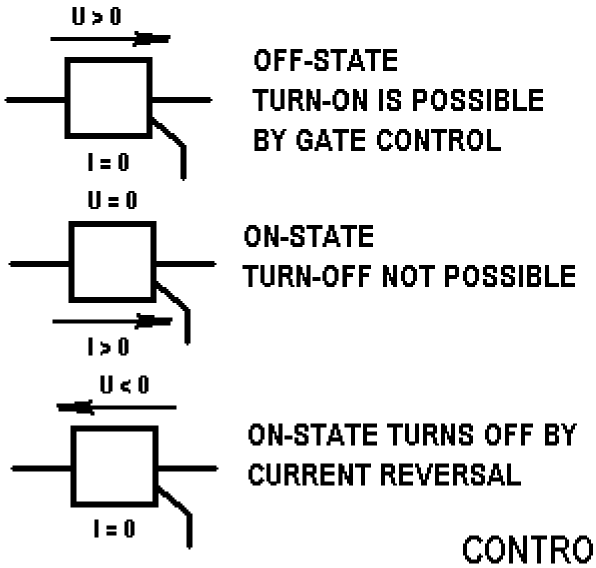
Here DC may also offer a solution which ensures the benefits of interconnection, while keeping the fault currents in check by decoupling.

4. THE TOOLBOX FOR AC/DC CONVERSION

4.1. The electronic switches applicable for HVDC applications

4.1.1. Controllable rectifier

Controllable rectifier: offers controllable turn-on, but no turn-off. Turn-off is ensured by natural zero crossing of current.



CONTROLLABLE
RECTIFIER

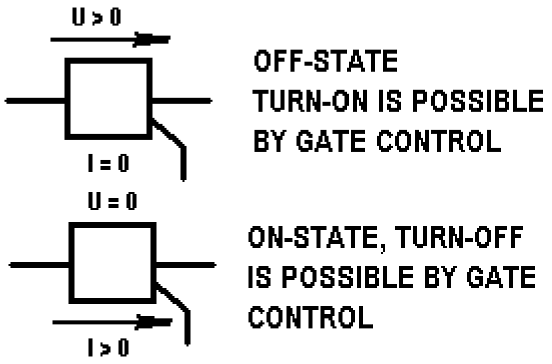
The controllable rectifier in six pulse bridge is the basic building block of the Current Source Converter.

Historically the mercury arc valve was used for this purpose. Today thyristor stack valves serve this purpose.

4.1.2. Fully controllable turn-on and turn-off switch

This switch combined with anti-parallel diode is the basic building block of the Voltage Source Converter.

Most common type is the IGBT switch.



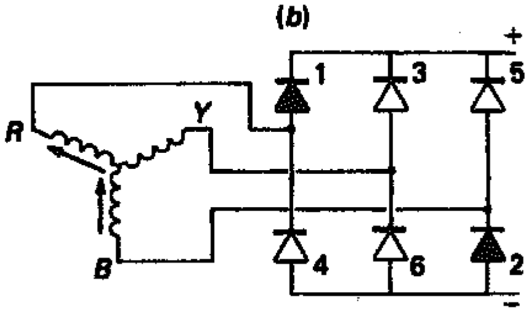
DC SWITCH

4.1.3. The Current Source Converter CSC

The CSC converter works on the principle of a highly inductive DC circuit, with a constant DC current.

The DC current is "commutated" between the AC side phases so as to form rectangular alternating current.

(b)



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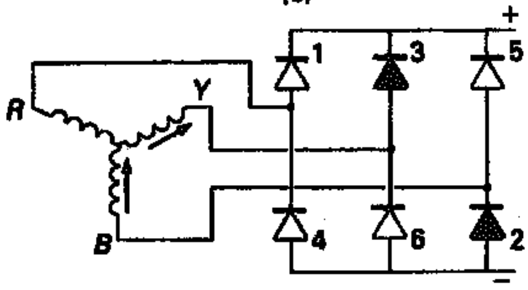
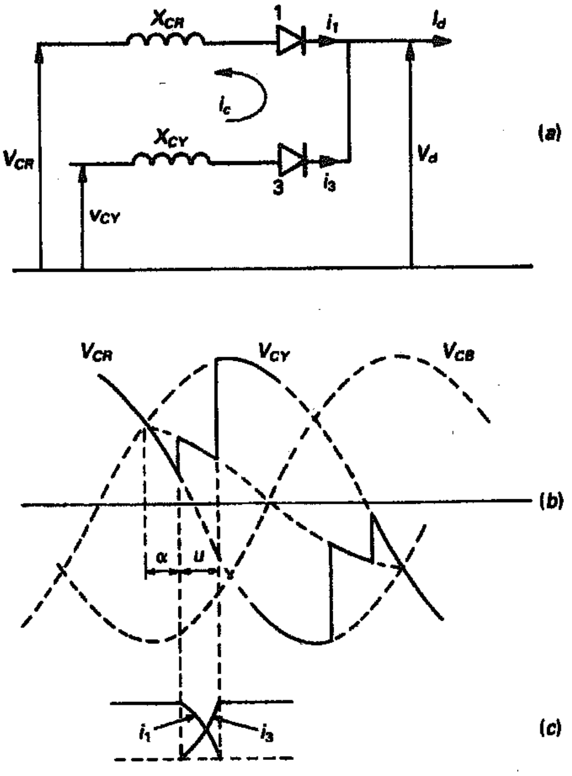


Current commutation by the AC source:

- The commutation is started by "firing" of the next phase controllable rectifier.
- The AC side sees a short circuit between phases and adds an AC short circuit current component.
- When the current in the first phase tends to reverse the controllable rectifier blocks and the commutation is complete.

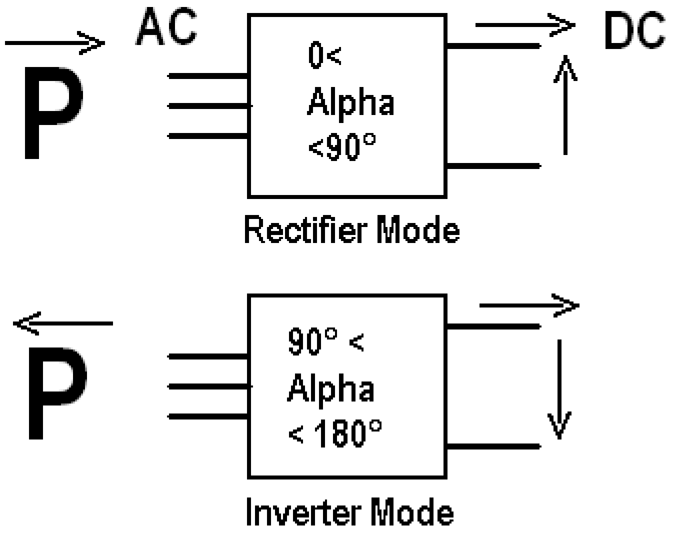
- In other words, the ac side voltage drives the commutation.



