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HIGH-VOLTAGE D-C. RAILWAY PRACTISE

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ABSTRACT OF PAPER

During the past 10 years, the operation of electric railways at d-c. voltages of 1200 and 1500 has become common and higher voltages have been shown to be practicable. The paper deals first with the fundamental differences in apparatus for 1200 or 1500 volts as compared with the former 600-volt standards and indicates the apparent tendency of general practise with regard to a number of alternative constructions which must usually be considered in each specific application of these systems.

Referring then to the use of higher d-c. voltages which is just beginning, it points out the tendency to reach an ultimate maximum by employing a multiplicity of voltages differing but slightly from each other, such as 2400, 3000, 3600, 4200, etc. for successive installations. It recommends, in order to avoid the confusion which must surely result from this, that efforts be made to establish at once a single standard for high-voltage lines.

The paper shows that final standards in voltage are usually fixed by broad economic considerations rather than by physical limitations and suggests that 5000 volts direct current would offer a very satisfactory voltage for such a standard if commercial apparatus for this voltage were available. Finally, it touches briefly upon the operation of the experimental 5000-volt line at Jackson, Michigan, which has been so successful as to give great hope that the system will be commercially developed.

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. On a few roads, it is true, 650 or even 700 volts was carried at the station and in an occasional rare instance, the use of a booster gave a maximum of 800 or 900 volts. Drop in the feeders, however, usually reduced these values considerably before they reached the car, so that these instances represented merely the generation of d-c. power at voltages above the nominal 600 rather than its utilization by the car motors.

Then suddenly the plan was suggested of coupling the 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 stations in a similar manner, so as to employ

1200 instead of 600 volts. Two railways then under construction were willing to try the scheme, and although there were some misgivings as to whether it would work or not, it did. The entire railway industry as a result has been given a lesson in open-mindedness which it should not soon forget and the use of d-c. voltages of from 1200 to 1500 for the operation of interurban railways has become so common that today we are able to discuss details of high-voltage d-c. practise.

Motors

Limiting ourselves for the time being to voltages of 1200 and 1500 in discussing the matter, the first element to be considered of a high-voltage car or locomotive equipment is of course the motor. As far as voltage between terminals is concerned, the requirements for motors to operate two in series on such voltages differ from those for low-voltage service only in the fact that slipping of the wheels to which one of the two motors in series is connected may interfere with the normal voltage distribution between them, and concentrate a large part of the total voltage at the terminals of one machine. Fear of this contingency at first led to the design of motors for high-voltage service with a much larger number of commutator bars than for corresponding 600-volt service. More extended experience, however, showed that such precautions were unnecessary.

Insulation and creeping distances on motors for high-voltage service must of course be made suitable for the full potential. This was accomplished at first by "main strength and awkwardness," as it were, and the limitations imposed by the extra insulation, extra creeping distances and extra commutator bars ordinarily carried with them a considerable sacrifice in capacity when a given motor was wound for operating two in series on 1200 volts instead of two in parallel on 600. As in the matter of commutator bars, however, wider experience gradually overcame this difficulty. 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 today 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.

In referring to motors above, I have spoken as if the coupling of two 600- or 750-volt motors in series was the only arrangement ever employed for utilizing 1200 or 1500 volts. There have been, however, one or two instances where motors have been wound directly for the full line potential. Speaking generally, such motors are heavier and depart more radically from standard low-voltage designs than motors for operating two in series, and moreover they do not lend themselves as well to the operation of the cars partly on 600 and partly on 1200 volts, which is so often required. In general, therefore, they seem to offer no particular advantages and are hence but little employed.

High-voltage d-c. railway practise, therefore, in the matter of motors 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 creeping distances.

Control

In control apparatus for high-voltage d-c. railway equipments, the fundamental requirements are to provide sufficient circuit-opening capacity to overcome the greater tendency to "hang" which the high-voltage arcs possess, together with the necessary means to confine these arcs within proper bounds.

The first result was secured in the early high-voltage apparatus by using two 600-volt switches in series at practically every circuit-opening point, and the second by liberal increases in the insulation and space surrounding all live parts. Thus our first 1200- and 1500-volt car equipments employed 13 pneumatically-operated switches, where with the same current at 600 volts eight would have been sufficient. The groups in which these switches were assembled, also, were approximately 24 in. (60.9 cm.) wide and 24 in. deep as compared with 18 in. (45.7 cm.) wide and 22 in. (55.8 cm.) deep for the corresponding 600-volt apparatus.

