recognizes the possibility of "interregional exchange which might make 500-mile point-to-point transmission feasible." Even so, he finds it difficult to justify direct current under the specific conditions expected. Furthermore, the a-c system has the particular advantage that it can readily supply intermediate load. Mr. Starr's reference to the constantly improving technology of a-c high-voltage transmission is worthy of special note.

We must all agree with Mr. St. Clair that "we should follow closely the developments and installations being carried out abroad and the operating experiences obtained with these installations." Though the basic experience and technology are now available in the United States, we agree that there are problem areas such as insulator contamination, overvoltage protection, corrosion, etc., that warrant immediate consideration. Such items are included in the activities of CIGRE Committee no. 10 on d-c transmission. Increased participation in this work will go far in providing answers to the many questions associated with the realization of a high-voltage d-c transmission system.

All discussers appear to concur that cable systems may well provide the most promising applications of d-c transmission in the United States. Therefore, there is particular need for additional work to evaluate more fully the conditions under which direct current would compete with alternating current in underground cable systems.

Work Done in the Soviet Union on High-Voltage Long-Distance D-C Power Transmission

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THE WORK conducted in the Soviet Union on high-voltage d-c power transmission is based on the fact that this type of transmission may be quite effective from a technical as well as an economical standpoint in several cases as power systems continue to grow and become more interconnected.

Design estimates show that direct current is quite economical whenever it is necessary to transmit large blocks of power over distances of 1,000 km (kilometers) or more. Under certain conditions it has been found that the transmission of energy along conductors of a transmission line may compete favorably with the transportation of coal over railways or with the transportation of natural gas over pipe lines because of the use of direct current.

Direct current opens up new technical possibilities that are important from the operating standpoint of consolidated power pool systems and, therefore, its use may be more advantageous and expedient not only for long-distance transmission, but also for intersystem tie lines of comparatively short length.

Direct current is indispensable whenever it is necessary to lay cable lines for power transmission and, in particular, for crossing over long water routes (e.g., in Sweden power is transmitted in this way to the Island of Gotland and a tie of this kind between the power systems of England and France is being designed).

Inroads on the problem are being made at present by scientific research and experimental design projects so that the technical and economic benefits of d-c transmission may be realized in the near future. It is very important to note that the results of many of these projects have already been put into practice successfully on the experimental-commercial d-c transmission line from Kashira to Moscow.[1]

At present preliminary work is being carried out in the Soviet Union for the construction of a d-c transmission line from the Stalingrad hydroelectric station to the Donbas.[2,3] This line will be a component link in the Consolidated Power System for the European part of the Soviet Union. The parameters of this line [transfer capacity, 750 mw (megavolts) voltage, ±400 kv; length of overhead line, about 500 km] place it in the same group with the most recent 3-phase extra-high-voltage high-capacity a-c transmission systems. It may be considered that the problem of d-c power transmission will be essentially solved by constructing the Stalingrad-Donbas line and putting it into commercial operation. The experience that will be gained in constructing and operating this transmission line will enable us to employ longer d-c lines with larger transfer capacities more confidently. This will be required when the Consolidated Power System for the entire Soviet Union is created.

Kashira-Moscow Transmission Line

The Kashira-Moscow transmission line, which was put in service at the end of 1950, consists of two terminal converter substations with 112 km of underground d-c cable line between them.

Normally, power is transmitted from Kashira (where it is generated by a thermal power plant) to Moscow (where it flows into a 110-kv network). At times, for experimental purposes, power was transmitted in the opposite direction. The substation equipment permits 200 kv d-c and 150 amperes d-c to be obtained and, therefore, 30 mw is usually transmitted over the cable at 200 kv.

The Kashira-Moscow transmission line has already been connected in several schemes and subjected to various operating conditions. Moreover, experimental studies of all kinds have been already carried out on a large scale. As a result, various measures have been taken and devices developed and put into operation which have improved the reliability of transmission considerably. Finally, a great deal of experience has been acquired, which is now being used in designing and developing the equipment for the Stalingrad-Donbas transmission line, and also in drawing up prospective plans for further use of d-c transmission.

During the first few years of operation of the transmission system, one bridge was used for converting the current at each substation. There were three mercury-arc tubes (rectifiers) connected in series in each arm of this bridge. Beginning in 1955, other converter schemes were tried. At one time a single bridge was in operation at each of the substations, which had one tube in each arm. The direct voltage in this case was reduced at first to 80 kv and afterwards raised to 100 kv (instead

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of 200 kv when three tubes were in each arm). The operation of the bridge was checked with two tubes connected in each arm. The present setup at the Moscow substation, which is usually subjected to inverter duty, consists of two bridges connected in series. There is only one tube connected in the arm of the first bridge, while there are two in the arms of the second bridge which operates at a higher voltage. The substation at Kashira still operates with three tubes in the bridge arms.

