The Role of High Voltage Direct Current HVDC

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1. Introduction

As a rule, electric energy systems employing alternating current for the production and distribution are widely superior to those employing direct current. A considerable interest has, however, been displayed in the development of power transmission systems based on HVDC. The reason is that HVDC can compete with or be more favourable than HVAC (high voltage alternating current) in different cases such as

- long-distance transmission of electric power either by overhead lines or cables
- delivery of electric power into densely populated areas (cities etc.)
- removing the output from large generating stations
- interconnection of AC networks or sectionalizing of existing large AC networks
- interconnection of networks having different frequencies.

From the economic viewpoint HVDC is more advantageous than HVAC above a certain breakeven distance which is longer for overhead lines than when using cables. This breakeven distance has been increased during the last two decades by the introduction of series capacitors and higher AC voltages. It may be noted, however, that HVDC offers the possibilities to build a transmission system in stages which reduces the early investment costs.

In the economic comparisons between the two alternatives not only cost of equipment and losses should be taken into account but also the cost of interruptions.

Interconnections between different power systems will come progressively. When using DC, the power in the tie can be easily controlled. There are no risks of power oscillations or frequency swings which can be a problem with AC, especially when interconnecting hydro-power and thermal-power blocks. HVDC links can also actively stabilize the networks at faults.

Increased short-circuit or earth-fault currents provide more and more severe conditions for the equipment. HVDC causes an insignificant increase of short-circuit power and is therefore a useful mean to split up extensive networks or for interconnection of such networks.

2. The development of HVDC

In the beginning of the 1940s the Swedish State Power Board was investigating means to transport electric power from the hydro-power stations in the north of the country to the load centre in the south, a distance of some 600 miles and a power which would ultimately reach some 10 000 MW. Both HVAC and HVDC were discussed, but when the decision had to be made in the mid-1940s it was considered premature to introduce HVDC. The Swedish State Power Board had built a laboratory for testing mercury-arc valves. These tests were continued and by the end of the 1940s it was decided to build the world's first commercial HVDC transmission between the Swedish mainland and the island of Gotland (Fig. 1).

In the meantime a lot of problems related to the use of HVDC had been studied. A joint committee including representatives of different bodies had been set up. Comprehensive investigations were carried out by this committee relating to the use of the ground as a return conductor, the effect on telecommunication systems, corona, etc. Later on, while considering to use the sea as a return for the Gotland link, the corrosion problem, the effect on fish from electric current and compass deviation had to be studied before the decision could be made.

The Gotland link got successors in different parts of the world with higher voltages and greater capacities. HVDC's breakthrough resulted in several other manufacturers becoming interested in the technique. In the beginning their development concentrated on mercury-arc valves, but they soon found that the thyristors would give quicker result, and therefore they diverted their efforts to this technique.

In May 1967 a thyristor prototype was installed for testing in the Gotland interconnection and in spring 1970 the capacity of this link was increased with a whole group of thyristor valves in both stations. This installation was successful and has now been followed by a number of others.

3. The work on HVDC within CIGRE

Due to the great interest in HVDC, a Study Committee was organized already in 1946. It has been interesting to note how open the discussion about operational experience and all kinds of equipment faults took place, in a way described by some manufacturer as a 'technical strip-tease'. Since the end of the 1960s, the Committee has collected information about faults, availability, etc. from the utilities according to an agreed protocol which has then formed the basis for a regular CIGRE Report. In this way, information has in a fair way been distributed outside the Committee's circles.

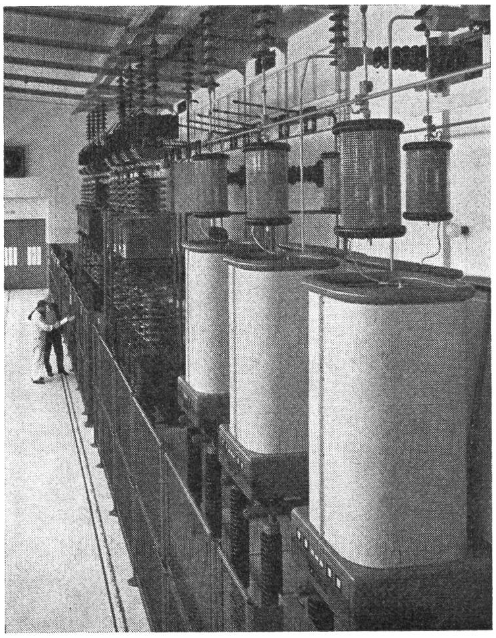

Fig. 1 Gotland substation. Background: mercury-arc valves, foreground: thyristors

