HVDC Overhead Line Performance Study

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ABSTRACT

The Electric Power Research Institute (EPRI) is documenting the various factors that should be considered when designing and building new high-voltage direct current (HVDC) lines or when converting AC lines to HVDC. Given the limited number of HVDC lines that have been designed and built around the world, even some basic factors (for example, insulator flashover in severely contaminated regions) are not completely understood. This report concerns a crucial first step in better understanding and improving the performance of HVDC lines—designing and circulating a questionnaire on HVDC line performance.

Extensive work has been done by the Conference Internationale des Grandes Reseaux Electriques (CIGRE) in determining the performance levels of HVDC converter stations. The focus of this work is to study and understand the performance levels of HVDC overhead lines.

The preliminary design for the HVDC Line Performance Questionnaire involved reviewing a wide variety of HVDC design concepts and present design practices. In addition, CIGRE members of Study Committee B2 were interviewed. After preparing an initial questionnaire, it was reviewed by several people, and a newly edited version circulated to a small number of knowledgeable engineers involved in HVDC line design and maintenance around the world.

The limited responses to the preliminary questionnaire are summarized in this report. Several suggestions regarding a future, more formal survey of line performance under the auspices of CIGRE Study Committee B2 are included.

Finally, the report includes a number of recommendations for future EPRI work regarding improved performance of HVDC lines.

Keywords
HVDC
HVDC line design
Line performance

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1 HVDC LINE PERFORMANCE ISSUES

As used in this report, high-voltage direct current (HVDC) lines designate DC transmission lines that cover the voltage range of ±100 to ±1000 kV. In general, alternating current (AC) transmission lines are designated HV for lines with a phase-phase voltage of 69–230 kV and extra-high voltage (EHV) for lines at 345 kV and 500kV and ultra-high voltage (UHV) for 765 kV or higher. In this report, the descriptors HV, EHV, and UHV refer to AC lines of different voltage classes. The possible application of DC to distribution voltage circuits is not considered here.

The conventional wisdom concerning HVDC line design is that it is a simple extension of AC design if one uses insulators with greater creepage length, credits the higher power flow capability and its controllability, and notes the flexible operation of such lines with various ground return arrangements. The cost of construction and the power flow on HVDC circuits is, however, much higher than with AC circuits so that design mistakes are amplified.

The purpose of this project was to identify key areas of uncertainty regarding HVDC line performance by preparing a questionnaire regarding the performance of existing HVDC lines and summarizing observations on line performance after circulation of the questionnaire to share practical experience with regard to existing HVDC lines.

The result of this investigation is to guide subsequent, more detailed gathering of HVDC line performance data with the goals of improving the design of new HVDC lines and increasing confidence in the conversion of existing AC lines to HVDC where appropriate. It may also provide information that may guide the development of future CIGRE technical documents on HVDC line design.

Observations on HVDC Line Design

In a physical sense, HVDC lines are similar to AC transmission lines in that both use bare stranded conductors and both must meet or exceed minimum specified electrical clearance to ground and to other conductors at operating voltage. There are, of course, advantages and disadvantages as there have been since the time of Edison and Westinghouse. Some of the advantages of an HVDC circuit are:

- "Failure" of an HVDC line can be quite different from that of an HVAC line. Flashover of any of the three-phase conductors of a single-circuit AC line causes breaker operation and takes the line completely out of service. A bi-pole HVDC line is somewhat like a double-circuit AC line in that the poles of the HVDC line can be operated independently, just like the AC circuits. The failure of one pole or circuit allows continued operation—although at a reduced power level.

- A bi-pole HVDC line needs only two conductors, instead of the three required by a single-circuit AC line or the six conductors in a double-circuit AC line. This normally requires a smaller right of way and a less visually obtrusive tower. Figure 1-1 shows schematically the tower configurations for 1200 MW (two circuits AC, bipolar HVDC) and 1500–2000 MW transmission at EHV AC single circuit or monopolar HVDC by alternative tower designs.

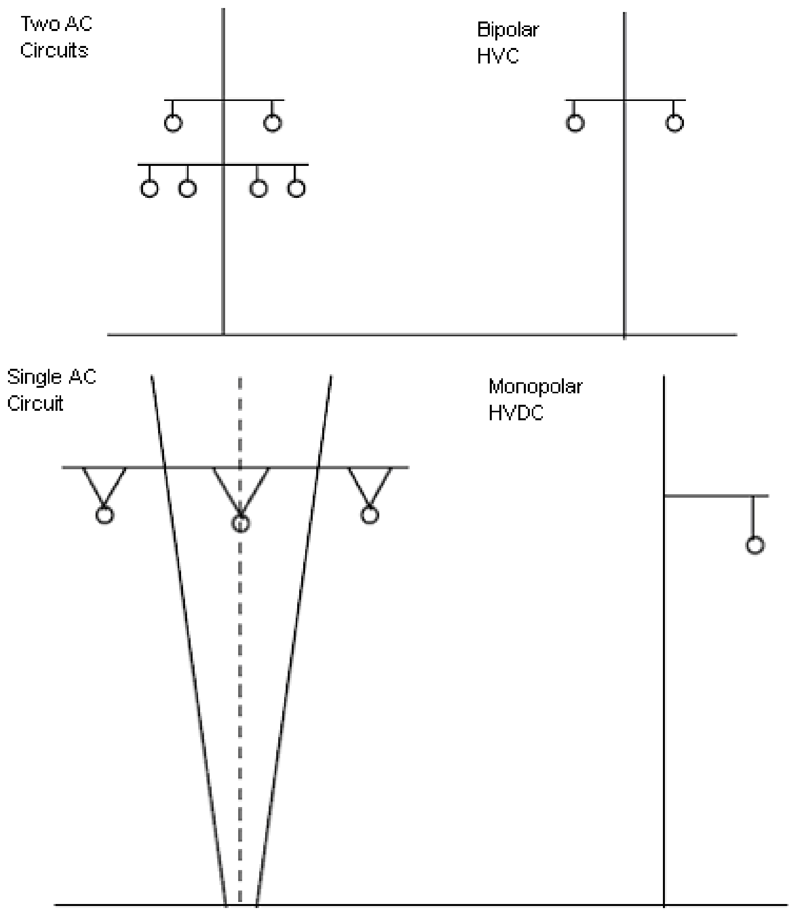

Figure 1-1
Comparison of physical size for HVAC and HVDC circuits with comparable power flow capacity [1]

- The conductors in an HVDC line do not experience "skin effect," so electrical losses are lower for a given power flow.
- DC lines offer power flow control, whereas HVAC lines are electrically passive. Depending upon the placement of the HVDC circuit within the AC transmission system, this advantage can be critical to system reliability during system emergencies.
- HVDC cables have no length limit as do AC cables, so HVDC cables can be used for long-distance transmission of power, either underground or undersea (submarine).

- There is no need for frequency synchronization between systems linked by DC, so HVDC circuits can be used to link systems that are not necessarily in frequency synchronization. The line portion of the circuit is not necessary to claim this advantage since a back-to-back converter station works similarly.
- The addition of an HVDC circuit does not increase the short circuit currents on existing AC switchgear.
- An HVDC link can be relied upon as part of a system's generation reserve.

Some of the disadvantages of HVDC relative to AC lines are:

- Corrosion rates and special provisions to control corrosion may well be different, especially if there is any significant operation of the HVDC line as a single pole with ground return.
- The "power flow control" feature of HVDC lines makes any loss of service event far more serious in terms of the overall transmission system. Yet the line is subject to ordinary line failure modes (insulator failure, lightning flashover, ice galloping). This would seem to require much higher reliability requirements for HVDC lines.
- DC lines have special substation equipment (converters) that, assuming the HVDC line is embedded in an AC transmission system, cannot be shared with other lines. When the HVDC line is out of service, the substation equipment (converter) is also lost (and vice-versa). When an AC line is out of service, other lines connected to the same bus can pick up some of the load flow.
- Power supplied to load by an HVDC link is more like a generating station than a line. The loss of that connection is replaceable only with higher cost generation over completely different paths. The model of picking up power flow on HVAC lines during an EHV or UHV AC outage does not apply as well to HVDC line outages.

A direct comparison of performance between HVDC and AC should consider the level of maintenance required to maintain acceptable outage rates. HVDC lines are made of essentially the same materials as AC lines of a comparable voltage level. Normal weathering of components of foundations, structures, conductors, splices, clamps, insulators, and shield wires should be similar in a +400-kV HVDC line and a 345–500-kV HVAC line.

Previous Studies of HVDC Line Performance

CIGRE JWG-B2/B4/C1.17 is planning to deliver a technical brochure, which is presently under development, concerning HVDC line economics. The author obtained a draft version for review. An earlier CIGRE technical brochure (TB186—Economic analysis of HVDC links [cable, lines]) was also reviewed.

In both CIGRE brochures, variety of HVDC line configurations and the consequences for each due to the loss of one pole and to total structure collapse are summarized. Table 1-1 shows this summary.

Table 1-1
Consequences for loss of one pole and total structure

Variant	**Remaining Transmission Capacity**		
	Loss of one pole		Tower breakage
	Ground return		
	Permitted	Not permitted	
Single monopolar line	0	0	0
Single bipolar line	50 (100)	0	0
Double bipolar line	100	100	0
Two monopolar lines	50 (100)	0	50 (100)
Two lines (bipolar or homopolar)	100	100	100

The technical advantage of HVDC, used with underground or undersea cable, is clear. HVDC cable can transmit power long distances without dielectric losses, with reduced capacitive charging current, and with lower resistive losses. The economic advantage of HVDC with overhead lines is less obvious. There are some line cost savings from fewer conductors, simpler structures, and reduced right-of-way width but, given the relatively high cost of meeting environmental and government regulations, the importance of reduced material cost is probably marginal.

Disadvantages of HVDC center on the cost of terminals and taps, reliable circuit breakers (no current zero), corrosion and other interference due to earth current, inability to transmit reactive power, and generation of harmonics.

As described in the draft version of CIGRE TB186 (Economic Assessment of HVDC Links—2000):

> "A transmission system needs to fit the demands expected of it with a minimal impact on the environment. Transmission usually, but not always, has spare capacity because that can readily be built into the original design. A system is spoken of as having (n-1) capacity, that is, it can supply rated power if any one single element is out of service. Some systems have (n-2) capacity; even if a double-circuit line suffers a tower failure, the system can still deliver full power. Some HVDC links consist of a single unit, where a single failure can interrupt power flow, but reserves are held elsewhere in the system as a whole."

An HVDC link has the following advantages:

- There is no technical limit to the length of a submarine cable connection.
- There is no requirement that the linked systems run in synchronism.
- There is no increase to the short circuit capacity imposed on HVAC switchgear.