The operating experience with converter schemes having one, two, or three tubes in the bridge arms which was acquired on the Kashira-Moscow transmission line indicated that series connection of the tubes in itself does not have any substantial effect on the reliability of the scheme in operation. The great expectations that were earlier held with regard to this connection did not materialize in practice.[4] It was discovered, in addition, that the series connection of several tubes has some drawbacks. For example, if one tube should not ignite, the full direct voltage of the bridge arm is applied to it, while a higher back voltage appears across the other tubes.[5]

Conversion from the scheme with one bridge to the scheme with two series-connected bridges at the inverter station results in better transient performance when one of the tubes breaks down, and also in better operating reliability of the transmission line as a whole. The current surges and voltage fluctuations on the cable line during transients were greatly reduced because of this change in the scheme. If individual tubes did not ignite for a short time, the operation of the inverter substation was no longer endangered.[5]

Extra-high-capacity d-c systems may require parallel or series-parallel connection of the tubes. Therefore, a series-parallel connection of six tubes in one arm of the bridge was made and studied (three tubes were connected in series in the other arms of the bridge). Experimental results and operation confirmed the merits of this connection, namely, insensitivity of the converter scheme to lapses in the ignition of individual tubes. At the same time, some new phenomena were discovered which do not take place with parallel connection of the mercury-arc tubes in low-voltage circuits. The unpleasant consequences of these phenomena were overcome by suppression of the high-frequency oscillations that arose when the tubes ignited.[6]

While making adjustments on the Kashira-Moscow line for normal operation, it was discovered that certain oscillatory processes, which arise during transient conditions, may cause dangerous overvoltages. One such process, for example, is the voltage oscillations that arise between the poles of the substation after the transmission scheme has been de-energized and the cable is still under voltage. By installing appropriate damping devices in the scheme, which consist of resistors and capacitors, these oscillatory processes can be suppressed and the overvoltages associated with them liquidated.

At first the transmission was unstable in operation and was frequently interrupted, primarily because of the instability of the mercury-arc tubes. Measures were taken along two lines to improve the reliability of the transmission: 1. to improve the tubes themselves, and 2. to lighten their duty in the scheme.

The tubes themselves were improved during their periodic repairs when various changes in design were made. Also their process of manufacture and high-voltage trial operation was brought up to date. Some of these tubes were replaced by newly manufactured ones of better design.

The duty of the tubes in the circuit was lightened by the introduction of appropriate damping devices and high-frequency reactors which reduced the rate of rise of the back voltage and the magnitude of the current surge at the instant the tube ignited. In addition, the high-frequency reactors connected in the plate circuit of each tube enabled the radiation to be reduced and the ratio interference to be brought down to a tolerable level.

Measures improving grid control as well as automatic control and protection played a positive role in establishment of normal, stable operation of the transmission system.[7–11] Among these measures, special attention should be given to the positive experience gained from the use of automatic reclosing by means of grid control. This enabled the pause in power transmission to be reduced to a minimum (0.1 to 0.2 second) after short-time phenomena such as arc back took place.

The experience acquired from the operation of the d-c cable line is of great interest. This line consists of two single-conductor cables laid alongside of each other in one trench. They have an aluminum conductor 150 square millimeters in cross section, a lead sheath, and paper insulation 12 millimeters thick, impregnated with an oil-rosin compound. At first the transmission worked without grounding on the d-c side. Under these conditions both cables were at a voltage of ± 100 kv. For the past 4–5 years the transmission system has been working with one of the d-c poles grounded and, therefore, 200 kv is applied to the ungrounded cable (maximum potential gradient is 31 kv per millimeter).

In reporting the operating experience with this cable line, it should be noted that cables from different firms were used. The best results were obtained with cables from the firm KWO in Germany and from the Moscable Works, USSR, which were laid out along a 30-km section. There was not a single fault on this section during the entire operating period. Tests in 1957 on pieces of cut-out cable and also on various couplings indicated that electrical strength was the same as when the cable line had been laid in 1950.

For a long time the Kashira-Moscow transmission line has been operating according to the "conductor-ground" scheme. Current flows in one direction through the ground between two special ground rods in the form of iron pipes pounded right into the soil. Studies that were carried out and also operating experience indicate that in the case of direct current it is quite permissible to use the ground as the return conductor. Protective measures may be required only for underground metal structures that are located comparatively near the ground rods.

One of the existing 3-phase 110-kv overhead lines running from Kashira to Moscow was used several times in an experiment on d-c transmission. Direct current was sent over two conductors at a voltage of ± 100 kv, and also over the conductor-ground scheme at 100 and 200 kv. The insulation of the 3-phase 110-kv line withstands quite reliably a direct voltage of 100 kv. At 200 kv there were cases where the insulator string flashed over during bad weather. Tests on the overhead line were made to single out the characteristics of transients and to check the damping devices limiting overvoltages.

From the foregoing survey, which is by far incomplete, of work carried out on the Kashira-Moscow transmission system, it is quite evident that the improvements made and the operating experience gained are of extreme importance.

