A. I. E. E. Discusses Tendencies in High-Voltage D.C. Railway Practice

At New York Meeting of April 14, the History of the High-Voltage Development Was Traced and the Possibilities of Standardization Were Considered—Some of the Factors Which Render Very High Voltages Uneconomical Were Pointed Out

At the meeting of the American Institute of Electrical Engineers held in New York on April 14, a paper prepared by Clarence Renshaw on "High Voltage D. C. Railway Practice" was read by N. W. Storer in the absence of the author. An abstract of the paper is given below. After reading the paper Mr. Storer gave an illustrated description of the equipment of the experimental Grass Lake line of the Michigan United Traction Company. This was covered in an article by Mr. Storer in the issue of the ELECTRIC RAILWAY JOURNAL for Oct. 2, 1915, page 660. The points raised in Mr. Renshaw's paper were discussed by Frank J. Sprague, New York, W. J. Davis, General Electric Company, San Francisco, Cal.; W. B. Potter and A. H. Armstrong, General Electric Company, Schenectady, N. Y.; Calvert Townley, Westinghouse Electric & Manufacturing Company, New York, B. F. Wood, United Gas & Electric Engineering Corporation, New York, S. I. Oesterricher, New York; and N. W. Storer, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.

High-Voltage D.C. Railway Practice

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Ten years ago the idea that approximately 600 volts was the maximum potential to be hoped for in the operation of d.c. railways was almost as firmly established as was the belief in the days of Columbus that the earth was flat. Then suddenly the plan was suggested of coupling four 600-volt motors ordinarily employed on interurban cars in pairs of two in series instead of two in parallel, and of connecting the generators in the station in a similar manner so as to employ 1200 instead of 600 volts. The plan was successful, and the use of voltages from 1200 to 1500 has become so common that to-day we are able to discuss details of high-voltage d.c. practice.

HIGH-VOLTAGE CAR EQUIPMENT

Motors.—Experience has shown that, in the design of motors, no precautions are necessary to provide against abnormal voltage distribution between motors due to slipping of wheels. Insulation and creeping distances on motors must, of course, be made suitable for the full potential. The extra insulation required for 1200-volt operation is now obtained by the use of better quality rather than greater quantity of material, and the extra distances by improved shaping and arrangement of parts. Generally speaking, therefore, motors are produced to-day for use in series on 1200 or 1500 volts with the same dimensions and weights as if made for use on only 600 or 750 volts.

There have been one or two instances where motors have been wound directly for full line potential. Speaking generally, such motors are heavier and depart more radically from standard low-voltage design than motors for operating two in series, and moreover they do not lend themselves as well to the operation of cars partly on 600 and partly 1200 volts, as is so often required. High-voltage d.c. railway practice, in the matter of motors, therefore, may be said to consist in the use of two machines in series, these being identical in construction with standard motors for low-voltage service except in the comparatively minor details of quality of insulation and length of creepage path.

Control.—Our first 1200 and 1500-volt equipment employed thirteen pneumatically operated switches, while with the same current at 600 volts eight would have been sufficient. Experience showed that by improvements in interlocking, and by using no more resistance notches than with 600-volt motors it was possible to cut down the number of additional switches necessary on account of increased voltage to two for small equipments, and three for large ones. In dimensions also, it has been possible to work out designs for 1200 switch groups with the same cross-sectional area and the same weight per switch as those for 600 volts.

Auxiliary Control Devices.—In the first equipments for use on 1200 volts, it was considered undesirable to employ this voltage for auxiliary circuits such as those for lights, control, air compressors, etc., and a dynamotor was included to provide 600-volt current. To reduce the capacity required in the dynamotor, the air compressor motor was next wound for full line potential, and later the two machines were combined into a dynamotor-compressor. In locomotives or other equipments where forced ventilation is required, the blower fan is now mounted on the shaft of the dynamotor.

On cars of small or moderate size even the above arrangement is handicapped in the matter of cost and simplicity as compared with 600-volt equipment, so the next step was to arrange the lighting and control circuits for operation directly on line voltage. These two general arrangements constitute a dual standard, and one of the first decisions to be made in planning any given installation is between these two schemes.

OPERATION ON TWO VOLTAGES

Many high-speed, high-voltage interurban lines enter towns over the tracks of 600-volt systems. High speed in the city is not permissible in any case, so that half speed on 600 volts is sufficient. Under such circumstances, it is usual to provide for reconnecting the lighting and control circuits to receive full voltage on the 600-volt section, so that the main motors will remain permanently coupled in series. If a dynamotor-compressor is employed, the same changes automatically connect it for full speed on both voltages. Where cars which operate in this way employ a high-voltage compressor instead of a dynamotor-compressor, no change is oridinarily necessary for low-voltage operation.