Great interest has been devoted to economic comparisons between HVAC and HVDC. A CIGRE Report was submitted in 1956 (No 417) and another one to the Conference of 1968 (No 42/43-01). Both reports show that it is always difficult to form general rules as to one system being superior to the other. Practice has also shown that the studies must be based on the prevailing specific conditions, appropriate expansion stages, reserve power requirements, etc. Moreover, the rapid component development plays also an important role.

The discussions within the Committee have, of course, also been concerned with other components than the valves, such as harmonic filters, cables, overhead lines. Other discussions have involved insulation coordination, pollution, corona, radio interference RI, earth return effects, DC links within AC networks, etc.

4. Design considerations

The converter equipment is considered to be the vital element in the HVDC transmission. A characteristic of the installations built with mercury-arc valves is that they have had certain teething troubles for a number of years. Despite this, the availability has been comparatively high although the number of outages caused by the valves or associated equipment has been high. This has in many cases incurred troubles for the associated AC networks. This type of plants has, however, been very much improved.

An interesting diagram (Fig. 2) taken from CIGRE Report No 14-09 1974 shows how the loss of availability for HVDC links has developed since 1968. It should be emphasized that the part of the loss of availability due to valves and other DC equipment in the stations is very small.

The future HVDC plants will, however be based entirely on thyristors, for a number of reasons. Thyristors have from the beginning proved to be nearly 100 percent reliable. The availability of complete DC stations is reported to be over 99 percent. Backfiring and commutation faults do not occur in valves of this type. This means that a number of secondary failures caused by high stresses on other equipment that are attributable to valve failures disappear, too. As a result, there is less reason now to build the stations with 6-pulse groups; one can proceed directly to 12-pulse groups, whereby the fifth and seventh tuned filters are eliminated and the DC switchyard is greatly simplified. This leads to reduced space requirements and lower costs.

If the trend of costs during the most recent ten-year period is studied, it can be seen that the specific costs (in monetary units) relative to kilowatts has remained nearly constant despite inflation. This trend describes a 'sawtooth' curve, with a certain 'index-regulated' increase which, after a number of years, is evened out through the application of new technologies. This trend can also be anticipated during the coming decade. Thyristors are currently available for up to about 1500 A and inverse voltage of some 3 kV. A development to 2000 A is foreseen within the next five years.

At present, the highest voltage per valve group reaches 500 kV. With this, it should be possible to achieve power of more than 1000 MW per valve group by the end of the 1970s. This seems to be an optimum unit in the build-up of a system in using overhead lines.