Further Developments in D-C Power-Transmission Techniques

Work on the development of d-c power transmission in the Soviet Union is carried out at the Scientific Research Institute on Direct Current of the Ministry of Power Stations, the Lenin All-Union Electrotechnical Institute, the Power Institute of the Academy of Sciences, the Institute of the Cable Industry, and in design departments of several large electrotechnical works. Several departments of educational institutes participate in the solution of some questions involved in the general problem. Direct-current transmission lines are being designed at the project institute's "Teploelectroproject" and "Hydroproject" in conjunction with the Direct Current Institute.

Scientific investigations and developments in design are co-ordinated by appropriately distributing the different work, by the organization of information exchange, and by joint conferences. All necessary work on Stalingrad-Donbas d-c transmission is co-ordinated by the Ministry of Power Stations and is carried out in accordance with a general plan. Research work on some topics is carried out jointly by several organizations in accordance with general programs. Most frequently it consists of large-scale experimental investigations carried out on the Kashira-Moscow transmission line. The results of work after its conclusion or at intermediate stages are generally discussed at meetings of scientific and technical councils of the institutes. Moreover, other organizations engaged in the solution of the general problem always have their representatives participating in the work of the council of the given institute.

Work on the further development of techniques for d-c power transmission is being carried out along the following main lines:

1. Schemes for the d-c transmission line are being developed as well as for its junction with a-c systems and large power stations. Special attention is being paid at present to questions of intermediate power take-off from d-c lines by creating the necessary taps and also of intermediate substations. The solution to the problem of directing power transmitted over an extra-high-capacity d-c line to two or even more points, instead of one, at the receiving system is part of the problem stated. Preliminary solutions to these problems indicate that difficulties encountered in protecting and automatically controlling d-c transmission systems with intermediate substations may be overcome. Moreover, in the more complicated case good use may be made of the possibilities of grid control of the tubes.

2. Converter schemes are being worked out, the theory of current conversion is being developed, and steady-state and especially transient and fault conditions in the operation of the converter substations of the d-c system are being studied. Special attention is paid to particular questions which arise in the event of cascade connection of several bridges on the d-c side so as to obtain a sufficiently high voltage, e.g., questions of uniform voltage distribution among the bridges after current has ceased to flow in the circuit, internal overvoltage protection damping oscillatory processes, reduction of high harmonic content by increase of converter phase number, reduction of the mutual influence of the bridges, etc. Efforts are also being made along these lines to create the best possible schemes and means for compensating the reactive power consumed by the inverter substation.

3. Studies are being conducted on joint operation of the d-c transmission line with an a-c system connected to it. Here we deal with questions such as how abnormal conditions in the transmission system influence operation of the receiving system, and also how fault conditions in the receiving system influence operation of the inverter substation. Ways are sought for using d-c transmission lines with their high-speed grid control to improve the transient stability of adjacent systems and of long-distance transmission lines.

4. Studies are being conducted on the performance of the insulator string as well as on the external and internal insulation of the equipment and apparatus when subjected to a large direct voltage, and also to a direct voltage with an a-c component of varying frequency superimposed. The results of these studies will lead to more rational design of the insulation for d-c overhead lines, high-voltage d-c cables, power transformers, capacitors, d-c instrument transformers, and other equipment for converter substations. Research on corona discharge at a high direct voltage related to this line of investigation is also being carried out.

5. High-voltage high-capacity mercury-arc tubes, the main element in the converter substation, are being developed. The design of these tubes is based on the results of extensive research of different physical phenomena, on the performance of sample tubes which are tested at special setups, and also under actual operating conditions on the Kashira-Moscow transmission line. The tube designed in the Soviet Union has only one plate no matter what its capacity in contrast to that of the Swedish firm ASEA (Allmanna Svenska Elektriska Aktiebolaget) in which the number of parallel-connected plates increases with the tube capacity.[12]

6. The following equipment is being designed for the converter substations: power transformers, insulating and instrument transformers, capacitors, special arresters, disconnecting switches for shunting, and other special apparatus. Work is being carried out on creating high-voltage d-c power cables, which is also associated with this line of activity.

7. Special automatic devices are being developed that generate pulses for the grid control and for the automatic control and protection of the d-c transmission line. These devices substantially influence the performance of the transmission system during normal as well as transient and fault conditions. Therefore, they are developed on the basis of all-round studies of these operating conditions.

Many of the investigations listed are carried out on laboratory installations, which are scale models of the actual d-c transmission system of the future. The parasitic parameters of real high-voltage installations, as well as the main parameters, may be modelled on these installations. This enables low-frequency as well as high-frequency processes (up to hundreds of kilocycles) to be investigated on these models. Models are powerful tools in the hands of research workers and designers of new devices and apparatus.