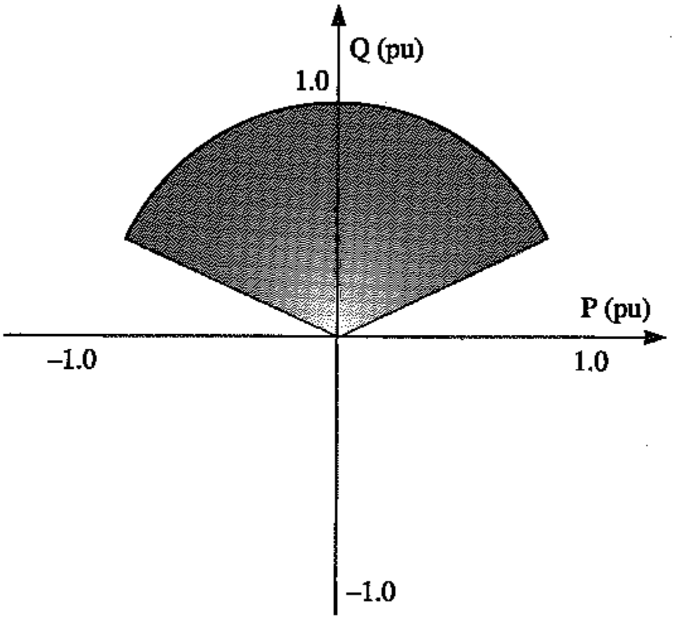
Power relations of the CSC converter:

- The firing angle defines the DC output voltage. For 0<α<90° the output ranges from maximum positive to zero. This is the rectifier mode: the power flows from AC side to DC side.
- For 90°<α<180° the output ranges from zero to maximum negative. This is the inverter mode: the power flows from AC side to DC side.

- The AC current is rectangular alternating and contains harmonics which need to be filtered out on the AC side.



- The DC current flows always in the same direction. Power direction depends on DC voltage polarity.
- Reversal of polarity reverses also rectifier to inverter mode and vice versa.
- Both rectifier and inverter consume reactive power on the AC side.



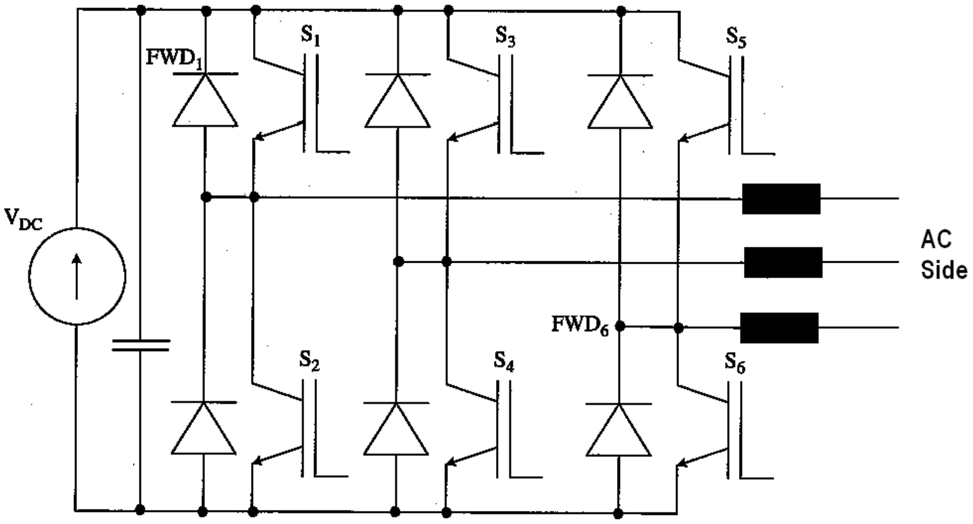
- The CSC converter is straightforward in point to point transmission, but becomes very complex in multi-terminal transmission.
- The AC sides should have adequate short circuit level to ensure the current commutation.
- Thanks to natural commutation the losses are relatively low (compared to VSC).
- Faults on the DC side are controlled electronically by suppression of firing signals. Fast recovery is possible for fugitive faults (air insulation in OH lines).
- CAPEX/kW converted is lower than in VSC.

4.1.4. The Voltage Source Converter (very basic scheme)

The Voltage Source Converter is based on a highly capacitive DC side.

The individual AC phases are switched successively to the positive and the negative pole of the DC side.

When switches turn off, the anti-parallel diodes take over conduction.

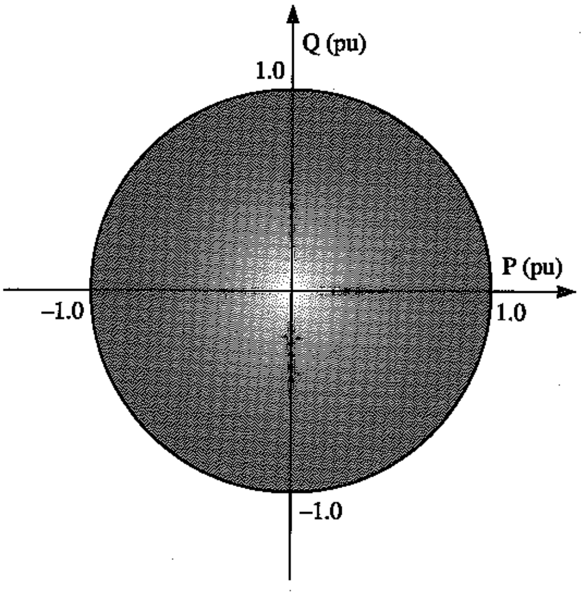


A variety of circuit configurations and switching patterns exist. The purpose is the best approximation of a sinusoidal voltage waveform at the AC side.

The power direction is function of the phase shift between the AC grid voltage and the AC voltage (fundamental) generated by the converter.

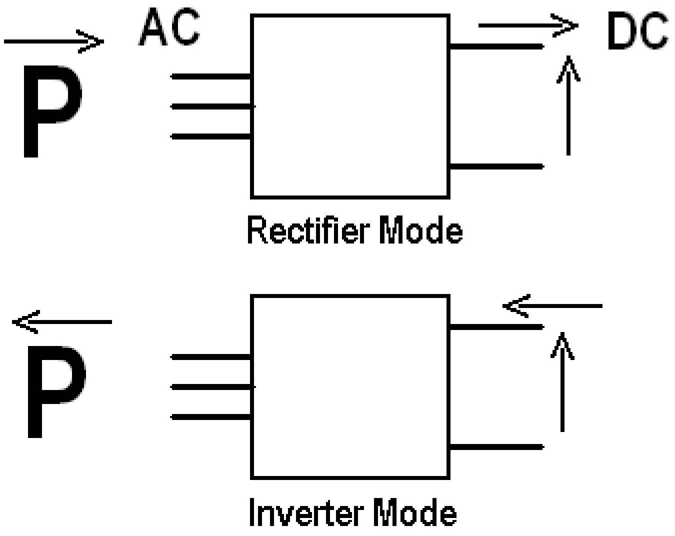
The reactive power at the AC side is fully controllable. The VSC may act as a static var compensator (Statcom version of SVC).

The presence of anti-parallel diodes fixes a lower limit for the DC voltage with respect to the AC voltage. Forcing DC voltage lower (e.g. as consequence of fault) causes uncontrollable fault currents to flow from AC to DC. These can only be cleared by the AC side circuit breakers.



Power relations of the VSC converter:

- The DC side voltage has fixed polarity, the DC output current may have both directions. DC power follows the DC current.
- Several Voltage Source Converters may operate in parallel at the DC side, without complex regulations.