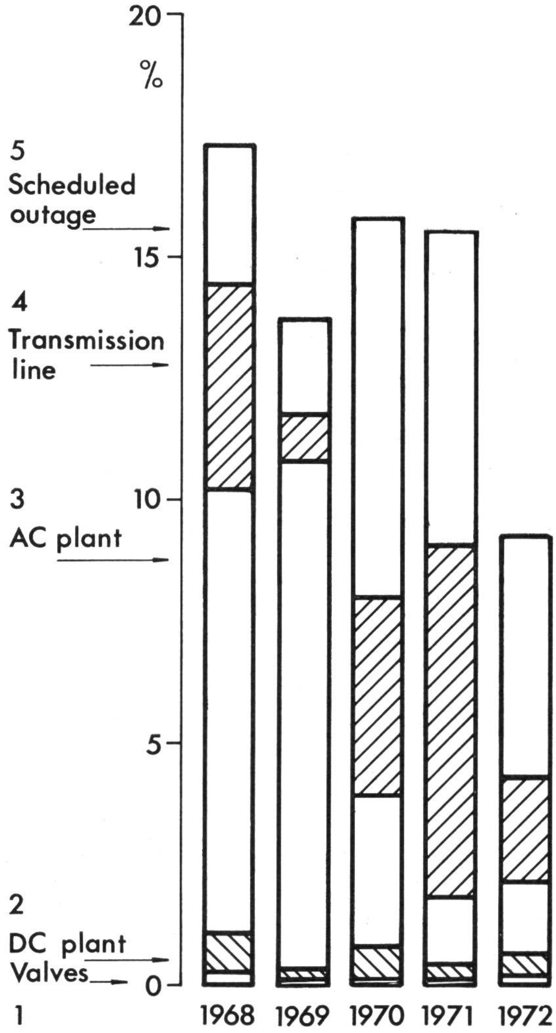

Fig. 2 Evolution of loss of availability of HVDC links

When dimensioning the overhead lines, overvoltages as well as normal operating voltages must be considered. The internal overvoltages produced in the stations have a relatively low frequency. They are also relatively small, amounting in certain fairly unusual cases to about 1.5...1.7 times the operating voltage. When an earth-fault occurs in one pole of a bipolar line, a steep overvoltage is induced in the other pole. In this case, too, the total voltage reaches an amplitude of 1.5...1.7 p.u.

When atmospheric overvoltages are concerned, the number of earth-faults can, of course, be reduced to a low level by using overhead ground wires. When a short circuit occurs, the fault is disconnected within a few tens of ms. In an HVDC system, the follow-current is limited to approximately 10 percent of the maximum load current (Fig. 3). Therefore, the dead interval can be made shorter than in the case of an AC system. An earth-fault is thus not too damaging to firm power transmissions, at least not for point-to-point transmissions. If, therefore, the isoceramic level is low, there are valid reasons for eliminating the overhead ground wire except in the approaches to stations or cables.

In any event, the need to take internal and external overvoltages into consideration in the choice of insulators is not great. The choice is more or less related to normal voltage

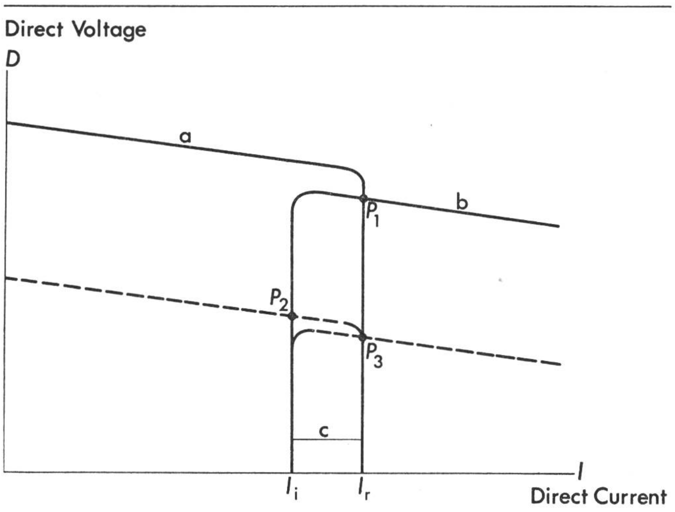

Fig. 3 Control Curve

behaviour, especially in polluted areas. It is sufficient to choose – based on practical experience – an adequate creepage distance per kV operating voltage. This distance is normally 2...5 cm/kV, depending on the proximity to salt water.

As to the clearances between conductor and structure or ground, the conditions are more favourable for DC than AC, thanks to the somewhat lower overvoltage factor. A view which is getting increased importance is the impact of overhead lines on the environment. The HVDC system offers here advantages since, compared with AC, large amounts of power can be transported within a narrower right-of-way. Moreover, the one-leg-tower is in many areas considered not to pollute the landscape too much (Fig. 4).

Regarding the present situation of DC cables, two types are in use: the solid type paper cable and the oil filled cable. The solid type can be manufactured up to 250...300 kV and 300 MW. The dimensioning factor for this cable is the polarity reversal test which is to be limited to a stress of 50 kV/mm. As this test should be carried out at twice the nominal voltage, it means that the nominal voltage is limited to 250 kV corresponding to 25 kV/mm. The manufacturers allow, however, the operational voltage to increase above this figure. The oil-filled cable can be manufactured up to 750 kV and 1500 MW. The maximum oil fed length is approximately 60 km. Regarding the maximum depth, it is, according to one manufacturer, possible to think of 1000 m; laying and recovery may be difficult.