Stalingrad-Donbas Transmission System

The Stalingrad-Donbas transmission system will be a great advance in the development and practical application of d-c power transmission techniques. This transmission system (Fig. 1) contains an overhead line approximately 500 km long and two converter substations, one of which is located in the building of the Stalingrad hydroelectric station, and the other in the Donbas region. The voltage between conductors is 800 kv (±400 kv relative to ground) and the rated transfer capacity is 750 mw. Provision is made for power transmission in both directions.

Eight generators are allotted at the Stalingrad hydroelectric station for the transmission of direct current. They are connected through power transformers to the rectifier bridges and 220-kv busses. The power generated by these eight units may be directed in part over the d-c line to the Donbas and in part to the 220-kv busses. Direct-current power coming from Donbas is directed to the 220-kv busses, and from there it is distributed, together with the power from all of the generators of the station.

The converter substation in the Donbas links the d-c line with the 220-kv a-c network there. Power is transmitted or received through several lines that run out from the 220-kv busses.

The mid-points on the d-c side at both converter substations are connected to special ground rods that are designed for continuous flow of the rated current of the transmission line. This grounding divides the transmission system into independent halves, and enables one half to remain in operation when the other one gets out of commission. In this case the current flows through the ground.

There are eight identical bridges connected in series at each converter substation. With this number of bridges any possible disruptions in the operation of one of them will little influence the operation of the other bridges and of the

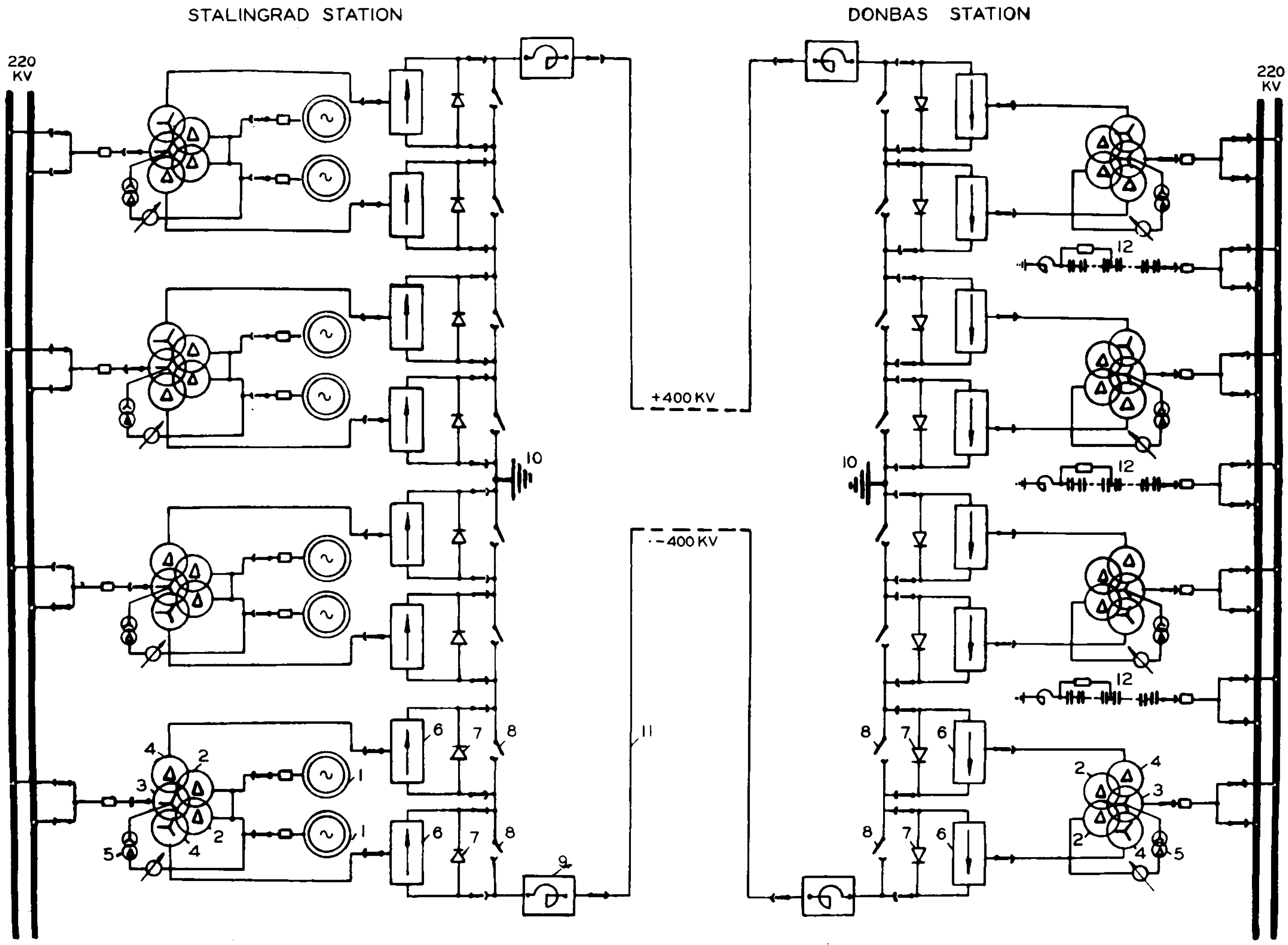


Fig. 1. Circuit diagram of the Stalingrad-Donbas d-c transmission system

1—105-mw 13.8-kv water-wheel generators
2, 3, 4—Power transformer windings
5—Regulating transformers
6—Bridges
7—Shunting tubes
8—Shunting disconnecting switches
9—Output devices
10—Working ground rods
11—±400-kv d-c overhead line
12—132-megavar 220-kv 3-phase bank of capacitors