As with the motors, however, greater experience led to a reduction of these differences in the fundamental parts. Some of the extra switches in the first equipments came into play only when the controller was "backed off" from parallel to series, and by improvements in interlocking the work of opening the circuit at this time was transferred to another point so that these extra switches could be omitted. Another switch had been employed because it was feared that the high-voltage motors might require more careful handling and hence more resistance notches than standard 600-volt motors. It was found later that such was not the case and this switch also was omitted in future equipments. In these ways, in the types of equipment most generally employed, the additional switches necessary on account of the increased voltage have now been cut down to two for small equipments or three for large ones. In dimensions also, it has been possible to work out designs for 1200-volt switch groups with the same cross-sectional area and the same weight per switch as those for 600 volts.

Auxiliary Control Devices. The introduction of the new element of operating at double voltage has greatly increased the number of possible combinations and alternatives which must be considered in any given case in order that they may be adopted or rejected.

In the first equipments for use on 1200 volts, it was considered undesirable to attempt to employ this voltage for the auxiliary circuits such as lights, control, air compressor, etc., and so a dynamotor was included as a part of the equipment to provide a supply of 600-volt current for such purposes. To reduce the capacity required of the dynamotor, the air-compressor motor was next wound for operating at full line potential, so that only the lighting and control circuits need be supplied at 600 volts. Even on this basis, the presence of the dynamotor in addition to the air compressor seemed unnecessarily burdensome, so that the next step was to combine the two machines in a dynamotor compressor. In this device, the air compressor, instead of being driven by a separate motor, as previously, is connected to or disconnected from the dynamotor when required by a suitable clutch controlled by the pressure governor. In locomotives or other equipments where forced ventilation is required, the operation is still further consolidated by mounting the blower fan on the shaft of the dynamotor so that the same machine in such cases serves a triple purpose. This offers considerable advantage in simplifying equipments, and the scheme of driving the compressor and providing 600-volt current for the auxiliary circuits from the same machine has become firmly established in high-voltage practise.

Where equipments are to be mounted on cars of small or moderate size, however, even this arrangement is somewhat of a handicap in the matter of cost and simplicity when comparison is made with the usual 600-volt equipment of the same capacity, so the next step was to arrange the lighting and control

circuits for operation directly from the line voltage. With electropneumatically-operated control, this was readily done and on such a basis, 1200 or 1500-volt equipments have been made practically as simple, reliable and easy to maintain as those for operation on 600 volts.

As the art now stands, these two general arrangements for handling the auxiliary circuits 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. The most prolific source of vexatious problems is the use of equipments part of the time on low voltage and part of the time on high. As far as the main-circuit apparatus is concerned, any high-voltage equipment will of course run on half voltage with a corresponding reduction in speed. In order that such operation may be satisfactory, however, special arrangements must be made to care for the auxiliary circuits.

Many interurban lines operate at high speeds over their own rights-of-way in the open country but enter one or more towns over the tracks of local 600-volt systems. High speed in the city is not permissible in any case and so approximately half of the normal speed when running on 600 volts is sufficient. For cars operating under such circumstances, it is common to provide for reconnecting the lighting and control circuits so that these will receive full voltage when the car is in the 600-volt section but so that the main motors will remain permanently coupled in series and thus operate at half speed.

If a dynamotor compressor is employed on cars which operate in this way, the same changes which are necessary in any case to care for the lighting and control circuits automatically care for the air compressor as well, connecting this for full speed on both voltages. In cases where approximately half speed on low voltage is sufficient for the main motors, however, the distances are usually short and half speed of the air compressor also is sufficient. Where cars which operate in this way employ a high-voltage compressor instead of a dynamotor compressor, therefore, no change is ordinarily necessary in its circuits for the low-voltage operation.

Since the motors on high-voltage cars are in general wound for only 600 or 750 volts each, the car can if desired be arranged to operate at full speed on both high and low voltage. Where this is required, a main change-over switch is employed which connects the motors of each pair either in series for high voltage or in parallel for low voltage, and which connects the two halves of each step of the main resistance in a corresponding way. Suitable connections for air compressor, lights and control circuits can also be included in the same switch so that the setting of a single piece of apparatus into one or the other of two positions changes the car at once for use on high voltage or on 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 effected. The simpiest method in either case of course 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 in this way but also for simultaneous operation throughout a train of cars.

To supplement the apparatus for changing connections on equipments so that they may be operated on either high or low voltage, protective devices are sometimes desired to prevent or minimize the trouble which may occur in case a car is subjected to high-voltage when its change-over switch is arranged in the low-voltage position. Such devices ordinarily consist of relays of some form which are so connected, when the change-over switch is in the low-voltage position, that they act quickly in case a voltage in excess of the normal is applied to the car, and cut off the circuits which are likely to be damaged.

The choice between automatic and non-automatic acceleration is not influenced particularly by the use of high voltages except that such voltages are more often employed for interurban lines where non-automatic acceleration is ordinarily considered preferable. The necessity for running on both 600 and 1200 volts in many cases also usually introduces certain complications in high-voltage equipments and there is a tendency to adhere to non-automatic control so that the simplicity of this will, as far as possible, offset the various complications which must be retained.