Extruded insulation cables have been tested up to 250 kV. The DC behaviour is a serious problem since the electric stress is only controlled by an unpredictable space charge distribution. As shown in Fig. 2, the loss of availability is largely dependent upon the behaviour of the cable connections. Several cables have suffered from mechanical damages from fishing trawls, etc. Therefore, when replacing 30 km of the Konti-Skan cable in summer 1974, the new cable was ploughed in the sea bed by means of a plough pulled by tugboats.

It seems that impregnated paper cables are more sensitive to mechanical stresses than for example plastic cables. The reason for this seems to be that, if the lead sheath is slightly hurt, a crack is developed within a certain time making it possible for water to penetrate through the insulation and thus causing a breakdown. Modern plastic insulated cables are also covered by a lead sheath but they are not so sensitive for cracks in the sheath. Development of plastic insulated cables for HVDC would therefore be highly appreciated by the power industry.

RI and corona problems are less severe at DC than AC, particularly because the RI level does not increase at bad weather conditions. When using a single conductor, a gradient of 25 kV/cm at the conductor surface gives acceptable conditions. With bundle conductors the RI level in µV/m increases with the square root of the number of subconductors. The gradient will, however, be so much reduced that the total result will be better than with one single conductor.

The convertor stations also produce radio interference. In order to reduce the level it is necessary to take such precautions as the screening of buildings and of the control cables leading to and from the valve hall. Experience and theoretical calculations show that the radio interference is harmless at a distance of some 300...500 meters from the station in the frequency range of 1...2 MHz. Radio interference produced in the stations is also transmitted along the overhead DC line, with the attenuation being dependent on the frequency. 10 km from the station, however, this interference is negligible.

To reduce telephone interference, the stations are equipped with harmonic filters which reduce the harmonics in the AC voltage to less than seven per mill of each harmonic or one percent overall, based on international (CCITT) standards. If, despite these measures, interference occurs in the telephone circuits, proper additional safeguards must be introduced on the weak current side, an approach that experience has shown to be effective. On the DC side the ripple content is greatly reduced by the smoothing reactor. In some cases filters have been introduced on the DC side.

During recent years the influence of the electric field on the human being has been very much discussed. Harmful effects