- Because there is precise delivery of power in response to the operator's setting; HVDC avoids the normal constraints of an HVAC system and therefore delivers power independently of impedance, phase angle, frequency, or voltage.
- The linked systems can preserve their independent management of frequency and generator control; the link "relocates" the remote generation or system at the inverter terminal, which can supply power output, frequency modulation, and voltage regulation just as a separate generator might.
- A link can be relied upon as part of a system's generation reserve. Though not loaded (or loaded in an exporting direction), a link to a separate system can remain connected but on standby and able to import power as soon as required. It can improve either or both HVAC systems' stability—and, therefore, internal power carrying capacity—by modulation of power in response to frequency, power swing, or line rating.

The HVDC line, needing as few as two conductors (one only for submarine with earth return) compared to the AC line's use of three, requires a smaller right of way and a less obtrusive tower. Figure 1-3 shows schematically the tower configurations for 1200-MW (two circuits AC, bipolar HVDC) and 1500–2000-MW transmission at AC single circuit or monopolar HVDC by alternative tower designs. (**Caution:** A single circuit or a single pole above 1600-MW capacity has not been built to date because of the effect on the system of the loss of such a high capacity circuit.)

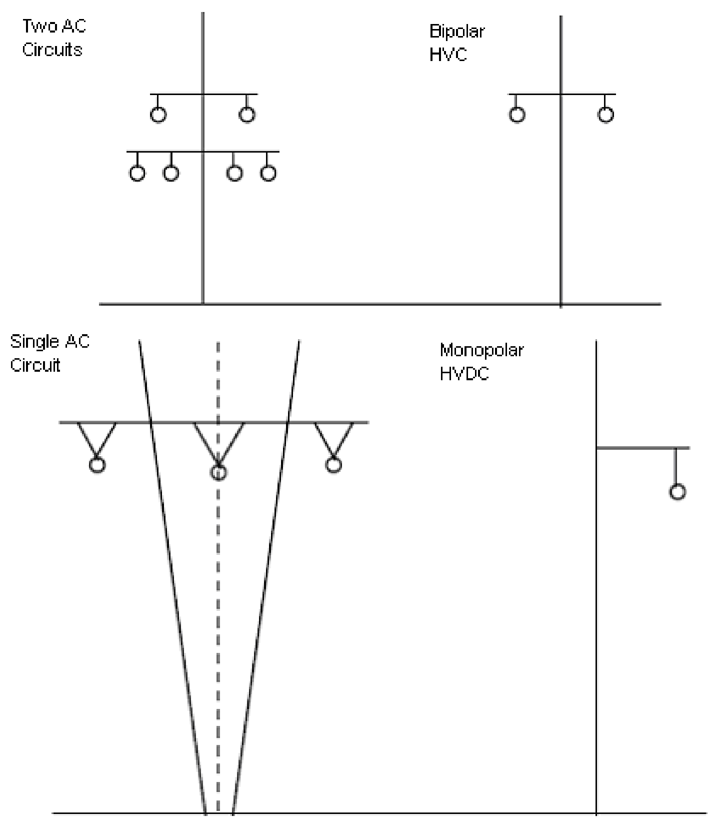

Figure 1-2
Comparable tower configurations for AC and DC transmission

Little has been written regarding the difference between HVDC and AC line construction costs since a very early treatment [2]. Some indication of comparative line costs is necessary to assist the reader's assessment of HVDC and AC transmission. Since terrain and local practices differ markedly around the world, CIGRE Working Group 14.20 has sought industry opinion by requesting not actual prices but cost ratios between AC and HVDC transmission line construction. Designers will be familiar with the actual costs of AC lines in their territories, and it was hoped that the ratios would apply—broadly—anywhere.

The working group suggested four applications of approximate equivalent capacity as tabulated below. Line designers were asked to calculate, for a typical situation familiar to them, the ratio of costs per km of each HVDC line, using the corresponding AC line cost as 1.0 per unit per km length. Suitable design parameters including conductor sizes, with which they were familiar for each case, could be used, assuming a simple bipolar tower without a metallic neutral return. The results are given in Table 1-1. The intent was to compare the cost of towers, conductors, and construction only, without taking into account other parts of the system.

Note that these figures are not derived from a statistically significant sample, but from only three approximate estimates by practitioners. The working group warns the reader that these figures may not be of great value due to the wide range that resulted. It may be concluded that an HVDC line has the potential to cost no more than two-thirds of an AC line of similar rating, but local knowledge pertinent to a project should be consulted.

Table 1-2
Cost ratios for DC and AC transmission line construction

Case	AC equivalent line	Cost per unit	HVDC bipolar line ratings	Range of costs per unit
1	230kV, double circuit	1.00	± 250kV, 500MW	0.68–0.95
2	400kV, double circuit	1.00	± 350kV, 1000MW	0.57–0.75
3	500kV, double circuit	1.00	± 500kV, 2000MW	0.54–0.7
4	765kV, double circuit	1.00	± 500kV, 3000MW	0.33–0.7

The working group has felt that cable costs have been outside its scope of work. Typical prices depend on the power to be carried, the distance, and the water conditions of depth, temperature, etc. They can be readily obtained from the manufacturers. CIGRE Study Committee 21 covers cables, and general articles are available [3]. Burial at sea has a considerable cost, but has proved to be a most valuable asset in terms of the reliability of the link, as demonstrated by the difference in performance between the first (unburied) and second (buried) cross-Channel links between England and France (see [4]).

HVDC transmission can be fitted more readily than AC to a gradual expansion plan for transfer of power. In this way, unnecessary investments can be avoided, or delay of investments can be obtained. AC transmission often has to be built from the start with a high capacity to maintain stability, but HVDC can be tailored to discrete stages.

The most common staging in HVDC transmission is first to build a monopole and later a bipole. To develop further from this stage, a new bipole can be added or the convertor stations can be upgraded in current and/or voltage by adding convertors in parallel or series.

In many applications, HVDC is chosen for large power transfers on a long-term basis. The transfer may, however, be low in the initial stage and higher after a certain period. Based on the build-up timing and having the investment costs for convertor stations in mind, it is natural to evaluate different approaches of a stepwise implementation of the total HVDC transmission scheme.

Another issue (a number are discussed in the CIGRE brochure) involves the cost of engineering and the difficulty of gaining regulatory approval for a line that is “different”. There have been some extended battles over HVDC lines.

Summary Observations

DC lines are constructed in special situations, whereas AC lines are everywhere. Thus, it might be expected that some problems might occur with HVDC simply because the location and operating conditions are unusual.

Several responses mention leakage distance of insulators. There was no comment on the application of special HVDC insulators, for example, porcelain insulators with different skirt shapes designed for HVDC contamination stress.

DC lines have varied applications, not just really long lines. Sometimes they are treated as extensions of the generating station for operating purposes. In Brazil the frequency difference between Brazil and Paraguay drove the use of HVDC lines.

2

CIGRE STUDY COMMITTEE B4 PERFORMANCE REPORTS

CIGRE Study Committee (SC) B4 (DC Systems) compiles performance data on HVDC circuits around the world and publishes the result biennially in summary form at the main CIGRE meeting as a technical paper. The result is extremely useful with regard to overall HVDC circuit performance, but less useful with regard to the details of HVDC line performance. The emphasis in these reports is upon the converter station equipment. Nonetheless, the line outage data provided are both useful and, at times, puzzling.

CIGRE SC B4 (WG04) has developed a protocol for use in collecting and compiling data on HVDC systems.

In the CIGRÉ information, the forced energy unavailability (FEU), together with the number and duration of outage events by category, is considered to be the most useful measurement of system performance for operation evaluation and for planning of future systems. The FEU is defined as the per unit amount of annual energy, based on full rated capacity, that cannot be transmitted over the HVDC system due to forced outages of a convertor station and other equipment. Therefore, the FEU values are in equivalent hours, which are the sum of unavailability hours after the durations have been adjusted in proportion to the percentage reduction in capacity. For example, for a 2-hour outage of one pole of a bipolar system (50% loss of capacity), the equivalent outage hours would be 1 hour.

From the data available so far, an important conclusion from the perspective of assessing overall system security and reliability is that a high percentage of the total FEU is due to faults within an individual valve group. Only small FEU contributions are due to pole and bipole outages. Another significant observation is that bipoles with only one convertor per pole appear to date to be more reliable on average than bipoles with two convertors per pole. This appears to support the logic that the more items of equipment, the more there is to go wrong.

The data published to date suggest that the FEU of two-terminal line/cable systems could be as follows:

(a) For two-terminal, one convertor/pole systems:

Valve group (VG) plus pole FEU = 0.3%; bipole FEU = 0.015%;

Total FEU = 0.315%

(b) For two-terminal, two convertor/pole systems:

VG FEU = 2.45%; pole FEU = 0.08%, bipole FEU = 0.015%

Total FEU = 2.55%

The above values are for both convertor terminals inclusive, but they exclude outages due to transmission lines or cables. Based on the average of all reports, the lines/cables have resulted in an average FEU of about 0.25% per scheme.

Considering all schemes, the overall performance of transmission/cable systems is comparable to back-to-back schemes. However, the average unavailability for schemes commissioned after 1985 is significantly increased by some high outage values in just a few bipoles due to special reasons. There were high Itaipu (Brazil) outage values in 1989/90, but in the subsequent four years, this scheme gave excellent performance with an average FEU of 0.33% for the two bipoles. Overall, the performance of transmission/cable systems continues to be very good, that is, in the range 95%–98%.

Burgess and Barker [8] describe an HVDC link built in Canada for energy interchange and exchange of reserve generation. This link was not required to be more reliable than a single generator in either of the systems it interconnects. It was, therefore, not necessary to have any spare transformers because the six-to-nine-month repair time was no worse than a similar event on a generator unit or its transformer. The link has, in practice, given 10 years of service without any transformer problems.

Depending on the degree of system reliability required and the sensitivity tolerated for transient and permanent line faults, various types of HVDC overhead lines can be constructed with different remaining transmission capacity after line faults (see Figure 4-1). An increase in reliability means an increase of cost of transmission lines. The figures in parentheses in Figure 4-1 assume that the two station poles can be switched to operate in parallel (at a small increase in station cost) and that the line conductors have the thermal capacity for twice the current. This may be inherently available because conductor sizes are selected to satisfy design limits for corona discharge.

Consider the results of the last two survey papers with regard to lines [5, 6].

Survey of HVDC Systems' Reliability Throughout the World, 2003–2004

- On-going B4 statistics show scheduled and forced outage data worldwide.
- Scheduled data do not help define maintenance with HVDC lines since the emphasis is on converter stations and the line maintenance is usually done at the same time as converter maintenance.
- Forced outages (2003, 2004) show certain circuits where the outage associated with lines is very large. The duration of a forced outage can be an outage of both poles or, when divided by 2, it may reflect extended single-pole operation (for example: Fennoskan, 2003, 1692 hrs; Kontek, 2003, 548 hrs; SACOI, 2004, 490 hrs; New Zealand Pole 2, 2004, 159 hrs.