The use of field control or non-field control also is not particularly affected by the employment of high voltages except as influenced by the same general idea mentioned above with regard to the choice in the type of acceleration. For the sake of simplicity, there is a tendency to adhere to non-field control to offset unavoidable complications at other points.

Alternatives in Control Apparatus. It will be seen from the above that even with common practise in high-voltage equipment fairly well standardized, a host of alternatives usually present themselves for settlement in almost every case. The most common questions are: should the voltage be 1200 or 1500; should the equipment be of the dynamotor compressor or of the non-dynamotor type; will it have to operate on high voltage only or on both high and low voltage; 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 voltages be necessary; must the change-over switch be arranged for indirect control or will manual operation be sufficient; if indirect control is required, can it be confined to the individual cars or will simultaneous operation throughout the train be required; is a protective device essential to guard against damage by the application of the wrong voltage or will this not be required? Other similar questions might be added to the list but these are the most important ones.

Most of these matters are largely influenced by the individuals who control the local situation, so that it is difficult to generalize with any degree of accuracy. As far as I can judge, however, current practise seems to be tending 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 volts, especially where small sizes of motors are required. So far, 1500 volts has been used in sections where 600-volt lines have been established only to a limited extent, that is, in comparatively virgin territory, while 1200 volts has been employed in sections where there has already been considerable 600-volt development. It seems probable that high-voltage practise 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.

Speaking broadly, the general tendency is toward the use of the dynamotor compressor on large expensive cars, particularly where full speed is required on half voltage, since this arrangement lends itself readily to such operation. Dynamotor compressors also are particularly suitable for locomotives where forced ventilation is utilized. For smaller and less expensive rolling stock, non-dynamotor outfits are generally employed, although there is and always will be a certain amount of overlapping.

In the older sections of the country where distances of four or five miles must sometimes be run on city tracks, and where through cars over 600-volt lines are likely to be employed, equipments are usually required to operate at full speed on half voltage. Equipments for operating at half speed under these circumstances, however, offer considerable advantage in weight, cost and general simplicity and will undoubtedly find a considerable field where circumstances are favorable to their use.

Where large cars are arranged for full speed on both voltages, the tendency is toward the use of full speed for the air compressor also. On smaller cars where as a rule the compressor has more margin, half speed of this device is ordinarily thought sufficient even where the main motors operate at full speed.

In the matter of change-over switches, the general tendency is to employ the simple manually-operated type except where cars are operated at close headway or are constantly used in trains. In most cases, also devices to protect against the wrong voltage are not considered necessary.

Equipments with Drum Control. I have spoken in all of the above with particular reference to equipments using indirect or multiple unit types of control and primarily with reference to those using electropneumatic control. While high-voltage equipments are occasionally used with drum-type controllers, especially double equipments with rheostatic control where cars for city service are operated in small towns by interurban companies, the number of these is too small to warrant inclusion in any generalization such as that with which we have been dealing.

Power Supply

Direct-current power for high-voltage lines was first obtained by the use of two 600-volt generators, either engine- or motor-driven, connected in series. Since there was no particular object in retaining two generators in series such as there was for retaining two motors in series on the cars, generators for

delivering 1200 or 1500 volts directly were soon produced. At first these were of the ordinary commutating-pole type. Such machines now, however, usually employ a compensating winding as well as commutating poles.

The next step in the production of high-voltage d-c. power was the use of two 600-volt, 25-cycle synchronous converters connected in series, and while this was considered a radical step at the time it was first proposed, the performance obtained was so satisfactory that single 25-cycle converters producing 1200 or 1500 volts on one commutator have now been developed and are in successful use. With 60 cycles, the maximum voltage so far employed from a single machine is 750 so that two machines in series are still required for high-voltage lines. The performance on this basis, however, is most excellent.

Common substation practise for high-voltage d-c. lines is now to employ single synchronous converters where power at 25-cycles is available, and to use either motor-generator sets or two converters in series, where 60-cycle power is employed. A particularly efficient substation arrangement on the latter basis is secured by installing three synchronous converters so arranged that any two of them may be connected in series. This gives a spare machine at a minimum expense. If a single bank of three transformers is used for supplying these converters, a spare transformer as well as a spare converter is also secured, so that the station is prepared for almost any emergency.

Switching

In the matter of switching, the principal changes which have been made in handling current at 1200 or 1500 volts instead of at 600 volts have been for the purpose of insuring safety to the operators rather than for any other reasons. For this purpose, switchboard panels have been made higher than for 600-volt service and the circuit breakers located on them so as to be out of direct reach. For opening and closing the breakers, long wooden rods leading to insulated handles on the lower part of the panel, are provided. Where two or more breakers are located side by side, large barriers are placed between them to prevent any tendency to flash across. Knife switches have also been located out of reach in a manner similar to the circuit breakers and arranged with rods for distant control.