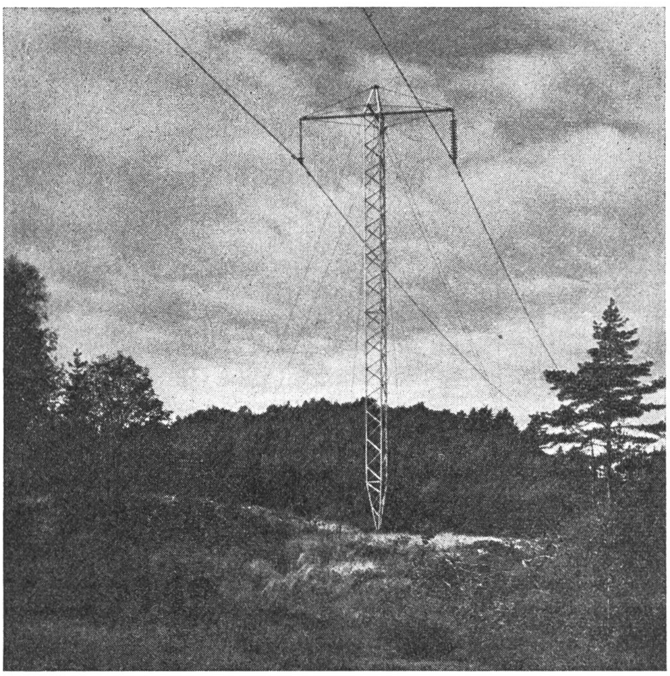

Fig. 4 HVDC Overhead line

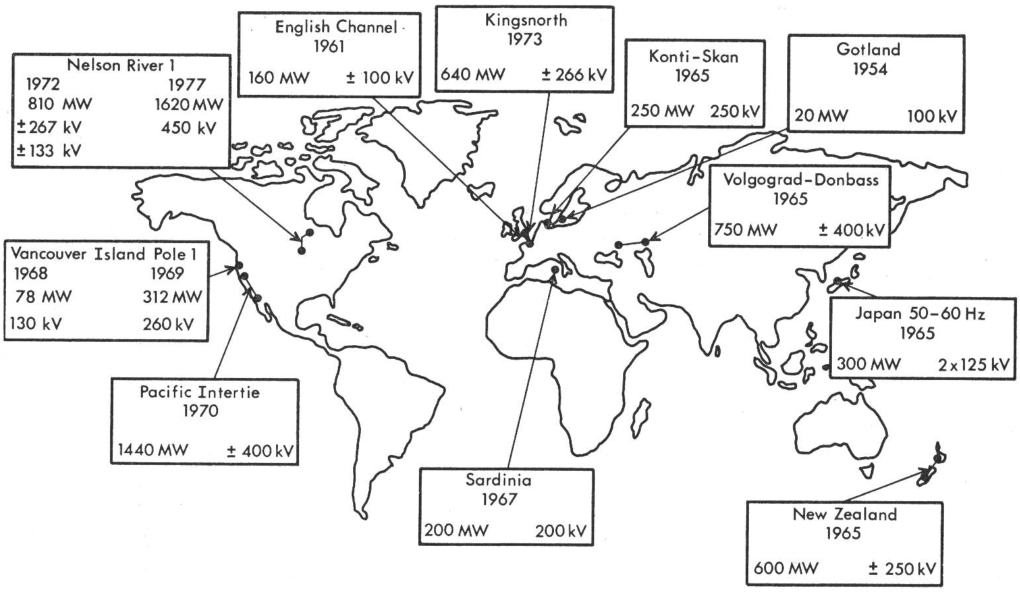

Fig. 5
Commissioned HVDC projects based on mercury-arc valves

are, however, said to exist at an electrical gradient of 50 kV/m and higher. This value is much higher than the one on the ground level under an HVDC line.

5. The future of HVDC

At present, a number of HVDC projects are using mercury-arc valves in operation (Fig. 5). The total rating of them is some 6000 MW corresponding to an average increase of about 500 MW/year. Fig. 6 shows HVDC projects using thyristors. These projects are either committed or under completion. Their total capacity is some 10 000 MW. This corresponds to an increase of about 1500 MW/year. If potential projects are also included in a market forecast, it is assumed that the annual increase would be some 3000 MW/year

The HVDC technique has been considered to be, and has infact been more complicated than the AC technique. Early HVDC plants have also suffered from a lot of teething troubles which have caused a lot of interruptions. Nevertheless, the availability has been kept at high values. It is easy to understand that the system planner has become slightly suspicious about the new technique. New plants have, however, displayed much better operational records why the confidence in this technique has considerably increased. Simultaneously the AC systems have turned out to be more complicated. New electronic devices are fully introduced; extensive networks are controlled and operated by means of different kinds of computers.

Another drawback for the HVDC system was that one could hardly assume more extensive systems than point-to-point transmissions. A Study Committee sponsored CIGRE-Report submitted to the 1974 Session analyzed very thoroughly different types of multiterminal links and gave a survey of the results in different countries. Multiterminal links have now passed the theoretical stage since parallel operation of stations is provided for Nelson River, Pacific Intertie and a lot of new schemes. A DC circuit-breaker will also be avail-