Survey of HVDC Systems' Reliability Throughout the World, 2005–2006

Forced outages (2005, 2006) show certain circuits where the outage associated with lines is very large. The duration of a forced outage can be an outage of both poles or, when divided by 2, it may reflect extended single-pole operation (for example: Butte, 2005, 40 hrs; Itaipu, 2005, 116; Fennoskan, 2005, 2096 hrs; Vancouver Island (capacity reduction - 1 pole), 2006,90 hrs; Fennoskan, 2006, 680 hrs; Kontek, 2006, 16 hrs; SACOI, 2006, 618 hrs.

3
QUESTIONNAIRE DESIGN

In designing the HVDC line performance questionnaire, a preliminary questionnaire was devised, comments from a few knowledgeable people were received, and the questionnaire was revised before it was sent to a limited number of responders for completion. The preliminary questionnaire as circulated is included in the appendix of this report.

The emphasis of the questionnaire is to solicit performance information that will be useful in both the design of new HVDC lines and the conversion of AC to HVDC. Some aspects of line design and operation are unique to HVDC. For example, insulator contamination and electrical clearance failures are a much larger concern with HVDC than with AC lines. Other aspects of line design and operation are not unique to HVDC lines, but even occasional outages due to problems such as wind vibration–induced conductor fatigue or structural failures during high wind and ice loads may have a much larger impact on load supply reliability when they occur on HVDC lines.

The questionnaire was designed to establish a basic description of the line geometry, conductor configuration, insulators, structures, and right-of-way. To aid the busy people being asked to fill out the questionnaire, a series of existing HVDC lines with corresponding data was taken from the *EPRI HVDC Transmission Line Reference Book* [7]. The user could simply indicate that the line whose performance was under discussion was one of those on the list.

In addition, an example questionnaire filled out by the very first responder (Dr. Jardini, Brazil) was included to provide an example that would help the responder understand what was expected as to detail.

Comments solicited from one or two early participants led to several useful modifications in the questionnaire.

In the next year, the questionnaire can be revised again, based on upon this experience, and circulated as an official CIGRE questionnaire, approved by the Technical Committee. This should lead to a great deal of useful information about HVDC line performance that will be helpful both to EPRI and to various CIGRE working groups dealing with HVDC line design.

4
SUMMARY OF HVDC LINE PERFORMANCE RESPONSES

As a result of circulating the preliminary HVDC line performance questionnaire informally to a limited number of knowledgeable engineers around the world, a total of four responses were obtained concerning seven existing HVDC lines.

In this section of the report, the most interesting and helpful of the preliminary answers are summarized and shown in *italics*. The **bold text notes in square brackets** were added to emphasize both uncertainties as to meaning and future improvements in the questionnaire.

Utility 1

The response was regarding the utilities' ±600-kV HVDC lines. One uses self-supporting steel lattice and the other guyed steel lattice structures. In both lines, the pole conductor is a four-conductor bundle of 1272 kcmil, 45/7 aluminum conductor, steel reinforced (ACSR) cable.

[The response concerns two lines that have the same conductor bundle and insulator configuration, but different supporting structures. The revised questionnaire should ask for one response per line to avoid confusion.]

Under planning issues, the response is not clear. The respondent says:

Planning Issues

1. Assuming two or three poles, what is defined as an n-1 outage?
   - *In my country the outage of one pole is the N-1 criteria (bipole is like an AC double circuit). However, for the DC scheme, the outage of one line pole was not a criteria because the two bipole can be paralleled in few minutes*
2. Is loss of a complete structure considered n-2?
   - *Yes. Planning studies only check this condition as for system dynamics and stability.*
3. Is single pole operation considered useful?
   - *Yes. In the initial stages of operation, operation after single pole outages and due to maintenance in one pole.*
4. Was operation with ground return considered in the planning process?
   - *Yes.*

[The questions under Planning Issues should be clarified. The meaning of n-1 and n-2 should be spelled out as should "single pole operation." Perhaps a multiple-choice format would work better.]

Operations Issues

1. Was the load control aspect of the HVDC circuit an essential reason for its creation?
   - No. The frequency of the inverter side (60 Hz) is different of the rectifier side (50 Hz). It was the main reason. (The question is not very clear.)
2. Have there been an excessive number of outages? How does the performance compare to that of an HVAC line at nearly the same voltage level?
   - The two bipoles carry 6300 MW and three 750 kV AC lines carry another 6300 MW in the same route (different right of way). Performance evaluated from 1993 to 2009 indicates:
     - *For AC => 0.174 transient fault and 0.852 permanent fault per 100 km per year. As lines are 890 km long means 7.6 permanent fault per year per line and a downtime of 57 h per year per line*
     - *For HVDC => 0.604 transient fault and 0.208 permanent fault per 100 km per year per pole. As lines are 800 km long means 1.6 permanent fault per year per pole and a downtime of 28 h per year per pole.*
3. Have there been instances of insulator flashover due to contamination? Were these events anticipated?
   - No.
   - Creepage distance (29 mm/kV).
   - Degree of pollution (clean agricultural zone).
   - Pass near heavily contaminated area ? (No.)
   - Insulator type anti fog, glass creepage distance 510 mm/kV.
4. How does the maintenance cost of this line compare to that of other HVDC lines or to AC lines that are similar in design?
   - As far as I know, there is no public data related to maintenance cost. Should be similar.
5. Can the line be operated with one pole and with ground return? Has this been done?
   - Yes, in the initial stages of operation, operation after single pole outages and due to maintenance in one pole.
6. Is there any evidence of unusual corrosion along the line or in the line itself?
   - No. Anyway, corrosion in a pipeline is being monitored from time to time.

7. Have there been other environmental problems unique to this line?
    - *No (Dc current in the neutral of existing power transformer near electrode).*

[It sounds as if there are no other environmental problems, but HVDC current in the neutral of a power transformer near the converter station grounding electrode raises an interesting question. Is there any transformer saturation attributable to the HVDC line? Transformer saturation would raise the magnetizing current and increase VAR flow. If instrument transformers saturate, it could cause metering or relaying inaccuracy. Perhaps this should be pursued in future performance reviews.]

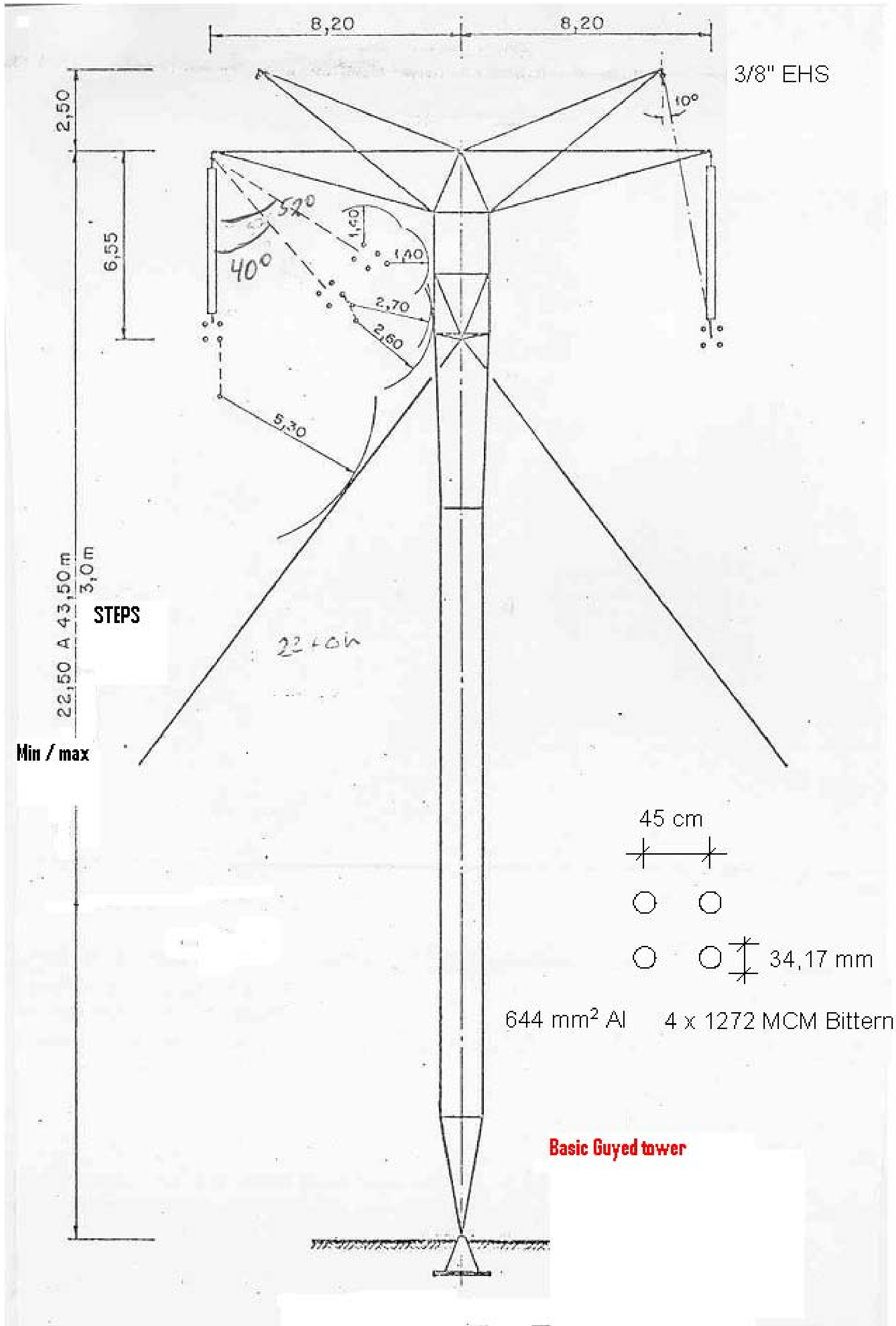

Figure 4-1
Utility 1 HVDC guyed structure

Utility 2

Preliminary Questionnaire (revised) on HVDC Line Performance

Design Parameters

1. Single or bipole design?
   - *Bipole.*
2. Line voltage (e.g. + 400 kV)?
   - *±400 kV, either or both poles can be operated at 300 kV.*
3. Length of line (in miles) between converter stations?
   - *435.8 miles – 701 km.*
4. Foundation structure type (concrete footings, steel lattice self-supporting)?
   - *Steel lattice self-supporting with 4 concrete footings per structure (see figures attached).*
5. Conductor types and pole configuration?
   - *2 – 1590 KCMIL ("Lapwing") ACSR conductors per pole with 18" bundle spacing – 40 foot horizontal pole spacing.*
6. Typical structure height (distance to lowest insulator attachment)?
   - *110 feet from ground to insulator attachment (typical), 96 feet from ground to conductor attachment.*
7. Type and size of phase and shield wire conductors?
   - *2 – 1590 KCMIL ("Lapwing") ACSR conductors per pole (1.504" diameter) – 2 – ½" steel shield wires.*
8. Is the line operating at its original design voltage?
   - *Basically yes – in 2002 the maximum voltage at the rectifier was increased to ±410 kV.*
9. How extensive is the end point grounding system?
   - *Question is unclear. Ground return operation is allowed. One ground electrode is approximately 6 miles from station, the other ground electrode is approximately 12 miles from station. Ground electrodes are designed for full continuous overload current rating of system.*