transmission system as a whole. In case one of the bridges is shunted, the remaining seven insure operation of the others within limits.

In order to reduce the high harmonic content on the d-c side as well as on the a-c side, the windings of each transformer connected to the bridges are connected differently in Y or delta. As a result, 12-phase conversion is obtained.

All the reactive power required at the Donbas substation is supplied by three banks of capacitors (having a total of 400 megavars), which are connected to the 220-kv busses, and at the Stalingrad substation by the water-wheel generators. Auxiliary elements are included in the converter substation to alleviate the duty of the main equipment, and primarily of the tubes, during steady-state as well as transient conditions. Some of these elements are as follows:

1. Capacitors and resistors limiting the magnitude and rate of rise of the back voltage.

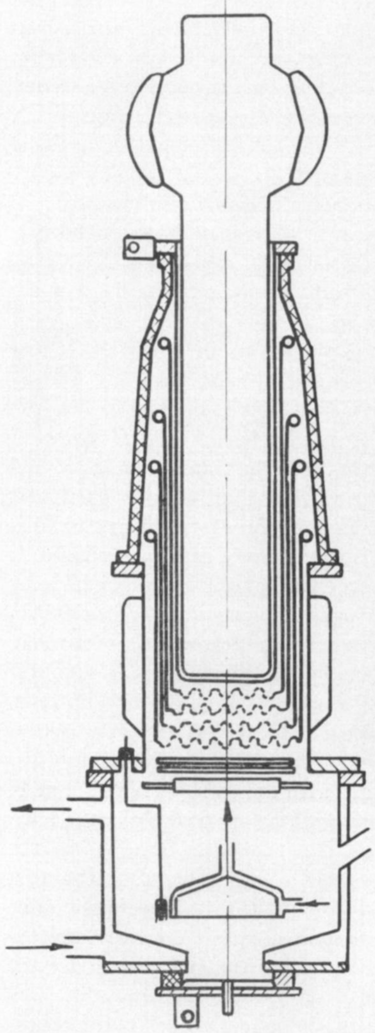
2. Plate reactors limiting the discharge current of the stray capacitances in the circuit through the tube at the instant it ignites.

3. Capacitors and resistors for uniformly distributing the voltage between the bridges and also for damping the voltage oscillations after the circuit is de-energized.

4. Special arresters serving as protection against internal overvoltages.

A shunting tube and a disconnecting switch are connected in parallel with every bridge between its poles. The shunting tube serves as protection during arc backs and breakdowns in the tubes as well as during other short-time disruptions in the operation of the bridge. The shunting disconnecting switch is used for cutting out the bridge for a long time, for example, when replacing a tube.

The converter substations use single-plate tubes for 900 amperes, 130 kv; Fig. 2. These tubes are six times more powerful than the tubes used in the Kashira-Moscow transmission system. Air is pumped out of the tubes. The lower metal part of the tube is cooled by circulating transformer oil, while the upper part of the tube containing the plate has