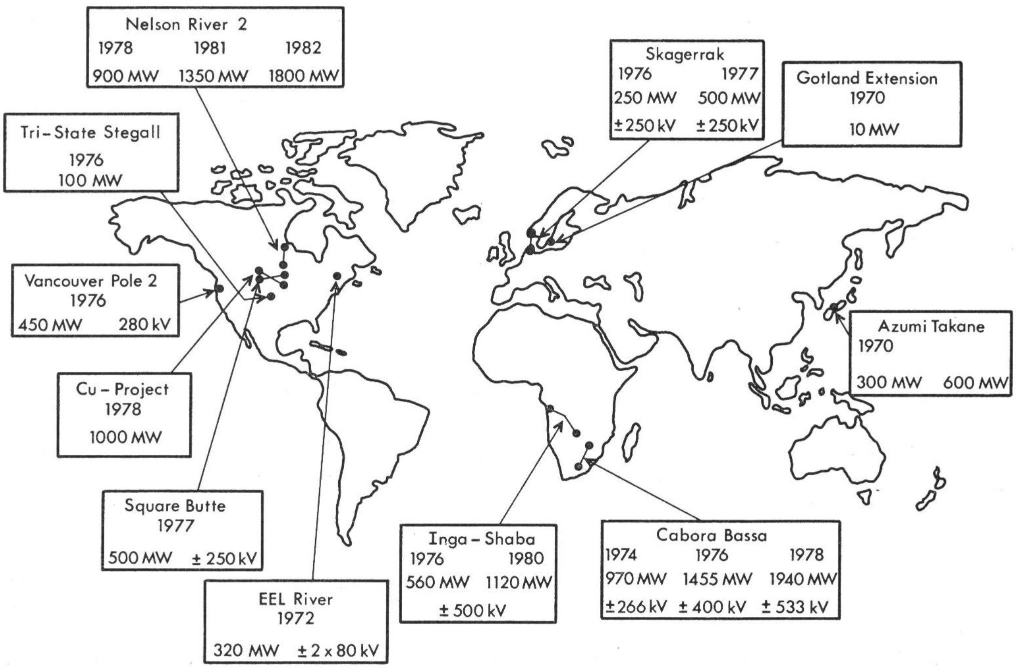

Fig. 6
Committed HVDC projects based on thyristor valves

able within the immediate future, which will make a large multiterminal system more attractive.

It is also possible that the energy crises has influenced the realization of long bulk power transmissions. Due to the crisis, it has been decided to develope remote located hydropower resources or coal fields and to transport the electric power to the load centres by means of HVDC (Canada and USA). Other schemes are considered, too, e.g. to exploit fully the few narrow corridors available for transmission lines.

Realizing the possibilities of further development work within the HVDC field resulting in still better technique and economy, there are good reasons for expecting a lot of new schemes based on HVDC all over the world in the future.

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Zusammenfassung der Themen und Diskussionsbeiträge

Verzeichnis der wissenschaftlichen Beiträge

Themengruppe 1: Berechnung elektrischer Felder

Diskussionsleiter: *H. Prinz,* München
Berichter: *H. Singer,* Hamburg

1.1 Rechenverfahren

1.1–01 *B. Bachmann,* München: Numerische Berechnung von Mischfeldern

1.1–02 *G. B. Denegri, G. Molinari, A. Viviani,* Genova: A programm for electric field computation using a finite difference method with curvilinear grid

1.1–03 *J. Deuse, P. Pirotte,* Liège: Three-dimensional electric field distribution near high-voltage lines

1.1–04 *F. Donazzi, G. Luoni, E. Occhini,* Milano: Automatic field calculation

1.1–05 *H. Froidevaux,* Lausanne: Une méthode par éléments finis pour le calcul de la distribution du potentiel électrostatique dans certains cas non-linéaires

1.1–06 *V. Hoppe,* Kopenhagen: A versatile field program based on the finite element method

1.1–07 *M. Khalifa Riyad, M. Abdel-Salam,* Assiut, Ägypten: Calculation of space charge effect on monopolar corona in air

1.1–08 *E. U. Landers,* München: Das koaxiale Zylinderfeld bei hoher Raumladungsdichte

1.1–09 *R. Leyvraz,* Zürich: Field calculation by an automatic and iterative grid generation with minimum discretisation error

1.1–10 *J. Planchard, M. Morin, G. Gallet,* Electricité de France: Améliorations mathématiques et informatiques de la méthode des charges équivalentes pour la résolution de l'équation de Laplace