- The AC side need no source of short circuit level. An inverter can generate AC voltage into a passive network.
- Depending in circuit and switching pattern the need for filtering on the AC side is limited.

- DC fault clearing is complex (via AC side breakers). DC breakers are in development, but still (far) away from industrial application.
- Both CAPEX and losses are higher than for comparable CSC.

5. TYPICAL APPLICATIONS OF HVDC

5.1. Two grids at different frequency

Itaipu (Brazil 60 Hz - Paraguay 50 Hz) HVDC line.

GCCIA (Saudi-Arabia 60 Hz - GCCIA Countries 50 Hz) Back-to-Back.

5.2. Two grids at same frequency but not synchronous

GB - The Netherlands (or Belgium?).

5.3. Massive long distance OH line

Inga - Shaba 1800 km.

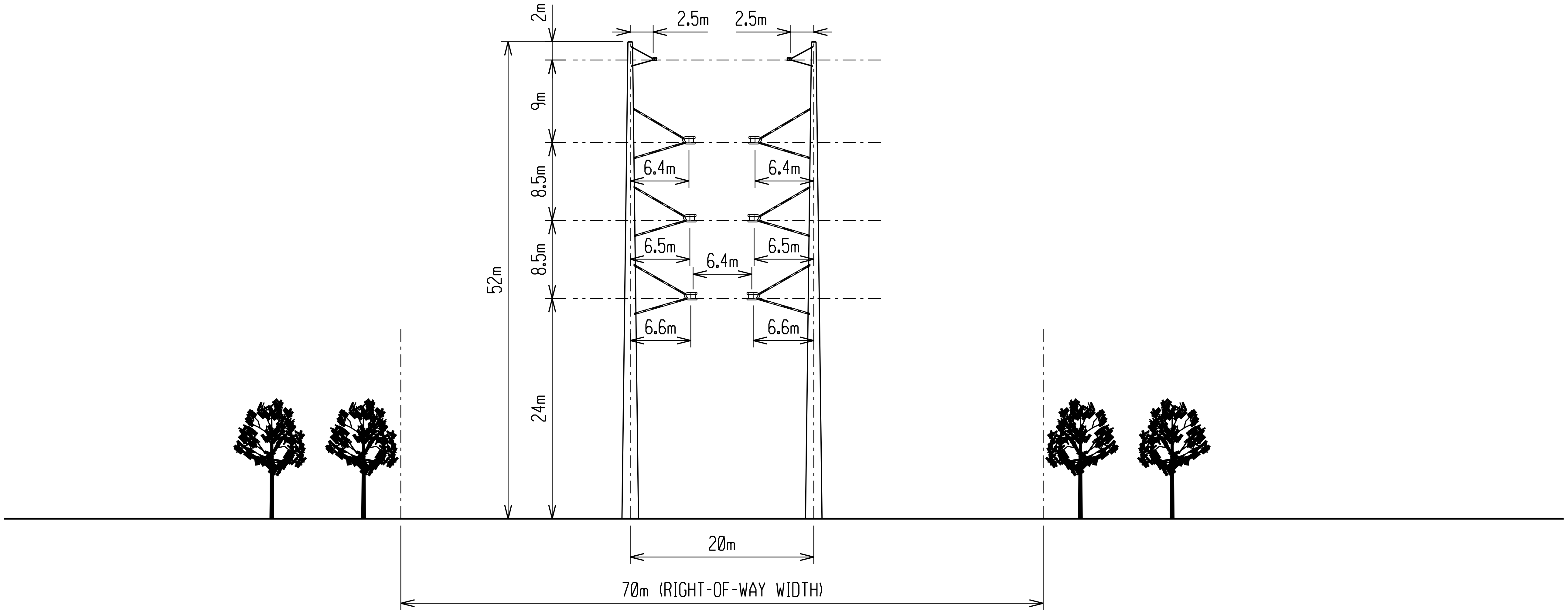
5.4. Long distance cable

Norway - The Netherlands 600 km.

ATTACHMENT 2

AC line solution
- Right of way

TYPICAL VIEW



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MINEZ - 380kV Intercon Doetinchem-Wesel

HVAC OVERHEAD CABLE SYSTEM 400kV
RIGHT OF WAY

TRACTEBEL Engineering
GDF SUEZ

TRACTEBEL ENGINEERING S.A.
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ATTACHMENT 3

DC transmission Line
- Right of way
- Line data
- End stations single line
- End stations bird view

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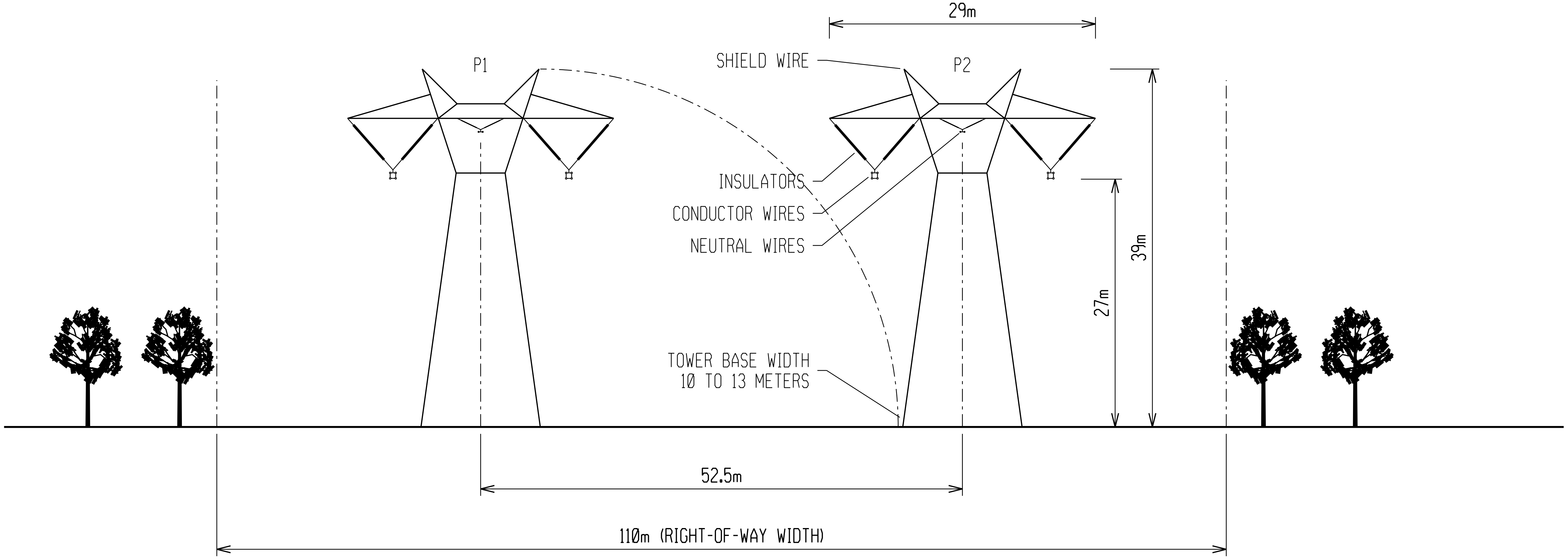
TYPICAL VIEW



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MINEZ - 380kV Intercon Doetinchem-Wesel

HVDC OVERHEAD CABLE SYSTEM +/-500kV
RIGHT OF WAY

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MINISTERIE VAN ECONOMISCHE ZAKEN
CONSULTANCY RELATIVE TO TECHNICAL ALTERNATIVES FOR DOETINCHEM-WESEL

Feasibility of technical alternatives for the 380 kV interconnection Doetinchem-Wesel
Overhead HVDC Towers and conductors

TABLE OF CONTENTS

1. ASSUMPTIONS

In order to produce a realistic case for the HVDC overhead line alternative, a look-up has been made of existing HVDC links with ratings comparable to the case Doetinchem-Wesel.