High-voltage cars can, in general, be arranged to operate at full speed on both high and low voltage. When the proper scheme of operation on the two voltages has been decided, the next point to determine is the manner in which the change-over should be affected. The simplest method is the use of a manually operated switch on each car. It is sometimes desirable, however, to have the change-over switch located beneath the car, and arranged for operation from the platform. In other cases, it is desirable to have the switches arranged not only for distant control, but also for simultaneous operation throughout the train. Protective devices are sometimes desired to prevent or minimize trouble, if the car is subjected to high voltage when the change-over switch is in the low-voltage position. These ordinarily consist of relays, which act quickly on excess voltage, and cut off the circuits likely to be damaged.

While the choice between automatic and non-automatic acceleration is not influenced particularly by the use of high voltages, there is a tendency to adhere to non-automatic control for simplicity. The same applies with regard to field control.

Alternatives in Control Apparatus

In designing high-voltage d.c. interurban lines the common questions are: (1) Should the voltage be 1200 or 1500? (2) Should the equipment be of the dynamotor-compressor or of the non-dynamotor type? (3) Will it have to operate on high voltage only, or on both high and low voltage? (4) If required to operate on low voltage as well as high, will half speed be sufficient on main and compressor motors, or will full speed on both motors be necessary? (5) Must the change-over switch be arranged for indirect control, or will manual operation be sufficient? (6) If indirect control is required, will it be confined to the individual cars, or will simultaneous operation throughout the train be required? (7) Is a protective device essential to guard against damage by the application of the wrong voltage, or will this not be required? As far as I can judge, the current practice seems to be turning in the following directions: Where the high-voltage cars must run over existing 600-volt lines to any considerable extent, the exact ratio between 600 and 1200 volts offers some advantages. Since high-voltage motors are made from existing standards also, there is a wider range of choice for 1200-volt operation than there is for 1500-volt operation, especially where small sizes of the motors are required. So far, 1500 volts have been used in sections where 600-volt lines have been established only to a limited extent, that is, in comparatively virgin territory, whereas 1200 volts have been employed in sections where there has already been considerable 600-volt development. It seems probable that high-voltage practice will continue to follow these lines except in the case of the electrification of branch lines on steam railroads or similar instances where connections with existing lines will have little bearing. The general tendency is toward the use of the dynamotor-compressor on large, expensive cars, particularly where full speed is required on half voltage. It is particularly suitable for locomotives where forced ventilation is utilized. In the older sections of the country where distances of 4 miles or 5 miles must sometimes be run on city tracks, equipments are usually required to operate at full speed on half voltage. However, equipments for operating at half speed offer considerable advantages in weight, cost and simplicity. Where large cars are arranged for full speed on both voltages, the tendency is toward the use of full speed for the air compressor. The general tendency is to employ the simple, manually operated change-over switch except where cars are operated at close headway or constantly used in trains. In most cases, devices to protect against the wrong voltage are not considered necessary.

Power Generation and Distribution

Power Supply.—D. c. power for high-voltage lines is generated in 1200- or 1500-volt machines which usually employ a compensating winding as well as commutating poles. Twenty-five-cycle rotary converters producing 1200 or 1500 volts on one commutator are in successful use, but with 60 cycles the maximum voltage so far employed for a single machine is 750, so that two machines in series are still required for high-voltage lines. Common substation practice is to employ single synchronous converters where 25-cycle power is available, and either motor-generator sets or two converters in series on 60 cycles.

Switching.—The principal changes which have been made in handling current at 1200 or 1500 volts have been for the purpose of insuring safety. Switchboard panels have been made higher and circuit breakers and knife switches located out of direct reach, long wood rods leading to insulated handles being provided for opening and closing the circuits. Barriers are placed between breakers to prevent tendency to flash across.

Line Construction.—Catenary construction is generally used, although third-rail is in successful use on several lines. The voltage surges to which the latter may give rise under some circumstances, the difficulty of clearing a car in case of accident and the general accident hazard incident to the maintenance of a large conductor so close to the ground, are likely to limit the use of this form of construction. A growing practice is that of carrying the feeders for a considerable distance from the station before tapping into the contact wire, so as to limit the possible current flow.