1.1–11 *G. Praxl,* Graz: Freie Potentiale bei der Methode der finiten Elemente

1.1–12 *H. Singer,* Hamburg: Ein Rechenverfahren zur Auslegung von Steuerbelägen in Durchführungen und Kabelendverschlüssen

1.1–13 *P. Weiss,* Mannheim: Das Hochspannungsfeld von Trichterelektroden

1.2 Anwendung

1.2–01 *V. Andriamiharisca,* Lausanne, *E. Contalbrigo,* Cossonay: Analysis of the electrostatic field by the finite element method for a high voltage cable termination

1.2–02 *M. Khalifa,* Riyad, *M. Abdel-Salam,* Assiut, *F. Aly,* Cairo, *M. Abu-Seada,* Cairo: Electric fields at bundled conductors of high voltage transmission lines

1.2–03 *T. Misaki* und *H. Yamanoto,* Okayama, und *K. Itaka* und *T. Hara,* Osaka: Techniques for finite element analysis of 3-dimensional asymmetrical field distribution in SF_6 gas insulated cables

1.2–04 *E. Nasser, M. H. Ibrahim,* Cairo: Gradient computation by charge simulation

1.2–05 *P. Sarma Maruvada, N. Hyltén-Cavallius,* Québec: Capacitance and induced voltage calculations for some basic electrode configurations

1.2–06 *D. Utmischi,* München: Objekte unter UHV-Freileitungen

1.2–07 *P. Weiss,* Mannheim: Das elektrostatische Feld bei Reihenanordnungen zweier Dielektrika

1.3 Optimierung

1.3–01 *B. Bachmann,* München: Optimierung von Isolieranordnungen durch Multitoroidsysteme

1.3–02 *W. Breilmann* und *T. Härder,* Darmstadt, und *D. König,* Ratingen: Anwendung des Differenzenverfahrens zur rechnergestützten Optimierung von koaxialen Isolatoren in metallgekapselten Hochspannungstrennschaltern mit SF_6-Gasisolierung

1.3–03 *H. Singer,* Hamburg, und *P. Grafoner,* Dortmund: Optimization of electrode and insulator contours

Themengruppe 2: Hochspannungsprüfanlagen

Diskussionsleiter: *J. J. Morf,* Lausanne
Berichter: *B. Staub,* Langenthal (2.1)
M. Aguet, Lausanne (2.2)

2.1 Hochspannungsgeneratoren

2.1–01 *H. Anis,* Cairo, und *N. Giao Trinh,* Québec: Effective performance of cascaded transformers in the generation of switching impulses

2.1–02 *F. Brändlin, K. Feser, H. Sutter,* Basel: An outdoor-impulse-generator for 5,6 MV

2.1–03 *J. M. Christensen, G. C. Crichton, I. W. McAllister, A. Pedersen, S. Vibholm,* Lyngby: A versatile automatic 1.2 MV impulse generator

2.1–04 *K. Feser,* Basel: A critical comparison of the characteristics of chopping gaps in the mega-volt-range

2.1–05 *P. Glaninger,* Wien: Stoßspannungsprüfung an elektrischen Betriebsmitteln kleiner Induktivität

2.1–06 *T. Harada, Y. Acshima, Y. Aihara,* Tokyo, und *T. Okamura* und *M. Hakoda,* Kyoto: A new voltage chopping system

2.1–07 *A. Lietti,* Lausanne: Radio frequency high voltage test equipment with very large power supply

2.1–08 *M. Modrusan,* Basel: Realisation of the prescribed exponential impuls currents for different kinds of test samples

2.1–09 *J. Moeller,* Bamberg: Metal-clad test transformer for SF_6-insulated switchgear

2.1–10 *A. Ramrus,* San Diego: High voltage triggered water switch

2.2 Hochspannungsprüfungen

2.2–01 *H. Bommer,* Bamberg: Suppression of partial discharges in a high-voltage test circuit by means of a tunable partial discharge rejection filter

2.2–02 *U. Brand, M. Marckmann,* Bamberg: Outdoor high-voltage compressed-gas capacitors using SF_6-insulated bushings with potential control

2.2–03 *I. Kuzhekin, W. Budowitsch,* Moskau: Untersuchung von Spannungsimpulsen bei Drahtexplosionen