- HVDC.
- bipolar ± 500 kV.
- 2 bipoles: each bipole rated 2635 MW.
- Line length: ~57 km.
- Conversion technology CSC or VSC technology (no impact on the line).

2. SIMILAR HVDC PROJECTS

Similar HVDC projects [IEEE], in terms of power rating and DC voltage level.

Project	Year commissioned	Power rating (MW)	DC Voltage (kV)	Line length (km)	Location
Itaipu 1	1986	3150 MW	± 600	785	Brazil
Itaipu 2	1987	3150 MW	± 600	785	Brazil
Rihand Delhi	1992	1500 MW	± 500	814	India
Three-Gorges-Changzhou	2003	3000 MW	± 500	860	China
Three-Gorges-Guangdong	2004	3000 MW	± 500	940	China
Three-Gorges-Shanghai	2006	3000 MW	± 500	900	China
Gui Guang I	2004	3000 MW	± 500	980	China
Gui Guang II	2007	3000 MW	± 500	1200	China

For a bipole power of 2635 MW, a derated voltage configuration of Itaipu 1 could be used.

At 500 kV DC the Itaipu configuration delivers 3150 x 500 kV / 600 kV= ~2535 MW.

3. TOWER AND CONDUCTOR CHARACTERISTICS

Here are a few pictures of ± 500 kV HVDC towers [Kim].

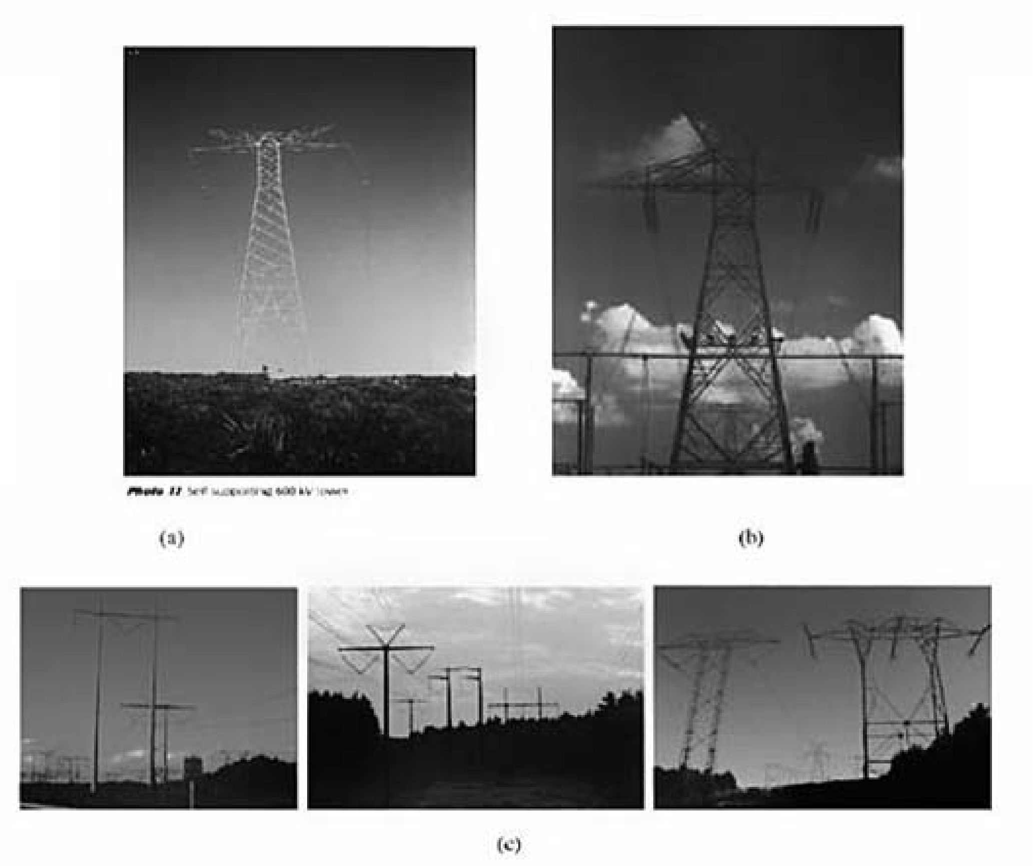


Figure 6.30 HVDC line configurations: (a) Brazil 600 kV tower; (b) Rihand–Delhi 500 kV HVDC; (c) Quebec–New England HVDC interconnection ± 450 kV line.

Figure 1

The following picture shows typical tower and ROW (right-of-way) sizes (Kim).

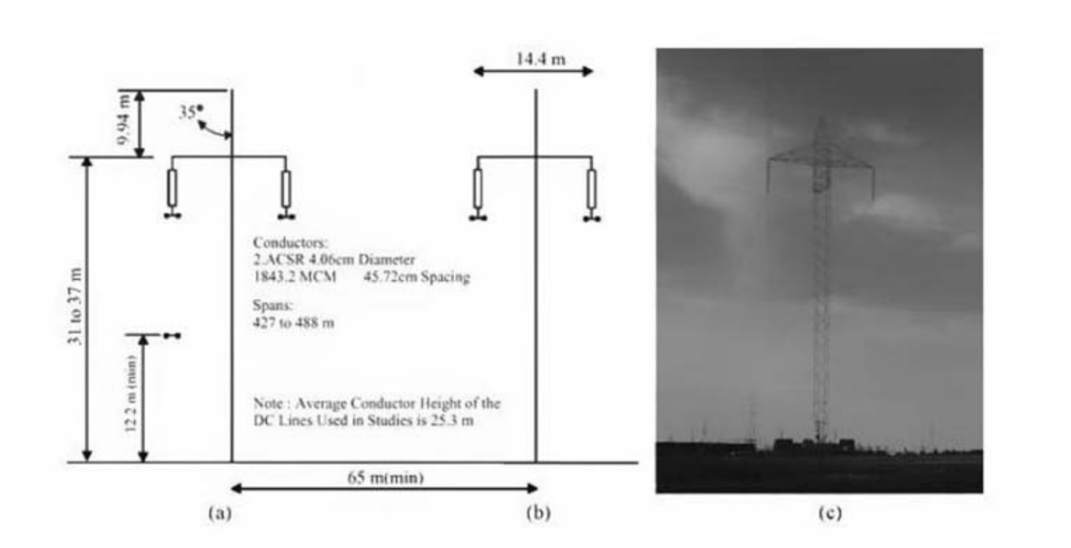


Figure 6.29 Basic ± 500 kV HVDC line configuration (Manitoba hydro).

Figure 2

See also files "Typical500kVTower.pdf" and "Electrical-Considerations-for HVDC-Transmission-Lines.pdf".