Planning Issues

1. Assuming two or three poles, what is defined as an n-1 outage?
   - *Loss of a single pole is an n-1 outage and a bipole outage is an n-2 outage.*
2. Is loss of a complete structure considered n-2?
   - *Yes.*
3. Is single pole operation considered useful?
   - *We operate a significant number of hours in monopolar metallic return mode during converter scheduled and forced outages. Bipole outages are very rare.*

4. Was operation with ground return considered in the planning process?
   - *Yes. Normally the line operates in bipolar mode with balanced pole currents. Following a pole trip, the other pole increases up to maximum power (if necessary) to attempt to maintain ordered bipole power. The un-faulted pole operates in ground return. Depending on the nature of the outage, the operator initiates an automatic sequence to transfer the pole to metallic return to eliminate ground current flow. This transfer is done at pole currents up to maximum overload. A similar transfer is initiated to go back to ground return when the other pole is ready to restart. Extensive coordination with pipeline companies and other underground facility owners was required to allow ground current operation.*

Operations Issues

1. Was the load control aspect of the HVDC circuit an essential reason for its creation?
   - *The HVDC transmission line is the primary outlet for the power plant. There is only limited outlet capability for the plant with the HVAC system interconnection. Basically all of the plant energy is for consumers in one state.*
2. Have there been an excessive number of outages? How does the performance compare to that of an HVAC line at nearly the same voltage level?
   - *The line is conservatively designed and has had a very low outage rate. Line restarts (similar to HVAC reclose attempts) are generally successful for pole faults. Assume line has similar or better performance than an equivalent HVAC design.*
3. Have there been instances of insulator flashover due to contamination? Were these events anticipated?
   - *Insulator flashover from contamination not significant due to conservative line design (Insulator creepage distance is 1 kV/inch).*
4. How does the maintenance cost of this line compare to that of other HVDC lines or to HVAC lines that are similar in design?
   - *Maintenance costs are average or slightly below average.*
5. Can the line be operated with one pole and with ground return? Has this been done?
   - *Yes. Ground return use is limited by agreements with pipeline companies, but permitted without limitation for emergencies (i.e. metallic return operation not available).*
6. Is there any evidence of unusual corrosion along the line or in the line itself?
   - *No.*

Perception and Annoyance

1. Have there been complaints regarding ion charging current?
    - *Was an issue during permitting and construction? No issues seen during operation.*
2. Have there been other environmental problems unique to this line?
    - *A number of issues were raised by protest groups during siting process due to unfamiliarity with HVDC. All of these were resolved prior to operation. Issues with ground current operation were greater than anticipated as ground electrode site was less effective than desired.*
3. How were the electric fields and ion currents calculated during design?
    - *Due to uncertainties about ion current assumptions, electric fields were specified by ignoring ion currents.*
4. Is audible noise a problem along the line?
    - *No.*

Line Siting Issues

1. Was there opposition to the line's construction because it was HVDC as opposed to HVAC?
    - *Opposition to the line was intense in a relatively small portion of the line route in one state. Probably there would have been similar strong opposition to an HVAC line of similar voltage and power rating. This was also the first facility to be sited in the state under a then new certificate of need and siting act. Unfamiliarity with HVDC (particularly in the area of potential health effects) in state agencies contributed to success of protest efforts to delay permitting and construction. A long distance 500 kV HVAC line was permitted and constructed in the state a short time later with no problems.*
2. Did the need for converter stations complicate the siting process?
    - *No. Converter stations were sited in rural areas.*

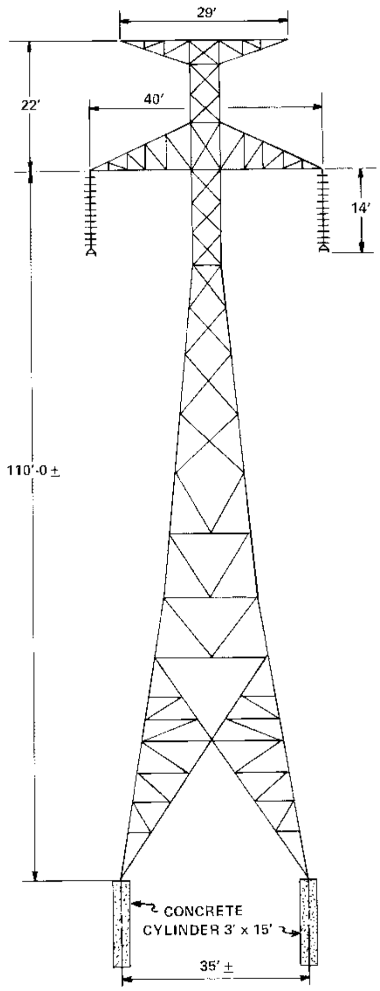

Figure 4-2
Typical structure for utility 2 HVDC line in the United States

Following a pole trip, the other pole increases up to maximum power (if necessary) to attempt to maintain ordered bipole power. The unfaulted pole operates in ground return. Depending on the nature of the outage, the operator initiates an automatic sequence to transfer the pole to metallic return to eliminate ground current flow. This transfer is done at pole currents up to maximum overload. A similar transfer is initiated to go back to ground return when the other pole is ready to restart.

"Extensive coordination with pipeline companies and other underground facility owners was required to allow ground current operation." "Ground return use is limited by agreements with pipeline companies, but permitted without limitation for emergencies (i.e. metallic return operation not available)." "Issues with ground current operation were greater than anticipated as ground electrode site in one state was less effective than desired."

(The fact that this shows up in three different answers in this response to the questionnaire is a real statement of concern expressed by underground facility owners. Note that the utility said they were monitoring a pipeline occasionally.)

Utility 3

The following statement was included with the revised Preliminary Questionnaire:

> CIGRE Working Group B2.41 is presently studying the conversion of HVAC lines to HVDC. Preferential Subject 2 at the most recent Study Committee B2 technical session concerned the same subject. Subsequent discussions in B2 raised the broader possibility that it may be useful for CIGRE B2 to develop a broad technical guide to HVDC line design. In response to these activities and discussions, this preliminary questionnaire was prepared.
>
> For one or more overhead HVDC lines in your transmission system, would you please provide answers to the following questions for each line? Also, if you think that the questions included are not clear or that certain aspects of HVDC line performance are not considered, would you please specify those items?
>
> In order to keep things simple, a pdf file of structure drawings (provided by EPRI) for certain HVDC lines is attached. If you are responding with information about one of these lines, just identify the line, and you can skip the “Line Parameters” section. In any event, please complete the questions on planning, operation, and perception issues.
>
> Also attached is an example response prepared by Utility 1 for their two DC lines. After receiving your response, a summary of preliminary results will be shared with all who respond. The information gleaned from your responses will help Working Group B2.41 and may lead to a new activity regarding HVDC line design. If the response to this preliminary questionnaire is helpful, then a formal questionnaire may be proposed to the CIGRE Technical Committee for approval and broader distribution.

1. Project:
    - *Two parallel HVDC lines (Bipole I & Bipole II).*

Line Design Parameters

1. Single or two-pole design?
    - *Two-pole design (both Bipole I and II).*
2. Line Voltage (e.g. + 400 kV).
    - *Bipole I: ± 450 kV.*
    - *Bipole II: ± 500 kV.*

3. Length of line between converter stations?
   - *Bipole I: 896 km.*
   - *Bipole II: 937 km.*
4. Typical structure (provide photos if possible):
   - *Construction type: Guyed lattice steel.*
   - *Conductor configuration: horizontal configuration.*
   - *Height (distance to lowest insulator attachment): 31m.*
   - *Weight: 3,385 kg (7447 lbs).*
   - *Shielding angle: 33°.*
5. Conductor type, size and bundling
   - *1843.2 MCM 72/7 ACSR, 40.64 mm diameter, 2 conductor bundle; 457 mm (18") bundle spacing.*
6. Shield wire type and size
   - *9 mm (3/8"), 7 wire steel strand, grade 180 steel.*
7. Insulator string: number of units, rating
   - *Suspension string: 21 x 160 kN (36,000 lb) units.*
   - *Dead end structures: 2 x 29 x 220 kN (50000 lb) units.*
8. Pollution level and selected insulator creepage distance
   - *Pollution level is low for both lines. Insulator creepage distance is 23.71mm/kV for Bipole I and 21.336 mm/kV for Bipole II.*
9. Is the line operating at its original design voltage?
   - *For Bipole I - No (operating at ± 463.5 kV).*
   - *For Bipole II – Yes.*
10. How extensive is the end point grounding system?
   - *Bipole I: Electrode 1: 11 km.*
   - *Bipole I: Electrode 2: 22 km.*
   - *Bipole II: Electrode 1: 11 km.*
   - *Bipole II: Electrode 2: 23 km.*

Planning Issues

1. Assuming two or three poles, what is defined as an n-1 outage?
   - *Valve group outage.*
2. Is loss of a complete structure considered as an n-1 or n-2 contingency?
   - *Loss of an HVDC tower is an n-2 contingency.*

3. Is single-pole operation considered useful?
   - *Yes.*
4. Was operation with ground return considered in the planning process?
   - *Yes.*

Operations Issues

1. Was the load control aspect of the HVDC circuit an essential reason for its creation?
   - *No, it's because of the economics of long distance transmission.*
2. Have there been an excessive number of outages? How does the performance compare to that of an HVAC line at nearly the same voltage level?
   - *It had been experienced in past but now it's not a problem. Poor performance as compared to an HVAC line of same voltage because of involvement of more equipment.*
3. Have there been instances of insulator flashover due to contamination? Were these events anticipated?
   - *Generally it's not the case. But it had been experienced in past due to smoke form forest fire.*
4. How does the maintenance cost of this line compare to that of other HVDC lines or to HVAC lines that are similar in design?
   - *No idea about the maintenance cost of other HVDC lines compared to HVDC lines because Manitoba Hydro doesn't have HVDC lines except these HVDC lines.*
   - *According to the history data the maintenance cost of HVAC lines is almost double compared to HVDC lines of similar design but the lines are at different locations and have different terrain.*
5. What are the main maintenance problems encountered?
   - *Frost-heave problem in foundations and guy anchors.*
   - *Wind induced vibration of cables.*
   - *Deterioration of rubber bushings in spacer-dampers (all had to be replaced after 26 years of service).*
   - *Damage of towers due to direct impact from farm equipment operations.*
6. Can the line be operated with one pole and with ground return? Has this been done?
   - *Yes, the line can be operated with one pole and with ground return. Once every four years a pole outage is scheduled for maintenance and that way mono-polar operation is used.*
7. Is there any evidence of unusual corrosion along the line or in the line itself?
   - *No.*