Line Construction

The first 1200-volt lines employed direct-suspension overhead trolley with a special form of porcelain insulators. The catenary form of construction offers so many advantages for such lines, however, that generally speaking, the most common practise is now to employ this. Several interurban lines are using 1200-volt third rail successfully for supplying power but the voltage surges to which this may give rise under certain circumstances, the difficulty of clearing a car in case of accident and the general safety hazard incident to the maintenance of a live conductor so close to the ground seem likely to limit the use of this form of construction.

A growing practise on high-voltage systems is that of carrying the feeders for a considerable distance from the station before tapping in to the trolley so as to limit the possible current flow in case of trouble of any kind on the cars. With the excellent voltage conditions which can so easily be secured on high-voltage lines, the slight sacrifice which need be made for the sake of protecting the substation apparatus in this way can usually be well afforded.

Economic Significance

In studying the development of 1200- and 1500-volt practise, the fundamental point which appeals to me is the ease, success and speed with which so radical a departure from previous practise has been carried out. In most developments of so far-reaching a nature, many sources of difficulty are usually overlooked at first and must be cared for in later apparatus at increased expense. In the high-voltage d-c. railway system, however, just the opposite has apparently happened. Many of the possible difficulties seem to have been over-estimated in importance and much of the trouble anticipated has failed to appear. It has therefore been possible to gradually simplify and cheapen the various fundamental parts which go to make up the system instead of having to follow the opposite and more usual procedure.

It is difficult to say whether this exceedingly gratifying condition was due to the more advanced engineering ability of the times, to the inherent simplicity of the d-c. railway apparatus, to the very excellent state which such apparatus for 600-volts had reached before its extension to higher voltages was attempted, or to the fact that the jump to 1200 or 1500 volts, while seemingly radical, really subjected the apparatus to conditions differing

comparatively little from those met with in 600-volt practise. Whatever the cause may have been, however, the result remains as a remarkable tribute to those who shared in its accomplishment.

The general results of the high-voltage d-c. system have been to make possible the construction of interurban lines or 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. The usual practise has apparently been a compromise between these two possibilities, which has served to finally transfer the electric line from the street car to the real railroad class as far as transportation possibilities are concerned, while still maintaining the relationship and similarity with reference to the simplicity and reliability of the apparatus. With practically no greater expenditure for substations and feeders than the usual 600-volt trolley line, such roads are able to employ freight or passenger trains after the manner of steam lines in accordance with the needs of their business instead of having to restrict them on account of limitations in the distribution of power.

2400 and 3000 Volts

The comparative ease with which the use of 1200- and 1500-volt direct current was transferred from the realms of uncertainty to the list of every-day standards soon suggested the employment of still higher voltages. Inasmuch as the 1200-volt system had been brought about by the use of two 600-volt motors in series and as a few motors wound directly for this voltage had been produced with no particular difficulty, the obvious procedure was to continue the geometric progression and connect 1200-volt motors and generators in series so as to operate at 2400 volts.

From a technical standpoint, there was apparently no particular difficulty in doing this, and one line installed on this basis has had a remarkably successful record. From a general standpoint, however, while the results have been welcome as a contribution to the development of the art, suitable applications for this particular voltage are apparently somewhat lacking. For trolley roads of the usual interurban class, it has the inherent disadvantage of requiring apparatus which departs too widely from the existing standards with which the operating forces have become familiar, as well as of not lending itself to interchangeable operation over 600-volt lines. For heavy traction, on the other hand, this voltage is much too low to solve the problem in a sufficiently comprehensive way to attract the investment of capital in electrification. Even 3000 volts, while overcoming the latter disadvantage to some extent, 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 2400-volt step.

Ultimate Limits of D-C. Voltage

The general limits upon which standard practise in any industry ordinarily settles are usually fixed by broad economic considerations rather than by physical limitations. It is entirely possible for instance to operate trains at maximum speeds of 90 miles per hour or more, yet the maximum ordinarily attained is from 60 to 80 miles per hour. Physically speaking, also, interurban cars can be run at speeds similar to these, yet the general average on such roads is from 50 to 60 miles per hour. These values have been established by gradual increases from lower ones until without any conscious effort, standardization has been automatically secured.

In the voltages which may be employed with the d-c. railway system, there is some tendency toward this same procedure. If no efforts were made to the contrary, it is not improbable that starting from the voltage of 3000, which we have today on the Chicago, Milwaukee & St. Paul, we would next hear of the employment of 3600 volts, then possibly 4200 volts and so on up in corresponding steps. Sooner or later, however, a point would be reached where, by common consent, these increases would stop, just as this has happened in the matter of speed.