Economic Significance.—The high-voltage d.c. railway development has been carried out with ease, success and speed, many of the possible difficulties seemingly having been overestimated in importance, for much of the trouble anticipated has failed to appear. This system has made possible the construction of interurban lines and the electrification of branch steam railroad lines at considerably less expense for a given grade of construction than with 600 volts, or to render possible for a given expenditure the construction of lines capable of handling much heavier traffic.

Voltages of 2400 *and* 3000.—Inasmuch as the 1200-volt systems have been brought about by the use of two 600-volt motors in series, and as a few motors wound directly for this voltage have been produced with no particular difficulty, the obvious procedure was to continue the geometric progression and connect 1200-volt motors and generators in series and operate at 2400 volts. One line installed on this basis has had a remarkably successful record. From a general standpoint, however, while the results have been welcomed as a contribution to the development of the art, similar applications for this particular voltage are apparently somewhat lacking. For trolley roads of the usual interurban class it requires apparatus which departs too widely from existing standards. For heavy traction, on the other hand, this voltage is much too low to solve the problem in a sufficiently comprehensive way. Even a voltage of 3000 does not do so completely. It is regrettable, also, that both 2400 and 3000 volts have been employed, and that in carrying on the upward progress in d.c. voltages, 1500-volt apparatus was not used at once for coupling in series for carrying on the geometric progression without the intermediate step.

Standardization of Voltage Desirable

Ultimate Limits of D.C. Voltage.—The general limits upon which standard practice in any industry is ordinarily settled are usually fixed by broad economic considerations rather than by physical limitations. It is entirely possible, for instance, to operate trains at a maximum speed of 90 m.p.h. or more, while the maximum ordinarily attained is from 60 to 80 m.p.h., and the general average for interurban cars is 50 to 60 m.p.h. These values have been established by gradual increases until, without conscious effort, standardization has been automatically secured. In the voltages which may be employed in the d.c. railway system, there is some tendency toward the same procedure. While in a way such procedure would be the conservative and natural way for progress to come about in the use of higher d.c. voltages, its disadvantages are numerous. The apparently more radical plan of trying to select in advance the voltage where progress would naturally stop, and going at once to this voltage, would hence seem to be the more rational, and it is with this idea in view that our efforts toward the use of that kind of 5000 volts are being put forth. The 5000-volt experimental car on the Grass Lake line of the Michigan United Traction Company averaged 5295 miles per month from Oct. 1 to March 5 on a schedule which allows only 15 m.p.h., and its record would have been better had it not been for numerous mechanical difficulties with trucks, wheels, brake rigging, stove, pilots, etc. From November to February, the average was 5813 miles per month. Only two of the failures were due in any way to the use of 5000 volts.

Conclusion.—The pernicious flexibility of the 1200 and 1500-volt systems and the innumerable alternatives which they present for application to any definite case in interurban work seem to give timely warning of the great desirability of early standardization in the matter of higher d.c. voltages. The comparative ease with which apparatus for each voltage has been developed gives the most encouraging feeling for the future development along the same lines. The possibilities which a d.c. system at 5000 volts would offer were the apparatus commercially available make this voltage seem a logical one, and the results obtained with the experimental equipment now in operation give great hope that this voltage may some day be established commercially as the standard of d.c. high-voltage practice.

Discussion

MR. SPRAGUE ON INCREASES IN POTENTIAL

The discussion of Mr. Renshaw's paper was opened by Frank J. Sprague, who traced the history of d.c. voltage increase, which he had consistently advocated. He stated that in the early days of stationary motor development he had built special machines to operate normally at from 500 to 600 volts, but on which in the exigencies of service the voltage had been boosted to 1000. In the experiment on the Thirty-fourth Street line of the Manhattan Elevated Railroad in the latter part of 1886 he had used 600 volts from the third-rail. The voltage 400 to 450, adopted for Richmond and St. Joseph was regarded as extreme, but the standard was gradually raised to about 600, where it remained for a long time.

Mr. Sprague stated that in the early nineties, he pointed out the possibilities of high voltage, setting a limit for direct current at from 1000 to 1200 volts on single motors, above which it would probably be necessary to put motors in series. In an article in the *Electrical World* in 1903, he suggested that with the three-wire system it might be possible to make use of a maximum trolley potential of nearly 4000 volts. In 1905, he offered to undertake the construction of a third-rail road to operate at not less than 1500 volts, stating that that was not the limit of practical d.c. operation, and he urged upon the engineers of the Washington, Baltimore & Annapolis line that they adopt 1200-volt, d.c. operation. His recommendation of 1200 volts with third rail for the Central California Traction Company was adopted, being the first installation of its kind.