The conductor configurations of the Itaipu project are as follows:

- 4*Bittern 644mm² 45/7 ACSR.
- Subconductor spacing 450 mm.

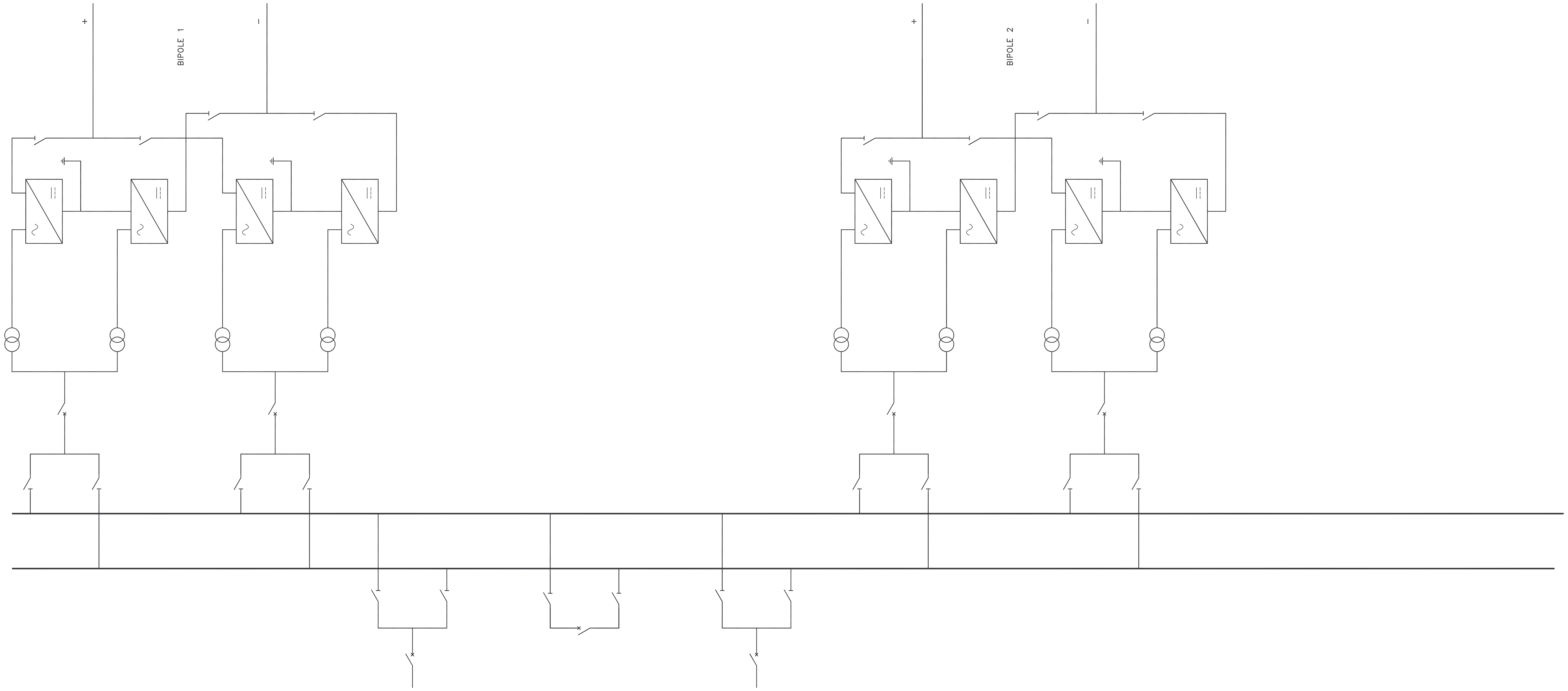
4. SUMMARY

The following characteristics are realistic for the Doetinchem – Wesel overhead HVDC alternative:

- By comparison with Itaipu, the 4 conductor bundle 4*644mm² ACSR seems appropriate for the power to be transmitted (2*2635MVA per bipole).
- 500 kV outline tower to be used. For the 4 conductor bundle the wider tower model should be considered (see e.g. "Typical500 kVTower.pdf" for example).
- ROW of about 70m.
- Tower height of about 40m.
- Tower width of about 30m.

5. REFERENCES

- [IEEE] HVDC projects listing existing, prepared for the DC and AC Transmission subcommittee of the IEEE Transmission and Distribution Committee, by the Working group on HVDC and FACTS Bibliography and records.
- [Rao] S. Rao, "EHV-AC, HVDC, Transmission and Distribution Engineering", Khanna Publishers.
- [Kim] Chan Ki Kim et al, "HVDC Transmission: Power conversion applications in Power Systems », Wiley 2009.



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HVAC/DC SUBSTATION LINES
SINGLE LINE DIAGRAM

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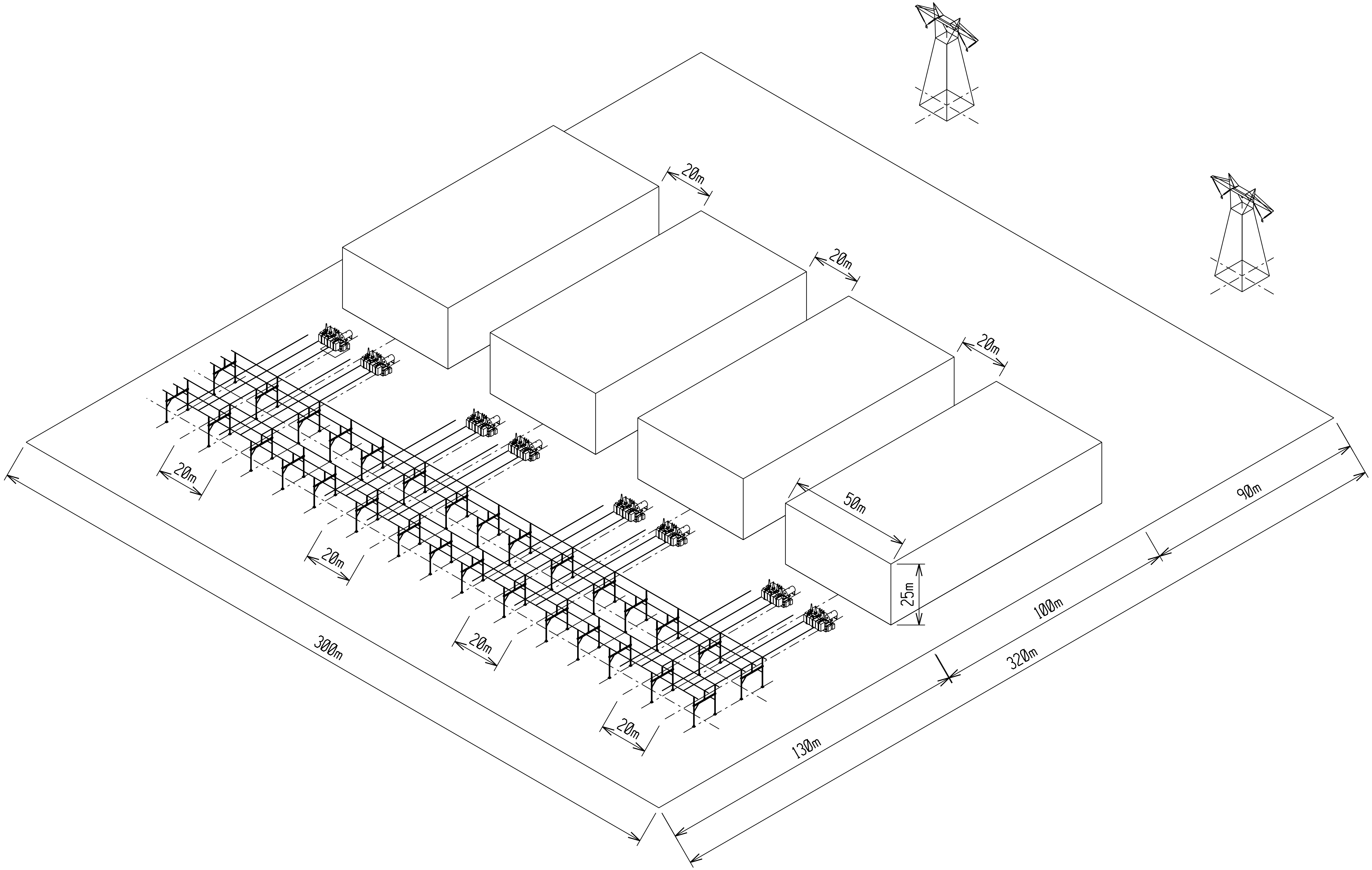