While in a way, such a procedure would be the conservative and natural way for progress to come about in the use of higher d-c. voltages, its disadvantages are too obvious to require mention. The apparently more radical plan of trying to select in advance the voltage at which such increases would naturally stop and of going at once to this voltage would hence seem to be the more rational and really the more conservative as far as the general good of the industry is concerned. It has been

with this idea in view that our efforts toward the use of direct current at 5000 volts are being put forth. With practical apparatus for this voltage available, the problems of distributing and collecting the necessary power for the largest locomotives likely to be required can be readily solved so that although further increases might be possible, they should be entirely unnecessary.

Operation of 5000-Volt Equipment

The general construction of the 5000-volt experimental equipment on the Grass Lake line of the Michigan United Traction Co. and the results of its first few months' operation have been so widely covered by the technical press that it is unnecessary to refer further to them except to say that the equipment is still in operation on the same successful basis, and that at the time this is written, it has run a little over 30,000 miles. During the five months from October 1st to March 1st, the car averaged 5295 miles per month on a schedule which allows only 15 miles per hour and its record would have been even greater than this had it not been for numerous mechanical difficulties with the trucks, wheels, brake rigging, stove, pilots and other mechanical parts of the car for which the equipment was in no way responsible. During the four months of November, December, January and February, which, on account of weather conditions, are ordinarily considered the worst in the year, the car ran 23,320 miles or an average of 5830 per month.

During this period the car operated through severe snow, sleet and rain storms and for a short period even ran with two of the commutator covers missing, these having been lost on the road. The motors and control were purposely allowed to go with a minimum of cleaning and other care, and various reports sent in by the men in charge refer to the presence of wheel wash, dirt and other obnoxious substances in the motors and switch groups, although no damage was caused by them.

A half-dozen or so failures have occurred during the winter but these have been mostly in the nature of broken motor leads or similar troubles which served merely to test the practicability of the use of such a voltage under the general rough conditions to which car equipments are subjected rather than to indicate any inherent weakness. These troubles showed that this equipment could as easily withstand such ordinary mishaps as any equipment for 600 volts. Only two of the failures were in any way due to the use of 5000 volts and these consisted of grounds on the grid resistance which took place through the water-soaked flame-proof covering on certain of the leads where the cables had not been properly insulated and supported. Such troubles can be easily guarded against on new equipments.

While as yet only the one equipment now in experimental operation has been built, various designs of other sizes have been considered and with the special double-armature type of motor and double-jaw type of switch which have made this equipment possible, unusual flexibility in meeting a wide range of conditions can apparently be obtained.

In most of the considerations of the use of d-c. voltages of 2400 and 3000, there has always been a certain minimum size of motor which could be economically produced and this size has been undesirably large for certain classes of service. With the special double-armature type of motor for 5000-volt equipments, however, the experimental equipment already in use is about as small as would ordinarily be required, although even this is apparently not the minimum limit. On the other hand, the design seems equally adaptable to large sizes.

Conclusion

Broadly viewing the high-voltage d-c. practise which we find today, and its significance to the industry, there are four ideas which appeal particularly to me. 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 these voltages has been developed gives a most encouraging feeling for further 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 a standard of high-voltage d-c. railway practise.

Discussion on "High-Voltage D-C. Railway Practise (Renshaw), New York, April 14, 1916

Frank J. Sprague:* Mr. Renshaw states that ten years ago the idea of approximately 600 volts as the maximum potential to be hoped for in d-c. railway operation was firmly established. I can claim that some engineers at least were not deluded with this conviction.

In the early days of stationary motor development I had built some special machines to operate normally at from 500 to 600 volts but which in the exigencies of service had been boosted to about 1000 volts; and on the 34th Street branch of the Manhattan Elevated in the latter half of 1886, where a number of the primary features of the modern electric railway were tried out, I operated at 600 volts from a third rail.

When, a year later, I took the contract for the pioneer trolley roads at Richmond and St. Joseph, I adopted a somewhat lower potential, 450 to 500 volts, which pressure and system were, however, even then regarded as extreme. This standard was gradually raised, however, to about 600 volts, and remained there for practically twenty years.

In February, 1890, at the Kansas City Electric Light Convention I stated, as follows:

"As regards the potential, other things being satisfactory, whatever pressure is demanded in the interests of economical and effective service will be used; and means will be found, consisting mainly in care of construction, which will make its use for the purpose, and as intended, safe and proper. We have in these matters to face the same questions as we have in the matter of steam pressure or of railway speed. To accomplish the larger engineering feats necessary to meet the demands of economy and commerce we will be governed more by the belief in our power to fully subordinate a good servant to our will than by our fears of its vagaries when allowed to become a master."

In my inaugural address as President of this Institute at the Chicago Meeting, June 18, 1892, I pointed out that we were at that time, if using d-c. motors, practically limited to a difference of potential of from 1000 to 1200 volts, and that to go above that limit it would probably be necessary to put motors in series as I had sometime before proposed for long distance power transmission.