Perception and Annoyance

1. Have there been complaints regarding ion charging current?
   - *No.*
2. Have there been other environmental problems unique to this line?
   - *No.*
3. How were the electric fields and ion currents calculated during design?
   - *Details not available.*
4. Is audible noise a problem along the line?
   - *It's not a problem in normal condition.*

Line Siting Issues

1. Was there opposition to the line's construction because it was HVDC as opposed to HVAC?
   - *No. However, we are now encountering opposition to the new Bipole III HVDC line.*
2. Did the need for converter stations complicate the siting process?
   - *No, but technical limitations complicated the siting process.*
3. What were the main challenges in line siting and licensing?
   - *Main challenges of the proposed Bipole III in line siting and licensing:*
     - *Government did not allow us to use a direct (shorter) route which would transverse boreal forest. As a result, 50% longer route will be used.*
     - *Concerns with interference with mining practices.*
     - *Environmental concerns (birds, animals, etc.).*
     - *Aboriginal concerns (sacred sites, trapping, traditional land use issues, and increased access by general public).*
     - *Effects on farming activities (including interference with GPS devices).*
     - *EMF effects on humans and farm animals.*
     - *Safety concerns with ground electrodes.*
     - *Property depreciation.*
     - *Aesthetics and visual impact.*

Utility 4

Preliminary CIGRE Questionnaire on HVDC Line Performance

If you have one or more overhead HVDC lines in your transmission system, would you please provide answers to the following questions for each line?

Design Parameters

1. Single or two-pole design?
   - *Two pole design.*

2. Line Voltage (e.g. ±400 kV)?
   - *± 535 kV.*
3. Length of line between converter stations?
   - *1800 km.*
4. Foundation Structure type (concrete footings, steel lattice self-supporting)? Photo?
   - *See sketches.*
5. Conductor types and pole configuration?
   - *4 x 500 mm^2.*
6. Typical structure height (distance to lowest insulator attachment)?
   - *See pictures.*
7. Type and size of phase and shield wire conductors?
   - *4 x Zambezi; 1 x open (shield wire).*
8. Is the line operating at its original design voltage?
   - *Yes but with only 1 pole.*
9. How extensive is the end point grounding system?
   - *Extensive (carbon earth electrodes).*

Planning Issues

1. Assuming two or three poles, what is defined as an n-1 outage?
   - *1 pole out or 1 line out. The two poles are on separate pylons only N-1 considered.*
2. Is loss of a complete structure considered n-2?
   - *N/A.*
3. Is single pole operation considered useful?
   - *Yes.*
4. Was operation with ground return considered in the planning process?
   - *Only for limited periods.*

Operations Issues

1. Was the load control aspect of the HVDC circuit an essential reason for its creation?
   - *In Africa, HVDC alone is not very attractive because the towns and population along the route cannot be supplied. For this line, one consideration was cost.*
2. Have there been an excessive number of outages? How does the performance compare to that of an HVAC line at nearly the same voltage level?
   - *Worse, because of civil war.*
3. Have there been Instances of insulator flashover due to contamination? Were these events anticipated?
   - *Yes, there were flashover incidents and they were not expected.*

4. How does the maintenance cost of this line compare to that of other HVDC lines or to HVAC lines that are similar in design?
   - *Don't know.*
5. Can the line be operated with one pole and with ground return? Has this been done?
   - *Only for limited periods. Carbon electrodes should help.*
6. Is there any evidence of unusual corrosion along the line or in the line itself?
   - *Don’t know.*

Perception and Annoyance

1. Have there been complaints regarding ion charging current?
   - *N/A.*
2. Have there been other environmental problems unique to this line?
   - *Yes, radio transmission/reception near the inverter station.*
3. How were the electric fields and ion currents calculated during design?
   - *N/A.*
4. Is audible noise a problem along the line?
   - *N/A.*

Line Siting Issues

1. Was there opposition to the line's construction because it was HVDC as opposed to HVAC?
   - *No.*
2. Did the need for converter stations complicate the siting process?
   - *Complicated by the need to find good earth.*

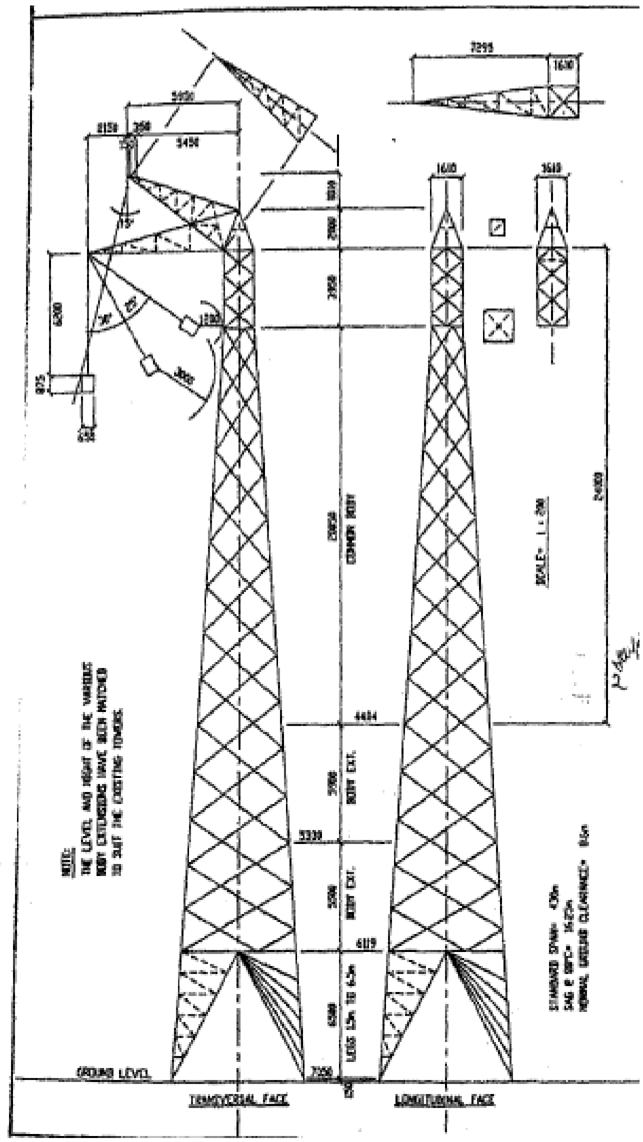

Figure 4-3
Utility 4 HVDC Line Structure

5 OBSERVATIONS BASED ON QUESTIONNAIRE RESPONSES

There are far fewer HVDC lines (about 100) in the world than HVAC. Therefore, detailed knowledge concerning the performance of existing HVDC lines is limited. In this brief project, EPRI has cooperated with CIGRE Study Committees B2 and B4 to develop and test the design of a preliminary questionnaire on the performance of existing HVDC lines in various locations around the world and to gather some initial information regarding HVDC line performance.

Although the responses to the preliminary questionnaire concerned only seven HVDC lines, some interesting—and sometimes puzzling—results were received. The following observations, listed by preliminary questionnaire categories, were distilled from the limited responses obtained:

Design Parameters

The voltages ranged from ±400 to ±600 kV with both one- and two-pole designs and two-, three-, or four-conductor bundles. All the lines are greater than 440 miles (708 km) long with no intervening taps.

Most of the lines have extensive end-point grounds.

There was no indication that any of the line designs were grossly inadequate or unreliable.

Planning Issues

From a planning perspective, the ability of HVDC lines to operate temporarily with a single pole is helpful. In one HVDC line in Africa, single-pole operation has in use for over 10 years. This is an extreme example of such operation.

In HVDC lines with separate structures for each pole, it appears that most consider the loss of both poles as an n-2 contingency. In most cases, the operation of the HVDC line with a single pole using earth return was anticipated. This is consistent with normal planning criteria for two parallel single-circuit AC lines where the loss of both lines (on separate structures) is usually seen as an n-2 contingency.

Presumably, in the case of an HVDC line with both poles on a common structure, the loss of both poles would be considered an n-1 contingency. Given the much higher power flow on HVDC lines and their limited presence in most AC systems, this may be a very important limitation on the use of HVDC.

Operations

The power flow control feature of HVDC seems to be useful, but not critical to the systems reporting.

No problems with insulator contamination-induced flashovers are reported. Reported maintenance problems seem quite similar to those of HVAC lines of a comparable voltage.

The maintenance costs for HVDC lines appear to be similar to HVAC lines. In the case of Utility 1, where there are three 765-kV HVAC lines roughly paralleling the two HVDC bi-pole lines for 800–900 km, the outage rate for the HVDC lines is about half that of the HVAC lines.

Perception and Annoyance

Most of the problems with noise, interference, and human discomfort appear to have been thoroughly reviewed before construction. A few cases of audible noise problems have occurred. There are no reports about human perception of ion currents.

The use of HVDC does not necessarily eliminate the issues of perception and annoyance, but does seem to change the topics normally of concern with AC line siting. The Utility 2 response described the rather heated debates with people who opposed the HVDC line segment in one state and the difficulty that state regulators had in dealing with HVDC since they had no experience with it.

Line Siting

Those lines built more recently and newer proposed lines appear to be encountering public opposition to much the same degree as similarly sized HVAC lines.

If a regulatory or environment agency is encountering HVDC lines for the first time, the review process may be somewhat slower than with HVAC, simply due to a lack of familiarity with HVDC line corona and noise issues.

HVDC does solve some environmental issues such as magnetic field levels and induced voltage on pipes and fences, but raises others such as corrosion due to ground current and ion current effects.

6 RECOMMENDATIONS FOR FUTURE STUDIES

This project was moderately successful both in developing a useful HVDC line performance questionnaire and in obtaining some preliminary results based on the responses of a limited number of HVDC line owners around the world. Cooperation with existing groups within CIGRE and EPRI was crucial to obtaining access to excellent technical documents and to locating knowledgeable and experienced engineers who were able to provide practical HVDC line performance data for existing lines and insight into that data and the process of line siting, design, planning, and operation.

There are a number of technical areas where future EPRI projects should be concentrated.