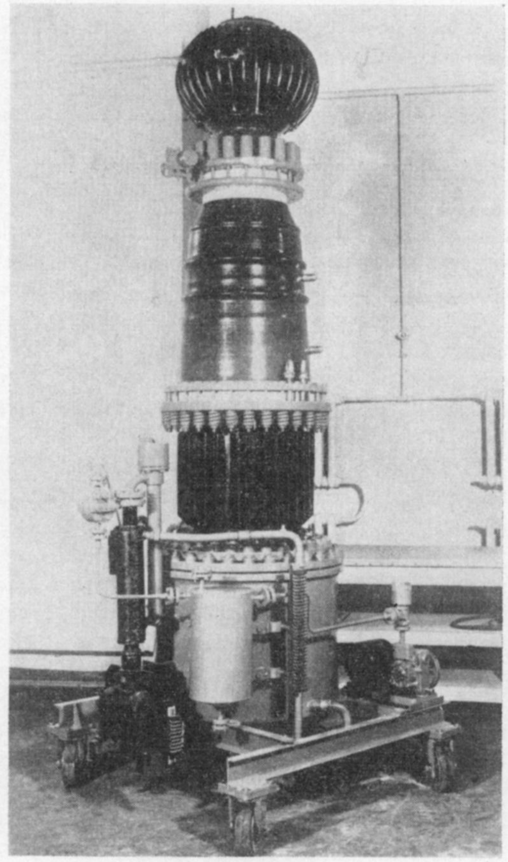


Fig. 2. Drawing (left) and actual view of a 130-kv 900-ampere tube

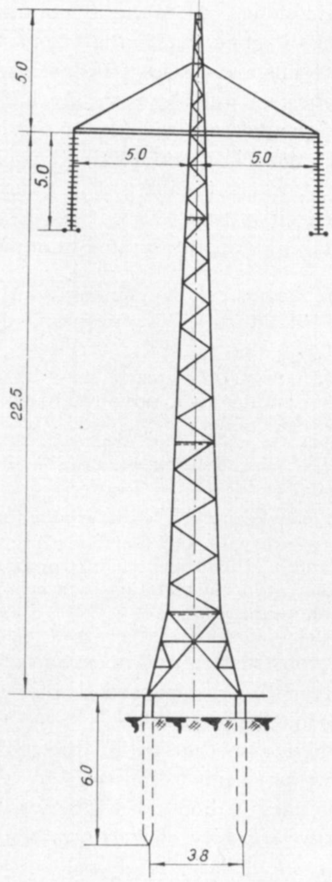


Fig. 3. Suspension tower for the ±400-kv 750-mw d-c transmission line (distances given in meters)

natural air cooling. The tube is 3.5 meters high and weighs about 2 tons.[13]

The power transformers are single phase and come in two insulation classes. Transformers closer to the grounded midpoint in the circuit from the potential standpoint are subjected to a d-c test voltage of 570 kv, while the others are subjected to a d-c test voltage of 1,000 kv.

The d-c overhead line is constructed with T-shaped steel towers; Fig. 3. Each line pole consists of two aluminum-steel conductors having a cross section of 712 square millimeters (the aluminum part), which are separated along the horizontal by 400 millimeters. The line is protected against direct lightning strokes by a single steel ground wire having a protection angle of 30 degrees. When designing the d-c line, it was possible to reduce somewhat the requirements levied on the lightning protection because of the advantages of the grid protection.

The length of the insulator string and the air insulation clearances were selected on the basis of limiting internal overvoltages to a value not greater than 1.7 of the rated working voltage. In order that voltage oscillations in the line do not exceed this value during transients, special transverse damping circuits of resistors and capacitors are connected at the ends of the line.

It should be noted that the length of the insulator string could not be made shorter by even further limiting the magnitude of these internal overvoltages of short duration amounting to tenths of a second, since shorter insulator strings would flash over during bad weather by action of rated voltage applied continuously.

The overvoltages arising on the line also will be applied to the substation equipment in the event that current stops flowing in the circuit. Therefore, the maximum magnitude of the overvoltage as given is relevent not only for the line, but also for determining the requirements of the insulation of all of the substation equipment.

A system of automatic regulators is used to attain the most economical operation for the transmission system under normal conditions and to maintain its stability during various kinds of transient conditions.

A given transfer capacity is maintained automatically regardless of the voltage fluctuations on the 220-kv busses of both substations. For this purpose regulating transformers, Fig. 1, are used and voltage regulation is employed on the water-wheel generators. If it should be necessary to change the direction of power flow over the transmission line, co-ordinated switching in the grid control devices is carried out at both substations.

When transmitting power to the Donbas, frequency control is provided at the receiving end by appropriately varying the transmitted power.

The grid protection worked out for the transmission system is quick acting. Therefore, in the majority of cases it should prevent the fault from developing, protect the equipment from being damaged, and enable normal operation of the transmission system to be restored after a fraction of a second.

The use of direct current for transmission from Stalingrad to the Donbas over a distance of 500 km does not result in any economical benefits as concerns first costs, losses, and the cost of transmitting 1 kilowatt-hour. The technical and economic characteristics of the ±400-kv d-c scheme and of the 400-kv a-c scheme are about the same. All of the gain obtained by using direct current in the line part of the transmission system (the line is 1.6 times cheaper, and its losses are half as much) is completely expended in this case by the more intricate terminal substations. However, the use of direct current for such an intersystem tie has definite advantages in operation; for example:

1. The frequency may be controlled independently in the two a-c systems that are linked.
2. The power transmitted may be controlled according to a pre-established program.
3. Faults in one system have a much weaker effect in the other system.
4. The single-circuit d-c line is much more reliable because of the possibility of using the ground as the return conductor, and because the automatic reclosing cycle is limited to its minimum value.

The construction and operation of the Stalingrad-Donbas transmission systems will permit the necessary experience to be accumulated so that within the next 10 years we may begin to construct d-c transmission lines at ±600 to ±700 kv having a transfer capacity of 2 to 4 million kw per circuit. These lines will serve to transmit large blocks of cheap power from the regions of central Siberia to the Urals, where fuel is expensive; that is, over a distance of 2,000 to 2,500 km. The use of direct current for such transmission systems will have a great effect on the national economy.