Mr. Sprague stated further that in 1906, in a discussion before the A. S. C. E., he mentioned three radical developments which had taken place in d.c. motor construction; the use of commutating poles which, with additional facilities in control, make possible the construction of motors at from 1200 to 1500 volts, with the further possibility of operating two in series on double potential. He quoted H. M. Hobart as predicting in 1907 that within ten years d.c. systems as applied to railway electrifications would employ line pressure of the nature of 2000 or 3000 volts.

In conclusion, Mr. Sprague said that for practically twenty years the potentials for d.c. railways remained unchanged at 600 volts. In ten years it has jumped to 3000 volts, as used on the Chicago, Milwaukee & St. Paul Railway, one of the typically most difficult, and embracing in its 437 miles of line more route mileage than all the trunk line electrifications in the world. The 11,000-volt, 15-cycle system which some engineers at one time thought would become standard, is non-existent, and no single-phase motors are now being installed except on the few systems remaining.

MR. DAVIS DISCUSSES VOLTAGE LIMITATIONS

Referring to the conditions on the Southern Pacific system, Mr. Davis stated that the electrification there presents no new problems. It has been in operation for seven years with very marked success. He stated that the voltage to be used in an electrification depends upon certain limitations as to tonnage and speed, the former depending upon the number of tracks in service. On a four-track road, the drop in voltage in the track is small, the tracks and third-rails respectively being in multiple, so that lower voltages may be used than on single-track roads having to handle heavy tonnages. Hence, as far as distribution is concerned, lower voltages are satisfactory with many tracks.

Mr. Davis showed that the most desirable voltage depends not only upon saving in copper, but upon the load factor on the substations, and the cost and number of locomotives required to handle the traffic. With single-track freight roads, very little improvement in load factor is obtained if the substations are spaced more than 30 miles to 35 miles apart. With this spacing, the copper required for 3000 hp. to 4000 hp. per train is not excessive, and the size of wire is fixed as much by mechanical considerations as by current capacity and voltage drop. Similarly, substation capacity as applying to the whole system, is not materially reduced because motor generator sets must be large enough to carry three times normal load, and as long as 33 per cent load factor is obtained there is no saving in apparatus.

From the standpoint of locomotive cost, Mr. Davis said that the locomotives of a single-track road cost about one-third of the cost of electrification. If, therefore, there is a material increase in the cost of 5000-volt locomotives as compared with 3000-volt locomotives, this increase might prove the determining factor in selecting the voltage. On the C., M. & St. P. Railway forty-two locomotives are required, and here an increase in cost of 30 per cent to 40 per cent would offset savings in the distribution system due to increase in voltage. On a double-track road, the difference would be still more marked, and would indicate the desirability of a voltage less than 5000.

MR. POTTER GIVES C., M. & ST. P. DATA

Mr. Potter indorsed Mr. Renshaw's statements that economic considerations must govern, and that we are more concerned with the future than with the past. He agreed with Mr. Renshaw's concluding sentence with the provision that the word "available" be changed to "economical." Thus modified the sentence would read "The possibilities which a d.c. system of 5000 volts would offer, were the apparatus commercially economical, make this voltage seem a logical one, etc."

Some of the factors in electrification are but little affected by the operating voltage, *e.g.*, power station equipment, high-tension transmission, bonding, etc. In general the cost of substations with equipment of established character is but little affected, as with the higher voltage there is an increased cost per kilowatt, offset in some measure by the less number of substations due to the wider spacing, but not directly as the individual capacity of each substation must usually be increased to handle the included traffic within the longer section. The feeder copper and rolling stock are the factors which are more directly influenced. In selecting the voltage for the C., M. & St. P. electrification, both 3000 and 5000 volts were considered. While the initial cost was about the same in either case, the saving in copper at the higher voltage was offset by the increased cost of locomotives, and from considerations of maintenance and depreciation it is obvious that, for the same total, the expenditure should preferably be in copper rather than in rolling stock.

The relation of cost for certain factors in the C., M. & St. P. electrification is substantially as follows: High-tension transmission lines, 10 per cent; overhead construction, feeder copper, etc., 28 per cent; bonding, 4 per cent; substations, 18 per cent, and locomotives, 40 per cent, the total for the substations complete, together with the direct-current copper, being less than for the locomotives.

Referring to 5000-volt apparatus, Mr. Potter said that such can be handled without doubt. The B., A. & P. locomotives were operated successfully as an experimental equipment in testing control equipment at this voltage. It is true also that the high-voltage arc burns less than does that produced at lower voltage, as it seems to spread around. Regarding the choice of 2400 volts for the Butte, Anaconda & Pacific Railway, he said that the voltage might have been 3000.