In March of 1904, in an article in the *Electric World and Engineer*, I said:

"While d-c. motors may always be somewhat at a disadvantage in the matter of individual potential, when there is a plurality of motors, as in the large locomotive, it is quite possible on a d-c. system to work up to 1700 or even 2000 volts on a single trolley line, maintaining a maximum as in regular use on the Berlin Elevated of from 850 to 1000 volts on individual motors; and if a three-wire system be used it is quite possible to make use of a maximum trolley potential of nearly 4000 volts."

*Abstract of discussion published in August, 1916, PROCEEDINGS.

On the introduction of the interpole in stationary motor construction, I recognized the benefits of this construction for railway motors and advocated its adoption, pointing out that it would make possible an immediate increase in potential for direct-current railway work from 1200 to 2400 volts, without question.

In 1906 I urged upon the engineers of the Washington, Baltimore and Annapolis line the adoption of 1200-volt d-c. operation, and in the fall of the same year, I recommended to the consulting engineer of the Central California Traction Company the use of a 1200-volt d-c. third rail. My recommendation was adopted and the installation, the first of the kind, went ahead on this basis.

A month later I discussed quite fully the details of the 1200-volt operation with the consulting engineer of the Southern Pacific Railway Company, and recommended this potential for the Oakland suburban lines of the Southern Pacific system.

In a discussion before the American Institute of Civil Engineers in Nov., 1906, I called attention to the fact that, comparing the condition of the art then and a couple of years earlier, three important and radical developments had taken place in d-c. motor construction, the first of which was the use of the commutating poles, which, with additional facilities in control, made perfectly possible the construction of d-c. motors at from 1200 to 1500 volts, with the further possibility of operating two in series at double potential.

The remarkable departure in the construction of the New York Central gearless locomotives, in which the hitherto invariable practise of maintaining the fixity of relation between the armature and the field magnet has been abandoned, gave me occasion to point out that this machine was a natural 1200-volt machine without commutating poles.

In 1906, after a personal inspection of the Sacramento Division of the Southern Pacific Railroad, I recommended an electrical equipment operated with an initial potential of 1500 volts at the substation third-rail junction, and described the possibilities of electrical braking, both direct and regenerative, through the use of independently excited fields as now used on the Chicago, Milwaukee and St. Paul equipment.

In my early experiments on the Manhattan Elevated in 1886, I used, for the field as well as armature, rheostatic control for speed variations. I described a plan of regenerative as well as direct electrical braking before the Boston Society of Arts in 1885.

In the *London Times and Engineering Supplement* of April 10th, 1907, Mr. H. M. Hobart made a curiously exact prophecy, as follows:

"My opinion is that within ten years, continuous-current systems as applied to railway electrification will employ line pressure more of the nature of 2000 or 3000 volts, and these systems will, in all probability, have come into extended use."

This is the year 1916. For practically twenty years the potential for d-c. railways remained unchanged at 600 volts. In ten years it has jumped to 3000 volts on the Chicago, Milwaukee and 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 is non-existent in this country, and not a new single-phase railway motor is now installed here except on the few systems remaining.

William J. Davis, Jr.: I do not think the Southern Pacific electrification presents any new problems at all. The discussion to-night seems to be along the lines of increases in voltage far beyond those used on the Southern Pacific. The Southern Pacific electrification has been in operation about seven years, and the success of the installation has been very marked.

As regards the tendency to higher voltages, it would appear that the proper voltage to be chosen for a given installation would depend upon the maximum tonnage to be hauled and limitations as to speed. The tonnage capacity of a system is dependent, we may say, upon the number of tracks that are in service. In a single-track road, if heavy tonnages are to be handled, it will be necessary to adopt higher voltages than would be necessary for a road having sufficient traffic to require two or three or possibly four tracks. In the case of a four-track road, all the tracks being in multiple, the drop in voltage in the track is greatly reduced, and we also obtain the advantage of the copper trolley wire or third rail for all four tracks in multiple, so that even when locomotives of very large powers are used, say 3000 or 4000 horse power it will be found in so far as the distribution system is concerned, that a moderate voltage, possibly 1200 or 1500, would prove as effective in handling the traffic as would 3000 volts, or more, in the case of a single-track or double-track road.

In a reduced number of tracks, some economy is gained in going to higher voltages, but the exact and most desirable voltage would depend not only on the saving in the amount of copper, but also on the load factor on the substations and the cost and number of locomotives required to handle the traffic.

In a single-track freight road, it will be found that upon the basis of the weight of trains now in use, very little improvement in load factor is secured if the substations are placed more than thirty or thirty-five miles apart. With this spacing, the copper required for delivering 3000 or 4000 horse power to a train is not at all excessive at 3000 volts, and is fixed almost as much by mechanical reasons and current carrying capacity as by the desire to secure a low drop in voltage.