Improvements in HVDC Line Performance Questionnaire

The preliminary questionnaire should be reviewed and discussed with the preliminary responders. Clearly, the preliminary form was reasonable, but modifications should be considered to maximize the usefulness of responses. In particular, HVDC line dimensions, conductor size, number of insulators, etc., are critically important in interpreting the responses, but an effort should be made to minimize the time it takes to enter such physical data. Our initial attempt to do this was to provide the data from the EPRI DC book [7] regarding line dimensions that the responder could simply select.

We might move away from a paper questionnaire design. Certain questions were misunderstood by at least some of the responders. An electronic questionnaire (perhaps made available on a website) could provide help at the touch of a button. If the question is not clear, the responder can quickly get clarification. If the question is clear, the responder can simply answer it and move on. If the questionnaire were electronic, it would be much easier for the questionnaire creator to see misunderstandings and provide more detail if needed.

Participation in CIGRE and IEEE Activities

This project depended heavily on the cooperation and support of CIGRE members, technical study committees, and technical documents. Uprating existing AC lines to HVDC is the subject of Working Group B2.41 and was a preferential subject at the 2010 meeting in Paris; Study Committee B2 is considering the formation of a new working group concerning the detailed design of HVDC lines.

IEEE has been far less active than CIGRE, but this may change in the immediate future as interest in HVDC lines, needed to move renewable energy from remote areas of both Canada and the United States, increases.

EPRI has a great deal of technical information that could be very helpful to these professional engineering groups. Cooperation with CIGRE and IEEE could benefit EPRI and these professional groups.

Insulators

In the B2 technical meeting held in August 2010, the subject of insulator performance in HVDC lines subject to severe contamination was a subject of interest. Even though the discussions centered on conventional glass and ceramic insulators, it seems likely that the use of composite insulators would be considered in new HVDC lines and particularly in upgrading existing AC lines to DC. Given the excellent insulator study work done by EPRI concerning composite insulators, it may be very helpful to extend such studies to HVDC applications.

Conductor Selection

Conductor selection for HVDC is somewhat different from AC applications. There is no skin effect, and much larger conductors might be considered as an alternative to the use of bundles or at least to reduce the number of conductors per pole.

A theoretical study of conductor selection should be relatively inexpensive and yet informative.

System Planning Investigation

It is clear that the value of HVDC lines is a function of how they are considered in system planning studies. Their unique capabilities—load flow control, much higher power flow densities, single pole operation, etc.—make for a very complicated impact on system reliability.

Clearly, this topic is outside of the area of line design and siting, but the insights, with regard to system planning and operation, have an enormous impact on whether HVDC is practical. This is particularly true when considering the conversion of an existing AC line into HVDC, where many conventional wisdoms regarding “breakeven length” and DC voltage come into question.

Because the evaluation of HVDC line options depends heavily on the particular details of various AC transmission system characteristics, it might be best to start by developing a questionnaire that specifically addresses the system planning aspects of HVDC and conversion of AC to DC lines. Alternatively, EPRI could sponsor a colloquium on this topic with the intent of summarizing the various presentations.

Development of Very Reliable HVDC Lines

Historically, the high cost and unreliable nature of converter stations dominated any concerns about the reliability of HVDC lines. The literature and manufacturer’s data make it clear that DC converters are becoming more reliable and less expensive. As this occurs, overhead HVDC circuit reliability will come to be driven by line reliability, much as it is for AC circuits.

AC transmission systems are planned such that the loss of a major component such as an EHV AC line does not result in a major outage. This is often accomplished by the automatic transfer of power flow from the lost EHV line to the “surrounding” HV line network. Given the much higher power flows and inability to use the converter capacity in the AC network, the loss of a DC circuit can have a much larger impact on system load reliability that the loss of an EHV circuit.

This observation implies that it would be worthwhile to investigate the design of “very reliable” lines for HVDC. This sort of investigation should consider the possible development of conductor systems and support structures with much lower likelihoods of failure or, at least, far more rapid restoration of service.

7
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2. P. Dey and G. Orawski, “Optimisation of Direct Current Overhead Lines,” IEE Conference Publication No. 107, p. 189.
3. R. D. Rosevear, “Cables for high voltage DC systems,” Power Technology International. p. 129 (1990).
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6. CIGRE B4-119-2008: Survey of the reliability of HVDC systems throughout the world during 2005–2006.
7. *EPRI HVDC Transmission Line Reference Book*. EPRI, Palo Alto, CA: 1993. TR-102764.
8. R.P. Burgess, I.E. Barker, “McNeill HVDC converter station,” GEC ALSTHOM Technical Review. No 5, p. 3 (1991).

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APPENDIX – QUESTIONNAIRE ON HVDC LINE PERFORMANCE

A preliminary questionnaire was prepared, suggested edits were solicited and implemented, and the following three documents were informally circulated to a limited list of responders.

Questionnaire with Cover Letter

CIGRE Working Group B2.41 is presently studying the conversion of HVAC lines to HVDC. Preferential Subject 2 at the most recent Study Committee B2 technical session concerned the same subject. Subsequent discussions in B2 raised the broader possibility that it may be useful for CIGRE B2 to develop a broad technical guide to HVDC line design. In response to these activities and discussions, this preliminary questionnaire was prepared.

Cover Letter

For one or more overhead HVDC lines in your transmission system, would you please provide answers to the following questions for each line? Also, if you think that the questions included are not clear or that certain aspects of HVDC line performance are not considered, would you please specify those items?

In order to keep things simple, a pdf file of structure drawings (provided by EPRI) for certain HVDC lines is attached. If you are responding with information about one of these lines, just identify the line, and you can skip the "Line Parameters" section. In any event, please complete the questions on planning, operation, and perception issues.

Also attached is an example response prepared by a utility for their two HVDC lines. After receiving your response, a summary of preliminary results will be shared with all who respond. The information gleaned from your responses will help Working Group B2.41 and may lead to a new activity regarding HVDC line design. If the response to this preliminary questionnaire is helpful, then a formal questionnaire may be proposed to the CIGRE Technical Committee for approval and broader distribution.

Questionnaire

Line Design Parameters

1. Single or two-pole design?
2. Line Voltage (e.g. + 400 kV)
3. Length of line between converter stations?
4. Typical structure (provide photos if possible):
   - Construction type
   - Conductor configuration
   - Height (distance to lowest insulator attachment)
   - Weight
   - Shielding angle
5. Conductor type, size and bundling
6. Shield wire type and size
7. Insulator string: number of units, rating
8. Pollution level and selected insulator creepage distance
9. Is the line operating at its original design voltage?
10. How extensive is the end point grounding system?

Planning Issues

1. Assuming two or three poles, what is defined as an n-1 outage?
2. Is loss of a complete structure considered as an n-1 or n-2 contingency?
3. Is single pole operation considered useful?
4. Was operation with ground return considered in the planning process?

Operations Issues

1. Was the load control aspect of the HVDC circuit an essential reason for its creation?
2. Have there been an excessive number of outages? How does the performance compare to that of an HVAC line at nearly the same voltage level?
3. Have there been instances of insulator flashover due to contamination? Were these events anticipated?
4. How does the maintenance cost of this line compare to that of other HVDC lines or to HVAC lines that are similar in design?
5. What are the main maintenance problems encountered?
6. Can the line be operated with one pole and with ground return? Has this been done?
7. Is there any evidence of unusual corrosion along the line or in the line itself?

Perception and Annoyance

1. Have there been complaints regarding ion charging current?
2. Have there been other environmental problems unique to this line?
3. How were the electric fields and ion currents calculated during design?
4. Is audible noise a problem along the line?

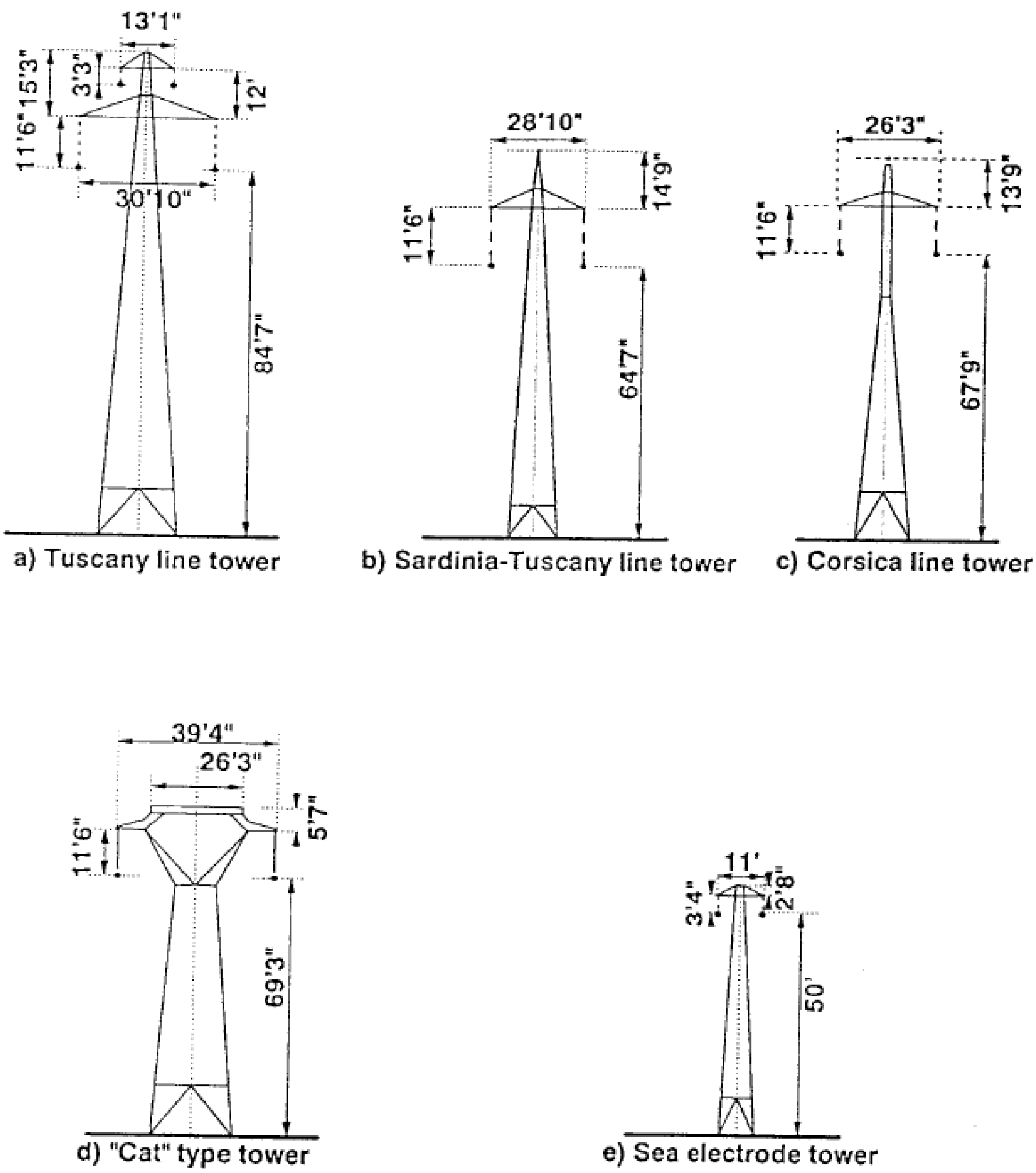
Line Siting Issues

1. Was there opposition to the line's construction because it was HVDC as opposed to HVAC?
2. Did the need for converter stations complicate the siting process?
3. What were the main challenges in line siting and licensing?