Expected Effect of Using D-C Power Transmission over Long Distances

By making use of design material that has already been compiled, it is possible at present to compare from the economic standpoint transmission by means of direct current with that by means of 3-phase alternating current, and also with the transportation of coal over the railways and of natural gas over pipe lines (all pertaining to conditions in the Soviet Union).

When comparing a-c and d-c schemes for a definite case of power transmission, the optimal solution to the problem using each of these schemes should be taken. By that we mean the optimal values of the line voltage, the conductor cross section, etc.

Calculations made for many different transmission systems with overhead lines indicate that the relationship between the optimal voltages is usually as given in the following.

It is shown that $\pm U_{=} = U_{\simeq}$, where U is the voltage of one line pole to ground in the d-c scheme, and $U_{\simeq}$ is the rms value of the line-to-line voltage, in the a-c scheme. The total conductor cross section selected in each scheme on the basis of the economical current density is 1.5 to 2.5 times smaller for d-c than for a-c. When these relationship are observed, the d-c line is always less expensive and has smaller losses.

The characteristics of two transmission lines, a d-c line and an a-c line, are given in Table I.[14]

From a comparison of the initial costs of both schedules it follows that the use of alternating current for transmission system 1 is more expensive by 25% while for transmission system 2 this figure rises, to 98.5%. There is some descrepancy here as regards the percentage distribution of the cost of the elements for both transmission systems. This cost distribution among the various elements is given in Table II.

It is seen that the use of direct current is expedient economically not only when constructing extra-long-distance extra-high-capacity transmission systems (transmission system 2), which is usually not questioned, but also in the case of transmitting 1,000 mw over a distance of about 1,000 km (transmission system 1).

The benefits of using direct current become greater not only for an increase in the transmission distance, but also for an increase in the power transmitted. When large blocks of power are to be transmitted the d-c scheme has additional advantages connected with the greater transfer capacity of its line. This follows clearly from the example of transmission system 2. In the a-c scheme three circuits have to be used instead of two as in the d-c scheme. The a-c line is more than twice as expensive and the losses in it are 1.4 times greater than in the d-c case.

Calculations have been made in the USSR comparing power transmission over conductors with the transportation of coal over the railways for various particular cases. In certain cases when the distances involved were sufficiently large, it was seen that power transmission using direct current is economically justified in comparison with transporting of coal. For example, d-c transmission from power stations working on cheap but untransportable coals to the industrial districts of the Urals over a distance of 2,200 km was compared with the transportation of more expensive high-calory coals from the Kuznets basin to the power stations in the Urals. The results show that the first costs for erecting the d-c transmission line are somewhat greater; however, the operating costs and the energy cost for the consumer are lower. These additional first costs will be reimbursed in the course of 4 to 5 years.

Plans exist in the Soviet Union for increasing the use of natural gas as the fuel at power stations. The following question may be asked: Is it more expedient to transport gas over a long distance through pipe lines or to build power stations at the place where the gas deposits are and to transmit power over conductors? Calculations indicate that when sending 2,000 to 4,000 mw over a distance of 1,000 km or more, the use of direct current for transmission is entailed with additional first costs as compared with the gas pipe line; however, reimbursement of these additional costs does not require a long period since the operating costs in the d-c scheme are lower. For example,

Table I. Economic Comparison of D-C and A-C Transmission Systems

No.	Basic Parameters	Transmission System 1 D-C	Transmission System 1 A-C	Transmission System 2 D-C	Transmission System 2 A-C
1	Length of line, km	1,000		2,200	
2	Capacity, mw	1,000		6,000	
3	Annual energy transfer, billion kilowatt-hours	7		42	
4	Voltage, kv	±500	500	±600	600
5	Number of circuits	1	1	2	3
6	Conductor cross section per phase or pole, square millimeters	3×712	3×712	4×712	4×712
7	Losses, %:				
	In lines	2.74	5.33	8.84	12.15
	At substations	2.70	1.44	3.20	2.19
	In compensating devices		0.58		1.40
	Total	5.44	7.35	12.04	15.74
8	Cost of transmitting one kilowatt-hour, kopeks	0.80	1.05	0.72	1.22

Table II. Cost Distributjon

	Transmission System 1 D-C	Transmission System 1 A-C	Transmission System 2 D-C	Transmission System 2 A-C
Lines	58.5	66.6	56.0	59.2
Substations	41.5	23.0	44.0	16.6
Compensating devices		10.4		24.2
Total	100	100	100	100

when transmitting 2,400 mw over 1,500 km the period for reimbursement of the additional first costs in the d-c scheme amounts to about 6 years.

Work done on d-c transmission schemes and on the design of the terminal elements indicates that one may expect cost reductions there.