From the standpoint of collection of current, 3000 volts potential is sufficient for the largest locomotive likely to be required. The B., P. & A. has roller collectors, operating with 800 to 1000 amp. For high speed these rollers must be carefully balanced, and as the C., M. & St. P. passenger service involves speeds up to 60 m.p.h., collectors which would not require balancing were found preferable. The wear on the contact wire was found to be due to incipient arcing rather than to friction, and it was reduced by increasing the pressure and by lubrication. Maintenance of contact between the pantograph shoe and the contact wire is necessary, and on the C., M. & St. P. the contact wire is slightly lifted by the pantograph. Currents up to 1800 amp. have been collected experimentally at 70 m.p.h. and up to 3000 amp. at lower speed.

In conclusion Mr. Potter said that the C., M. & St. P. electrification operation has been very satisfactory. The regulators used in connection with the motor-generator sets caused some trouble, easily overcome, due to their being small for the duty. Some of the cam-operated switches caused trouble due to defects in manufacture. An interesting operating feature was the frosting of cold electric locomotives when they were taken into the roundhouse. The regenerative system has been successful, eliminating the necessity for stopping trains for inspection. The use of 3000 volts was only an incident in connection with regenerative operation, the principal value of which is in permitting the making of schedules.

On the general topic Mr. Potter stated that he did not consider 3000 volts the limit, but he emphasized the fact that as railroads are operated for profit, standards cannot be established arbitrarily.

MR. ARMSTRONG CONTENDS THAT STANDARDIZATION CANNOT BE ARBITRARILY IMPOSED

Mr. Armstrong pointed out that some of the statements in the paper by Mr. Renshaw discredited the electrifications for which high-voltage direct current has recently been adopted. The questions to be asked are: "What is the trouble with the voltages in use?" and "What is the purpose in suggesting the use of 5000 volts?" Five heavy electrifications have been put in recently at from 2400 to 3000 volts, three of which are in operation, and two will be so in a few months. The inadequacy of these voltages must be proved before a higher voltage is adopted.

High-voltage equipment is necessarily expensive. From the standpoint of distribution it should be noted that on the C., M. & St. P. electrification, a 500,000-circ. mil feeder is used on most of the lines, and with this the average drop is but 10 per cent, and the maximum not over 20 per cent. This road has nineteen substations of a combined capacity of 59,500 kw., and the aggregate capacity of the forty-two locomotives is 126,000 kw. The substations are spaced about 30 miles apart. A greater spacing would increase the necessary aggregate capacity due to the fact that the trains would be bunched on the substations.

Mr. Armstrong did not agree that 5000 is the proper voltage for standardization. Such standardization is not an easy matter, and must come as a result of long effort on the part of many engineers.

Referring to the Grass Lake experimental line, he commented on the absence of d.c. circuit-breakers, necessitating the opening of the a.c. circuit, with the attendant difficulties. He regarded the 5000-volt line as an interesting experiment, but as leading to no definite conclusion.

Mr. Townley expressed his opposition to any attempt to establish a standard voltage, or to state the limits beyond which progress cannot go. If improvements in what may be termed "the fundamentals" can be carried out, the advance must be welcome. Transmission voltage is such a fundamental. Increase in a fundamental is a permanent advance and equipment can be improved to correspond. Mr. Townley attributed the sudden increase in d.c. railway voltage during the past few years to the demands of heavy traction and to competition with the single-phase system. He regarded the high-voltage development as a step in the direction of interchangeability. Mr. Oesterreicher directed attention to a high-voltage d.c. road in Austria-Hungary designed by Dr. Fisher of the Budapest City Railroads. A storage battery with Pirani control equipment is a feature of this. The speaker described the construction of the road with the aid of lantern slides.

Mr. Wood stated that what the steam railroads want is dependability in operation. Standardization is important to this end.

In closing, Mr. Storer said that he had never opposed the use of the d.c. locomotive, but had advocated alternating current on account of the higher voltage which could be used with it. He said that a system that is reliable will have low maintenance cost, but that no system would be suitable for standardization that is not thoroughly reliable. While the 5000-volt system seems promising it has not yet been proved out. There is no doubt that current collection at 3000 volts is satisfactory, but there is nothing to show that 5000-volt equipment will be more costly than that for lower voltage.

To sum up the whole situation, however, Mr. Storer said that engineers must get together on standards.