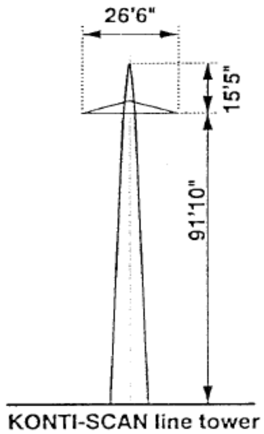
Excerpt from EPRI HVDC Transmission Line Reference Book

To save time, the responder can select an HVDC line design from the following designs that are described in the *EPRI HVDC Transmission Line Reference Book* [7]:

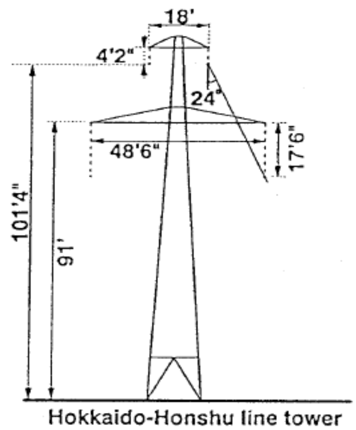
SACOI 1 – 215kV line



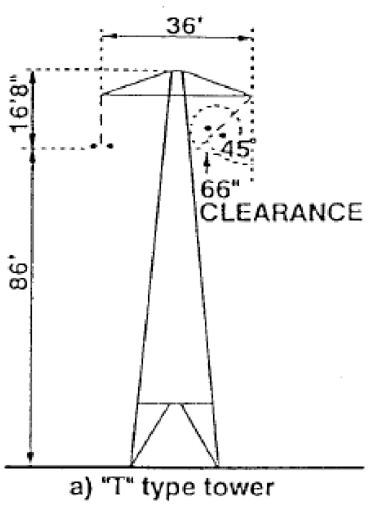
Konti-Scan 250kV Line

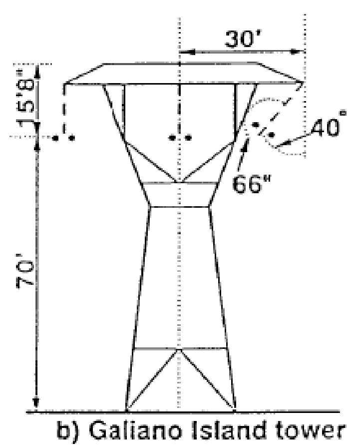


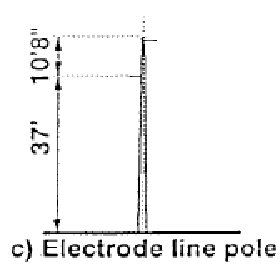
Hokkaido-Honshu 250kV line



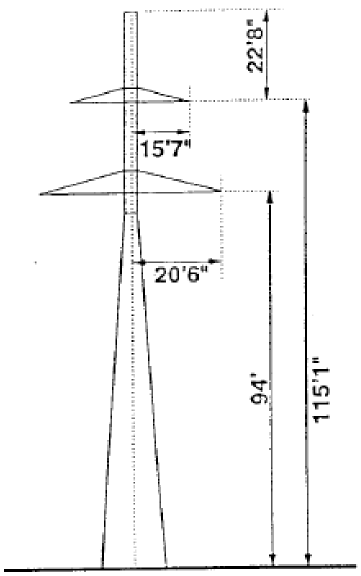
Arnott-Vancouver Island Terminal HVDC +250kV, -280kV Line