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Discussion

M. M. Morack and **G. D. Breuer** (General Electric Company, Schenectady, N. Y.): The authors are to be complimented on their fine paper which evaluates many of the technical and economic aspects of d-c power transmission. One must agree that the 200-kv d-c 150-ampere 30-mw Moscow-Kashira system, put into service in 1950, provides an excellent facility for developing and furthering the technology of d-c transmission.

It should be emphasized, however, that the smaller American systems, the Mechanicville-Schenectady test and the commercial Carnegie-Illinois frequency changer, have provided solutions to some of the same problems and form the basis of the following conclusions:

1. The Carnegie-Illinois system has proved that mercury-arc rectifying devices can be built to give long life and trouble-free operation in rectifier-inverter applications. Of the 48 tubes placed in service in 1943, the last information we had indicates that seven of the original tubes were still in service without overhaul. There is a significant difference between the tubes described in the Russian paper and the tubes used in the American experience. We have been using sealed ignitrons. Our experience indicates that better vacuum conditions can be maintained in properly design sealed tubes, and therefore, better operation and longer service life between reconditioning operations should be achieved with sealed types.

2. The long experience with high-power electronic converters in America also proves the practicability of fast, automatic suppression of electronic and system faults by grid control. While it has been the hope that tubes could be improved to the point where electronic faults could be eliminated, this has been wishful thinking. The constructive point of view first used on the Mechanicville system and now applied in other quarters accepts the fact that electronic faults are inevitable and takes measures which render the faults harmless and scarcely noticeable factors in practical systems.

3. Although the American systems have been operated at much lower voltage levels than the Moscow-Kashira link, they, too, have demonstrated the unpleasant consequences of high-frequency oscillations which arise from the steep wavefronts attending arc ignition. High-frequency series impedances had to be installed on the Mechanicville system to suppress radio interference propagated from the inverter station and finally a broadcast receiver could be operated in the converter room with tolerable noise level.

Preliminary tests on the Carnegie-Illinois system also proved the need for appropriate damping devices to relieve tube duty. During the first hours of operation, inverter faults were so frequent as to cause light flicker on a large utility system and the converter had to be removed from service. After installation of damper components, the faults decreased a hundredfold, to a few per day. These faults are cleared automatically and go unnoticed.

In comparisons of d-c transmission and coal-by-railroad, the Russian studies found that for 1,300 miles, direct current was the economical alternative. Inasmuch as the curves for d-c transmission and coal-by-railroad in another study[1] are parallel out to 400 miles and beyond, the curves for conditions in the United States would not be expected to cross to show the optimistic picture for d-c transmission presented by the authors' comparison.

It is of interest to note that the authors' studies indicate that as a result of optimizing line voltage, conductor size, etc., for a given power and distance, the resulting optimum direct voltage to ground is equal to a-c line-to-line rms voltage. For conditions and total costs that would be encountered in the United States, it is expected that a higher a-c line-to-line voltage than direct current to ground would be selected for comparison.

In the tabulations of the costs comparing d-c and a-c transmission systems, the costs of substations and lines are given only as percentages of the total system. By this manner of presenting the data, it is not possible to obtain direct comparisons of a-c versus d-c costs of terminal stations and lines, and it would be very informative if the authors could present this additional information. Another area of interest is the variation of d-c terminal station cost per kilowatt as a function of system voltage that has been found in the authors' experience and any information in this regard would be appreciated.

Reference

1. D-C Transmission: An American Viewpoint, **G. D. Breuer, M. M. Morack, L. W. Morton, C. A. Woodrow.** *AIEE Transactions*, see pp. 504–15 of this issue.

H. K. Sels (Public Service Electric and Gas Company, Newark, N. J.): Mr. Nekrasov and Mr. Posse have presented a detailed and complete account of the work done on d-c power transmission in the USSR which is interesting and informative. In recounting the many troubles which they have had, I detect a similarity to the early troubles that we had in the United States in the early application of rectifiers which were traceable to improper performance of personnel and poor designs. It is not clear whether these are recurrences, or not, or whether they are attributable to a new application. These troubles emphasize the care that must be taken with the innumerable elements associated with d-c transmission which are infinitely more complicated than those associated with a-c transmission. I trust that these have been properly evaluated in the comparison of annual costs of capital, depreciation, taxes, and operating and maintenance expenses as we know them in the United States.

The authors have correctly listed the technical advantages of the d-c system for intersystem ties. Their extensive outline of their planned development of new techniques will be a valuable contribution to the art of high-voltage transmission. It is interesting to note that much of the ground work is done on laboratory models. However, a word of caution is in order that one must be sure that all the factors involved are represented in their true relative magnitudes that do not lead to misleading results. At the same time it is not always possible to represent true deteriorating influences with time which will forecast the ultimate performance of life-size installations. In building the Stalingrad-Donbas transmission system, the Ministry of Power Stations is removing some of this guesswork from a purely technical approach. As we say, "The proof of the pudding is in the eating."

In drawing conclusions from the economic comparison presented, it is well for us to