MINEZ - 380kV Intercon Doetinchem-Wesel

HVAC/DC SUBSTATION LINES
GENERAL IMPLANTATION

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ATTACHMENT 4

DC transmission cable
- Right of way
- Line data
- End stations single line
- End stations bird view

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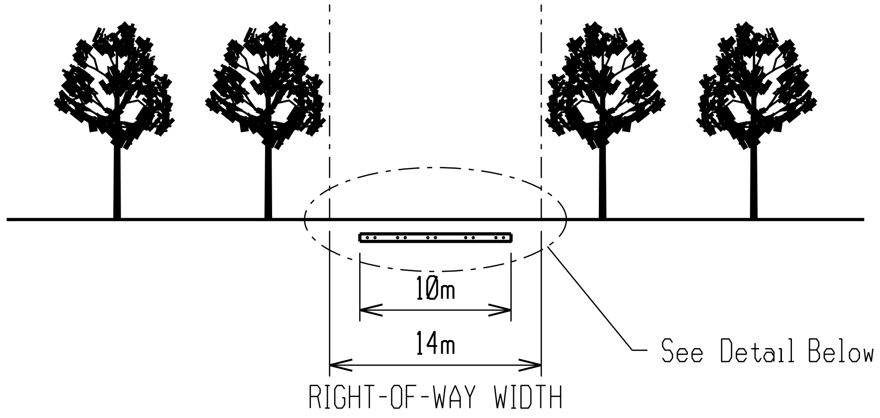
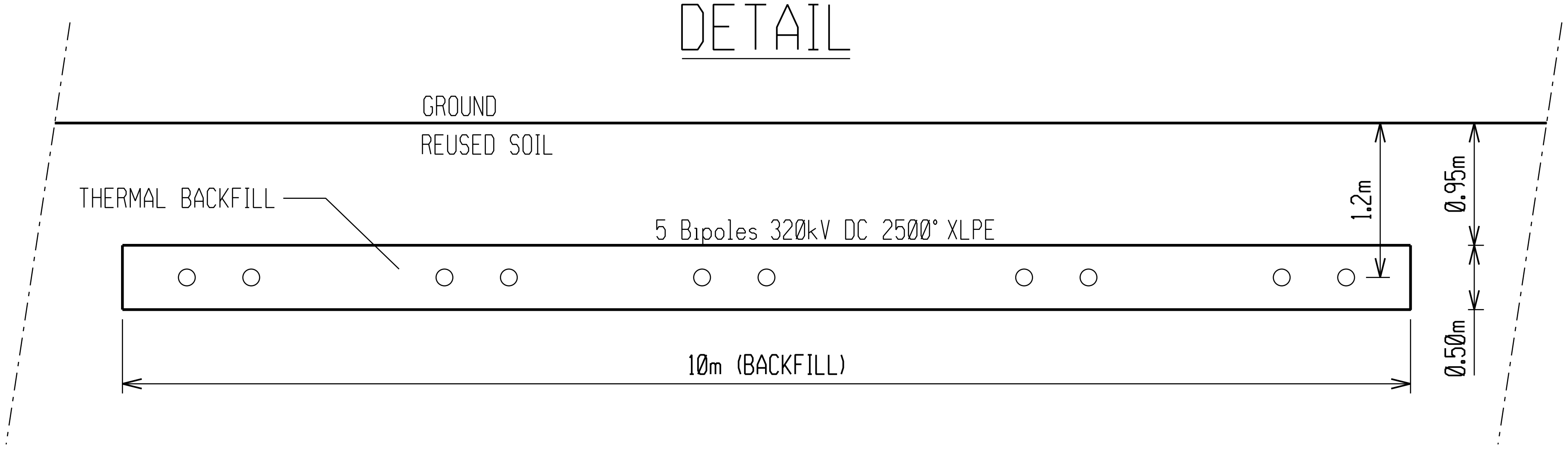
TYPICAL TRENCH



DETAIL



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MINEZ - 380kV Intercon Doetinchem-Wesel

HVDC UNDERGROUND CABLE SYSTEM +/-320kV
RIGHT OF WAY

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Project Code MINEZDC	Type 578	Running Number 1254447	Sheet 002	Rev. 00