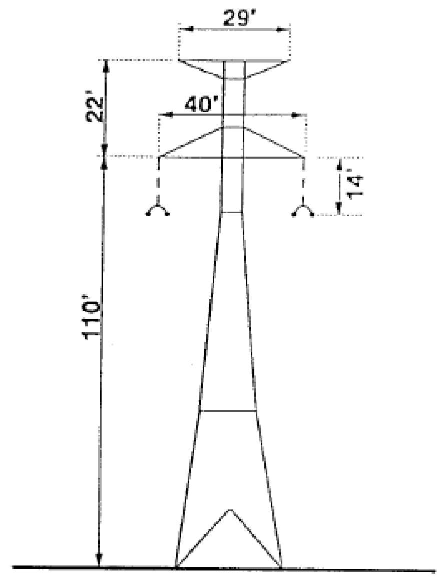


Skagerrak 250kV Line



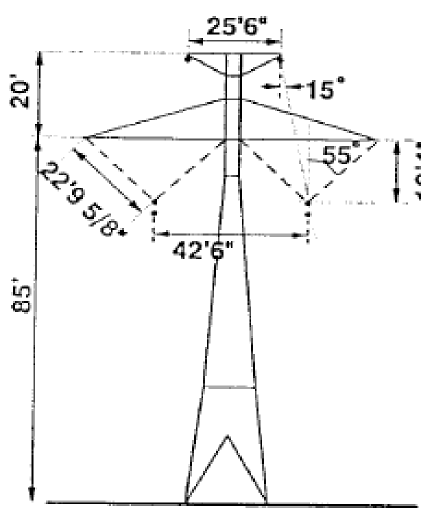
Skagerrak line tower

CU Project / Coal Cree – Dickinson 400kV Line

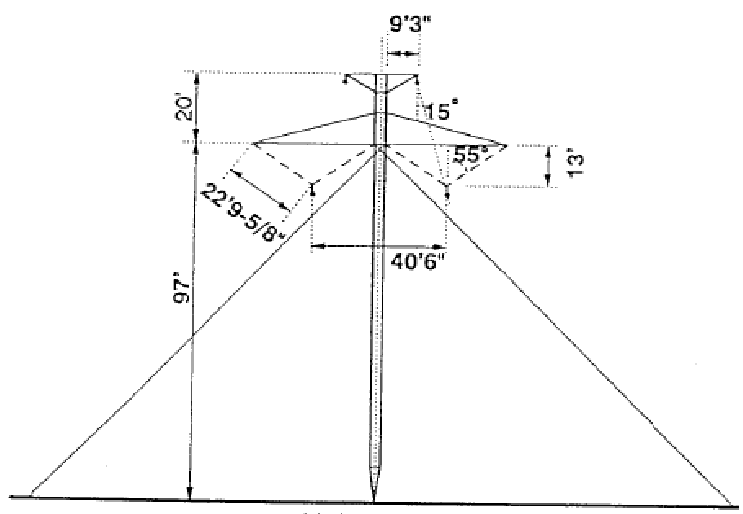


CU Project / Cook Creek - Dickinson tower

Walker County – STP HVDC Transmission Line 400kV

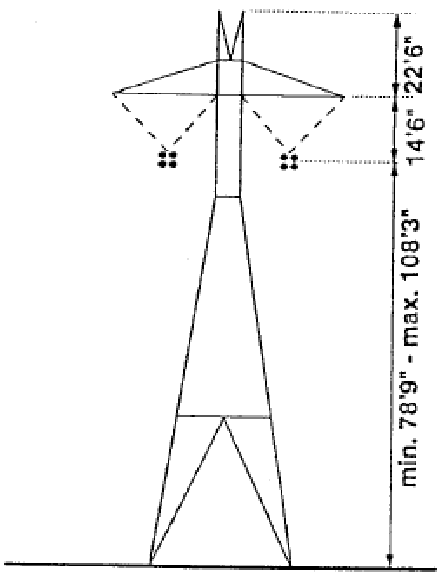


a) Lattice tower

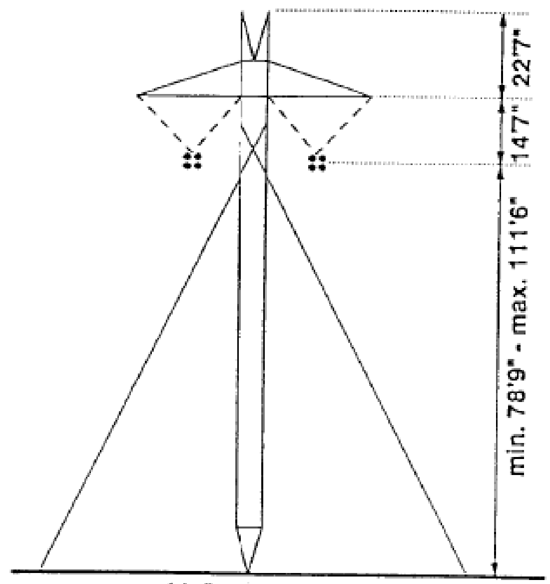


b) Guyed tower

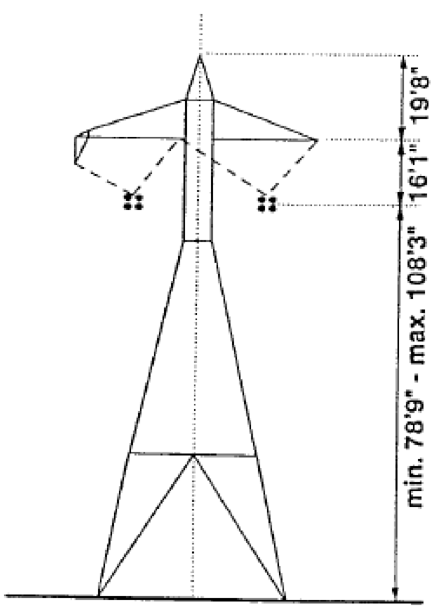
Des Canton – New England 450kV Line



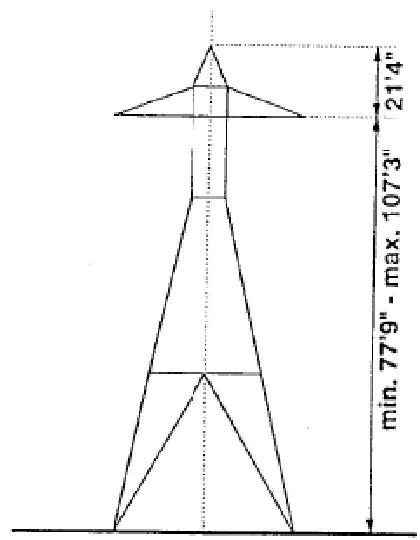
a) Rigid tower



b) Guyed tower

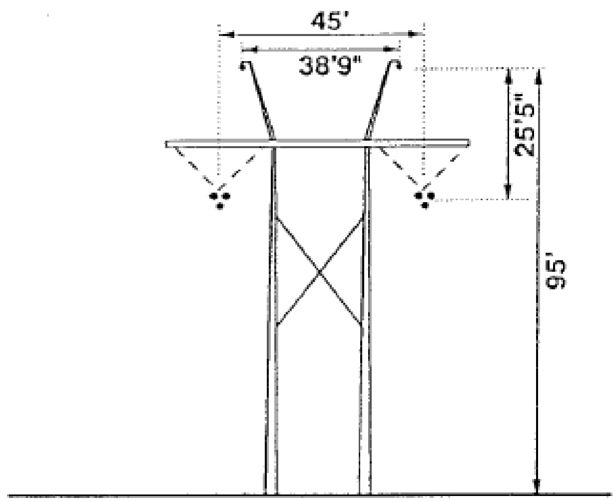


c) Angle tower 5°- 30°



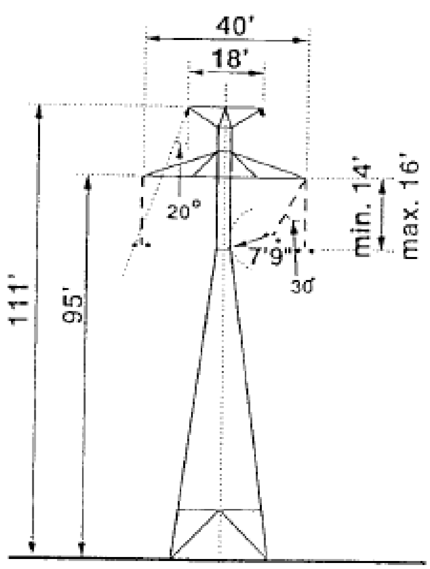
d) Angle tower 30°- 60°

Phase 1 Quebec-New England HVDC Interconnect 450kV Line

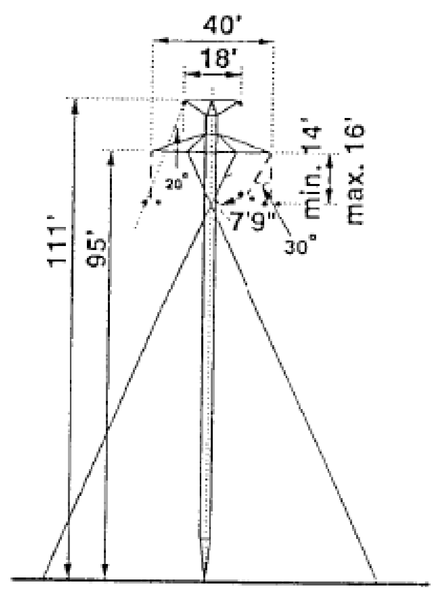


Tangent tower

Pacific NW-SW HVDC Intertie/Sylmar-Oregon 500kV Line

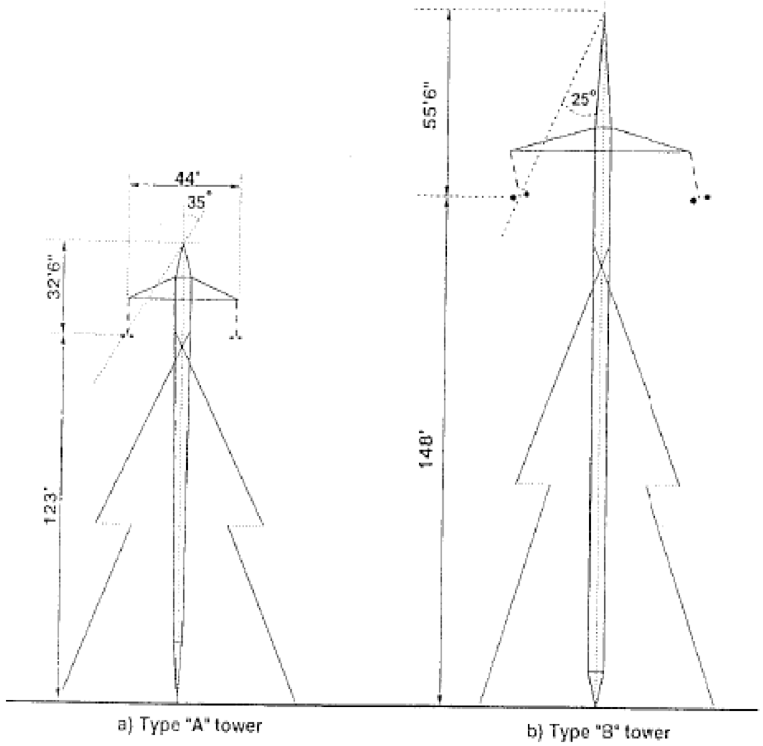


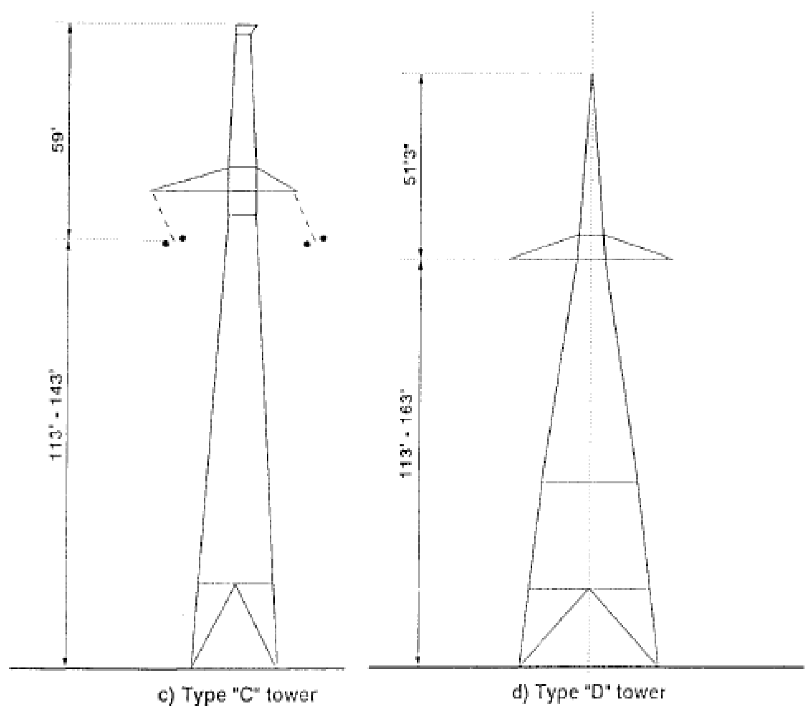
a) Free-standing tower



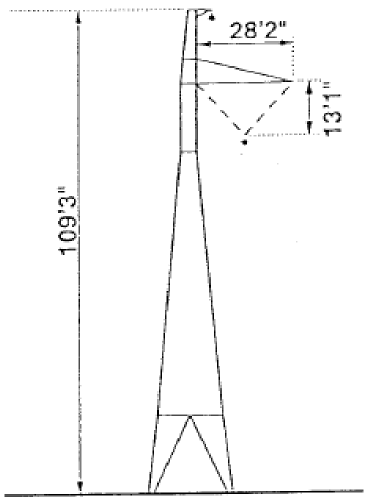
b) Guyed tower

Nelson River Project/Bipole 1 Radisson-Dorsey (450kV), Bipole 2 Henday-Dorsey (500kV) Line

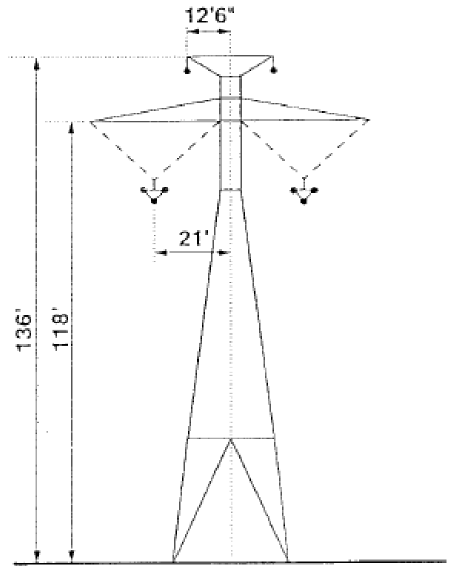




Inga-Shaba HVDC Inter-tie 500kV Line **Intermountain-Adelanto 500kV Line**

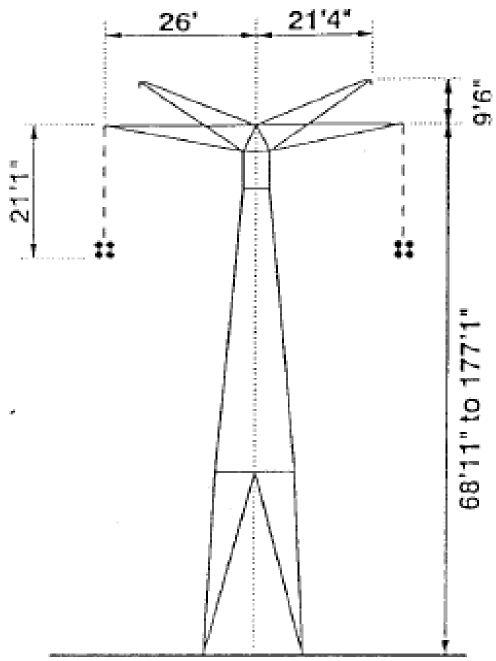


Monopolar tower

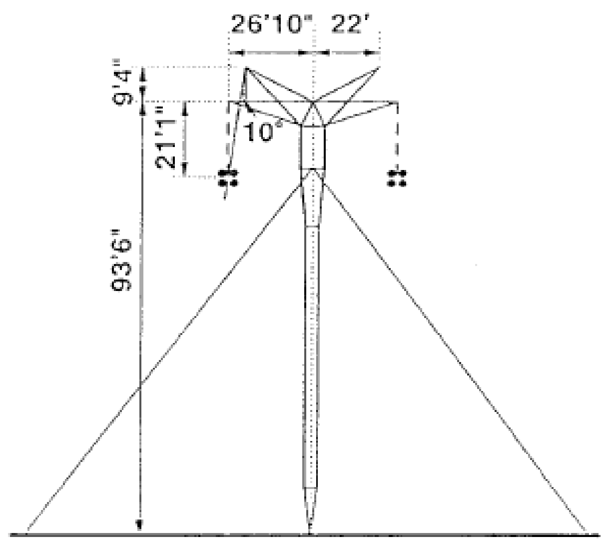


Free-standing suspension tower

Itaipu Bipole 1 and Bipole 2 600kV Line



a) Lattice type tower



b) Guyed type tower

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