Substation capacity also as applying to the whole system is not materially reduced, for the reason that the synchronous converters and motor generator sets are usually designed to stand three times normal load for a short time, and so long as at least 33 per cent load-factor is secured there will be no saving in the total amount of substation apparatus.

The whole problem, therefore, appears to be narrowed down to the question as to the number of locomotives required on a given division and their cost. As a general rule, the cost of the locomotives required for handling the traffic of a single-track road will amount to about one-third of the total cost of the electrification. If, therefore, there is a material increase in the cost of a 5000-volt locomotive as compared with one for 3000 volts, this increase in cost may prove the determining factor. In the case of the Milwaukee electrification, forty-two locomotives were required, and an increase in their cost of fifteen per cent, due to an increase in voltage, would exceed the total cost of feeder copper for the entire system as required for 3000 volts. In the case of a double-track road in which the locomotives would be greatly increased in number, this difference would be still more marked, and would point to limitations of voltage possibly not exceeding 3000 volts as applying to most of the heavy freight traffic now obtaining on trunk line railroads.

William B. Potter: It is a pleasure to endorse much of what Mr. Renshaw has said as to the excellent features of high-voltage direct current. We are, however, rather more concerned with the future than with the past, and I think that the text of the ultimate is very well covered in his statement that: "The general limits upon which standard practise in any industry ordinarily settles are usually fixed by broad economic considerations rather than by physical limitations." He mentions as an illustration, that while it is possible to operate trains at higher speeds than the usual practise, it has not been found economically advisable to do so. I believe the question of higher d-c. voltages will be subject to the results of experience, and whether the limit will be 3000 or 5000 volts, or some other voltage, will ultimately be determined by "broad economic considerations."

In any railway electrification there are certain features which may be considered separately as parts of the general scheme. Under d-c. operation the initial cost, maintenance and depreciation of some of these features are but little affected by the operating voltage, while other features are so directly affected as to be a determining influence in the selection of voltage most favorable to economic results. The power station, high-tension transmission lines and track bonding are in the class of features first mentioned, and to a considerable extent, the substations as well. Sub-station equipment of established type generally increases in cost per kilowatt capacity with the increase in voltage for which it is designed; and while there would be fewer substations at higher voltages, the amount of included traffic usually becomes greater by reason of the longer distance between substations, and therefore there is little or no reduction in the total cost of substation equipment.

The two features principally affected by the choice of voltage

are the secondary distribution copper, including contact conductors and the rolling stock. A careful study of the respective merits of 3000 and 5000 volts was made in connection with the Chicago, Milwaukee and St. Paul electrification. There appeared to be little difference in the initial cost as a whole, the reduction in copper at the higher voltage being offset by increased cost of the locomotives. On the basis of 3000 volts the relative value of the different features in respect to each other may be illustrated by the following percentages: the high-tension transmission line complete, about 10 per cent; track bonding, 4 per cent; substations complete, about 18 per cent; the overhead construction, feeder copper and trolley complete, about 28 per cent; and the locomotives about 40 per cent. The 3000-volt copper for feeders and trolley only being something less than 20 per cent, and the locomotives being about 40 per cent it is not surprising that the reduction in copper at 5000 volts would have been offset by greater cost of the locomotive.

Considering depreciation and maintenance, it is better that an equivalent expenditure should be in copper rather than in locomotives which require maintenance and upkeep. To economize in copper and pay an equal amount for more expensive locomotives would be a transaction on the wrong side of the balance sheet.

Mr. Renshaw's comment with respect to 2400 and 3000 volts is in the main well taken. The Butte, Anaconda and Pacific might well have been 3000 volts. Occasions may arise, however, where the use of developed apparatus may be utilized to advantage at some other voltage than that for which it was originally designed,—a case in point is an electrification requiring locomotives with the same tractive power as those used on the Milwaukee, but at a speed of 12 instead of 15 miles an hour. It would be unnecessary expense to redesign this equipment for lower speeds when the same equipment at 2400 volts will give the speed desired.

Within the requirements of railway motor design multiples of 750 volts seem to be about the higher practical limit for advantageous winding. For the speeds usually required it is about as easy to wind a motor for 1500 as it is for 1000 volts, therefor multiples of 600 or 750 volts as a maximum naturally fall into line as the preferred voltages for d-c. operation.