Summary Results

CYMCAP 6.0 rev. 5

Study: MINEZ - Doetinchem-Wesel AC versus DC

Execution: Corridor DC 5270MW ±320kV

Date: ######

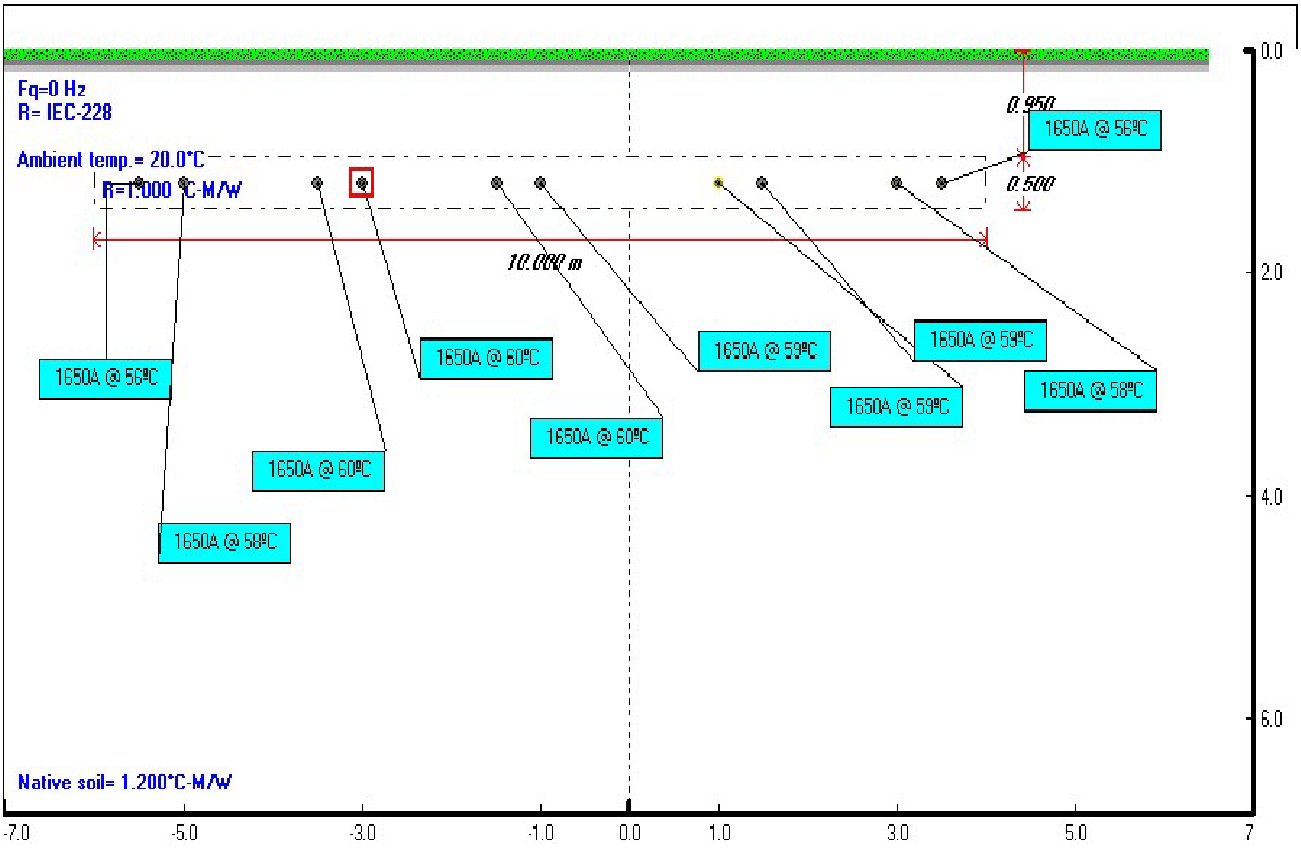
Frequency: 0 Hz

Conductor Resistances IEC-228

Fraction of conductor current returning through sheath for single phase cables: 0

Installation Type: Backfill

Parameter	Unit	Value
Ambient Soil Temperature at Installation Depth	°C	20
Thermal Resistivity of Native Soil	°C.m/W	1.2
Thermal Resistivity of Backfill	°C.m/W	1
Backfill Width	m	10
Backfill Height	m	0.5
Backfill X Center	m	-1
Backfill Y Center	m	1.2
Non-Isothermal Earth surface modeling	Enabled/Disabled	Disabled

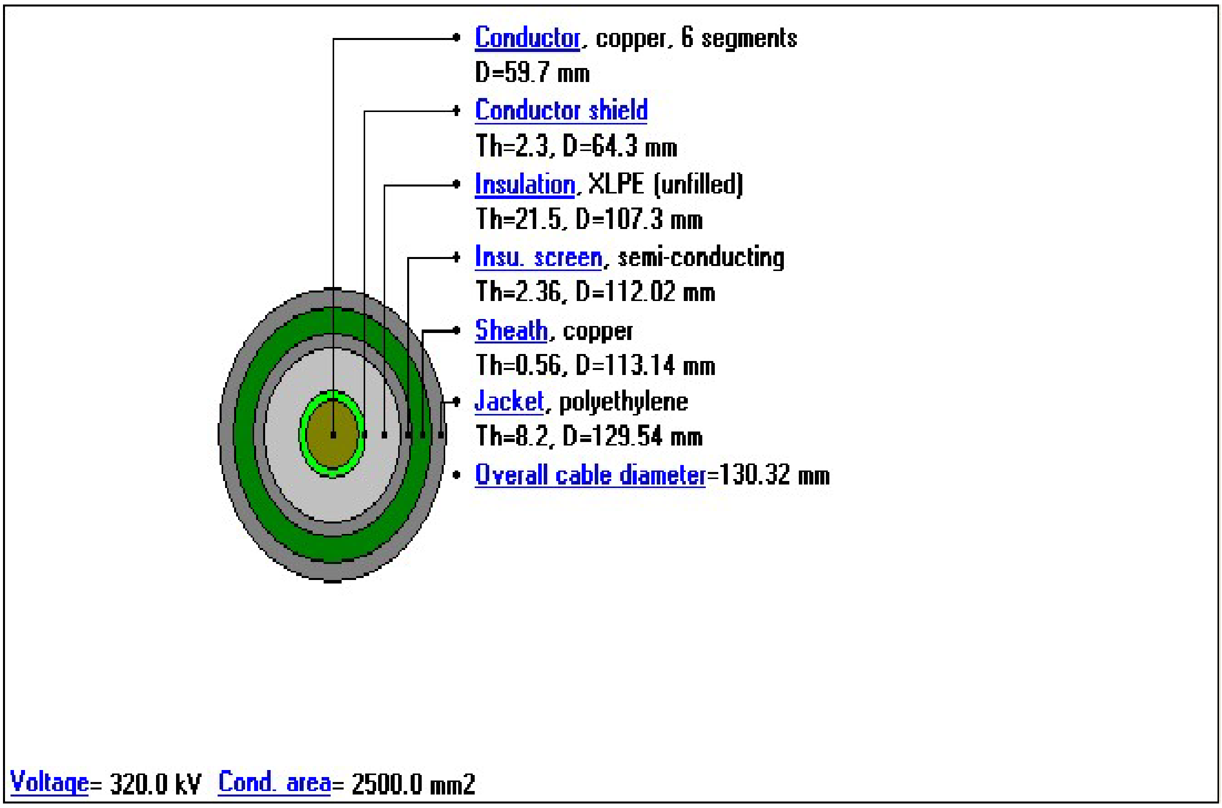


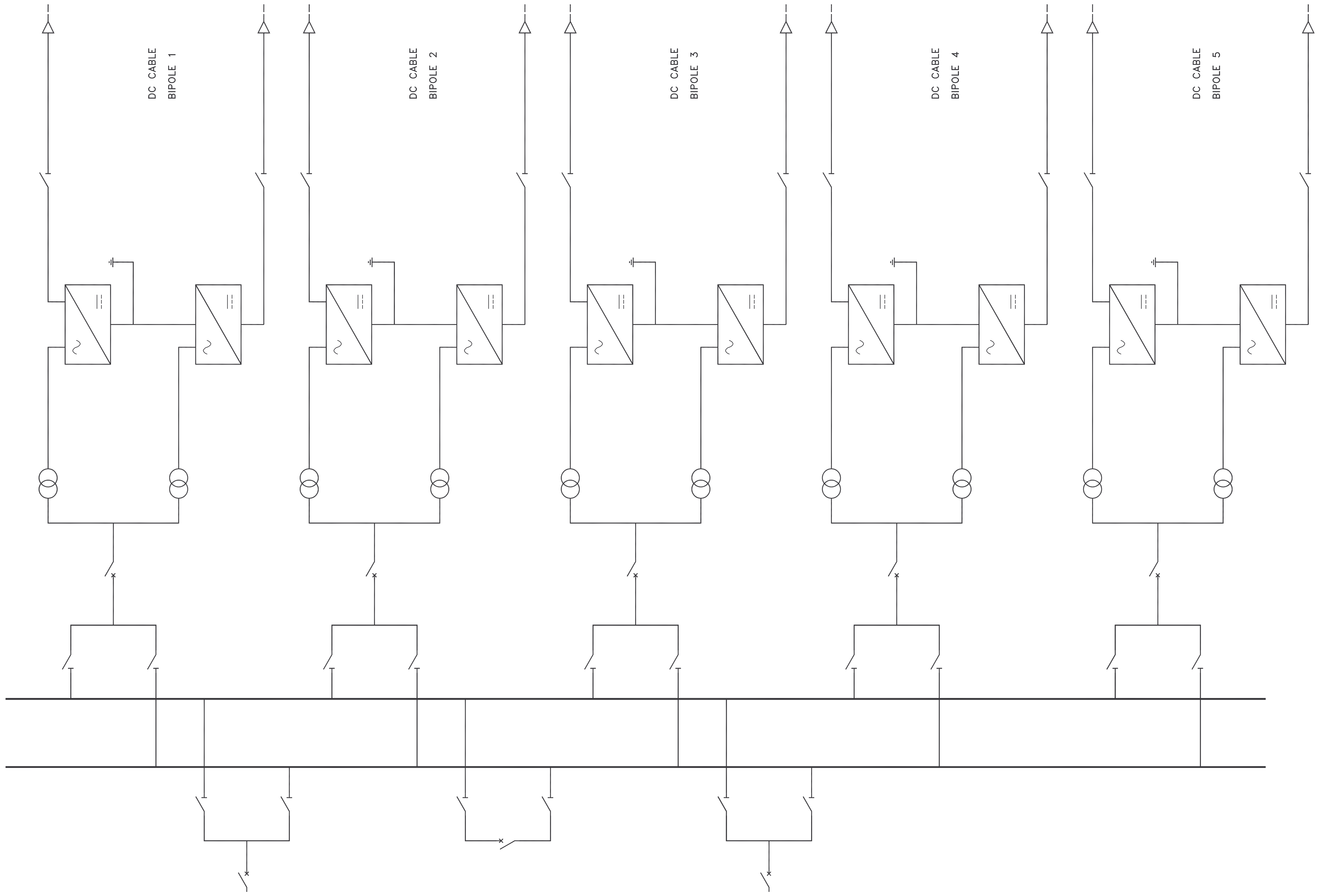
Summary Results

Solution converged

Cable\Cable type no	Circuit	Phase	Location		Load Factor	Temperature	Ampacity
			X[m]	Y[m]	[p.u.]	[°C]	[A]
1 \ 1	1	A	-5.5	1.2	1	56.3	1649.8
2 \ 1	2	A	-5	1.2	1	57.7	1649.8
3 \ 1	3	A	-3.5	1.2	1	59.8	1649.8
4 \ 1	4	A	-3	1.2	1	60	1649.8
5 \ 1	5	A	-1.5	1.2	1	59.9	1649.8
6 \ 1	6	A	-1	1.2	1	59.4	1649.8
7 \ 1	7	A	1	1.2	1	58.9	1649.8
8 \ 1	8	A	1.5	1.2	1	59	1649.8
9 \ 1	9	A	3	1.2	1	57.5	1649.8
10 \ 1	10	A	3.5	1.2	1	56.1	1649.8

Cable title: 320 kV DC 2500 mm² Copper - XLPE





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HVAC/DC SUBSTATION CABLES
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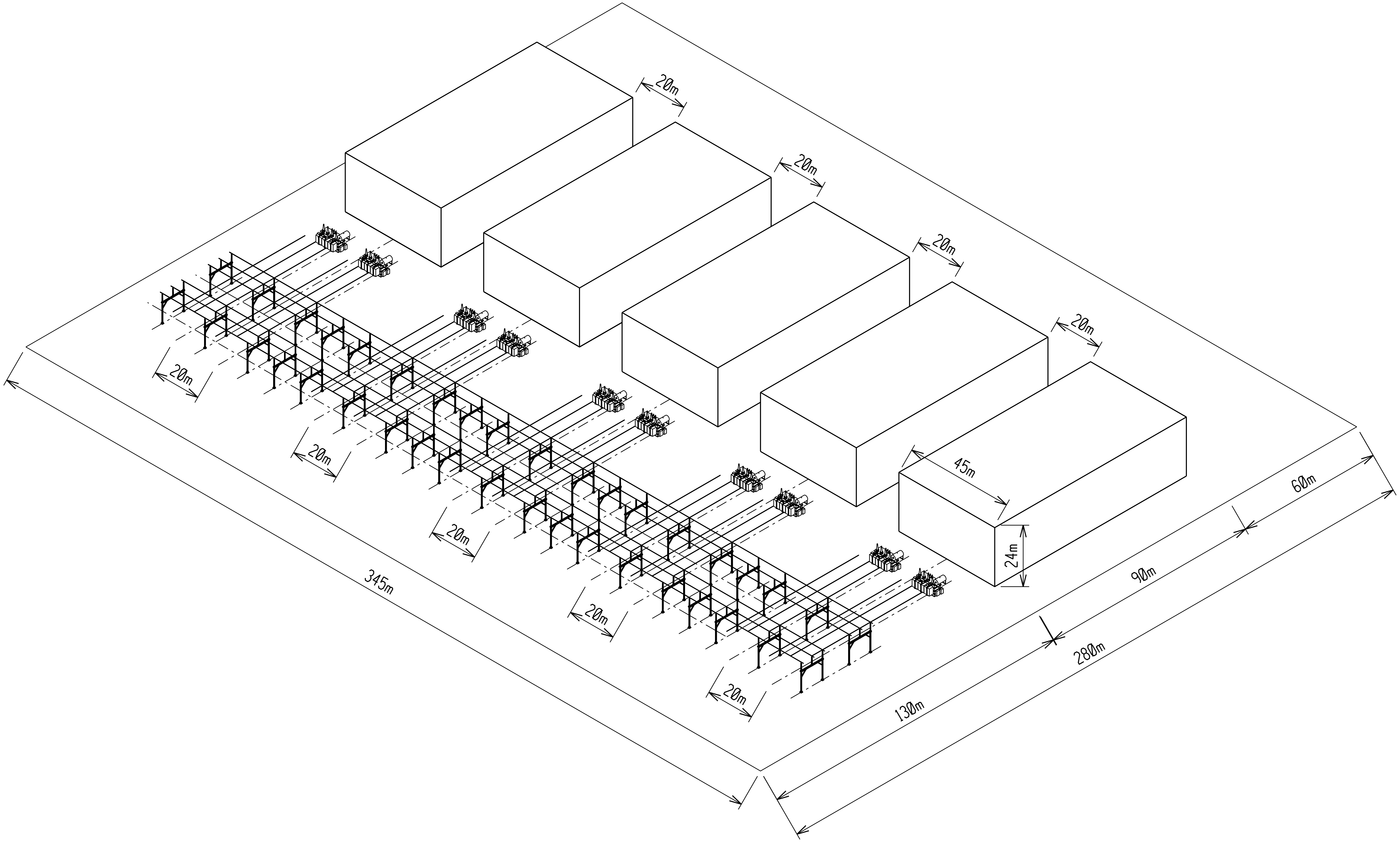

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MINEZ - 380kV Intercon Doetinchem-Wesel

HVAC/DC SUBSTATION OF CONVERSION
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