Mr. Renshaw in advocating 5000 volts makes this comment,—"With practical apparatus for this voltage available, the problems of distributing and collecting the necessary power for the largest locomotive likely to be required can be readily solved, so that although further increases might be possible they should be entirely unnecessary." There is at present no necessity for 5000 volts to successfully handle the distribution and collection of the necessary power for the largest locomotive likely to be required. The collection of power for the Milwaukee locomotives at 3000 volts is a complete success, there being no sign of arcing at the contact between the pantagraph and the trolley wire in either freight or passenger service. Although the locomotives are equipped with two pantagraphs, a single one only is used; the current taken on the mountain grades being 800 to 1000 amperes, at 15 miles an hour by a single freight locomotive, and the same current at about 30 miles an hour in passenger service. The problem of successful current collection is greater at the higher speeds, and experimentally over 1500 amperes have been collected at over 60 miles an hour with a single pantagraph and no sign of arcing. The success on the Milwaukee is due both to the arrangement of the pantagraph collectors and method of supporting the contact conductor. Each pantagraph is provided with two collecting pans lined on the bearing surface with copper strips, and the contact conductor is two 4/0 copper wires which are in contact with each other in the same horizontal plane. The hangers supporting each of these contact conductors from the catenary are alternated so that the hanger of one conductor is midway the span of the other. The object of this arrangement of hangers being to minimize any inflexibility in the support of the conductors. For the successful collection of current without arcing it is absolutely essential at all speeds that intimate contact be maintained between the pantagraph and the contact conductor, and this can best be accomplished by so supporting the conductors with loop hangers, allowing freedom of vertical movement without the added inertia of the catenary. The upward pressure of the pantagraph should further be sufficient to slightly lift the contact conductors. The contact conductors are, therefore, lifted and carried free of the supporting catenary by the pantagraph in its passage. We found through a series of tests, that the wear of the pantagraph collector and the contact conductor was due not so much to the friction or mechanical wear as it was to the arcing due to collecting current, even an incipient arcing, so small as to be hardly visible, having a destructive effect. As an illustration, when collecting 1000 amperes, the rate of wear with 20-lbs. pressure against the contact conductor was about double what it proved to be at 30-lbs. pressure, the latter being the pressure adopted for the Milwaukee service. Running copper to copper we found, as might have been expected, that lubrication of the contact surfaces was essential to maintaining a smooth surface, and for this purpose a mixture of grease and graphite was used. It might be expected that lubrication would increase resistance of the contact surface. The most careful examination seemed to indicate that the conductivity is rather improved than otherwise. So far as we can judge from the tests, and from other lines operating under similar but less favorable conditions, the contact conductor on the Milwaukee will last for a number of million pantagraph passes.

There is no doubt that substation and locomotive equipment of 5000 volts can be successfully operated. The substation

equipment would not differ materially from a 3000-volt installation. The locomotive motors, however, because of the additional insulation required, and doubtless some change in the design would have less power for given size and weight, and in all probability, a greater number of motors would be required for a given service. The locomotive control equipment for 5000 volts seems to be principally a question of the additional space required for insulation and for the more extended arcing of the contactors. Experimental operation of the Butte, Anaconda and Pacific locomotives at 5000 volts gave opportunity of trying out the control devices under conditions approximating service operation. Arcing and flashovers at 3000 or 5000 volts are more startling, but seem to be even less destructive to the apparatus, than at 600 volts. The high-voltage arc seems to spread over more surface with less local burning than at the lower voltage.

The results of operation on the Milwaukee have been extremely gratifying. Nothing has occurred in connection with the use of 3000 volts that might not well have happened with 600 volts. Minor troubles have developed in the auxiliary devices, particularly on the locomotives, which are more annoying than serious, and can easily be corrected.

The regenerative feature of the Milwaukee locomotives has in every way been as successful as anticipated. The eastern grade of the Rocky Mountains is 2 per cent for 20 miles, and both freight and passenger trains are taken down this grade without air brakes more steadily and smoothly than they run even on the level, and without the delay incident to inspection of brake shoes and wheels as required when air brakes are used. On the lesser grades, where an occasional application of air brakes has formerly been required, regeneration is also made use of to control the train at whatever speed desired. The flexibility of d-c. regeneration makes it particularly suitable for the regulation of trains over a variable profile.

I quite agree with Mr. Sprague that it would be unwise to say that 3000 volts is a finality, and having in mind the economic problems that have to be dealt with, and that railroads are operated for profit, there would be even less wisdom in the arbitrary establishment of a standard not based on experience.

Calvert Townley: I can endorse the last speaker's remarks against the establishment of a standard voltage or trying to say now what shall be the limitations of future practise. I believe that the Institute and all engineers individually should encourage every possible advance in the art, and developments such as the one described in Mr. Renshaw's paper clearly indicate that substantial progress is still being made. Every improvement in fundamentals even if accompanied by some unfavorable construction limitations which are not fundamental should be welcomed and encouraged.

In commenting on the necessity for looking at every problem from all angles when selecting a system, the last speaker quite properly favored a greater investment in the excess copper required by a lower voltage system and which depreciates very little, against the same amount put into the increased cost of the motors and auxiliaries of a higher voltage system where the maintenance and depreciation are both greater. It must be borne in mind, however, that a system which permits the use of a higher voltage scores a distinct fundamental and permanent advance in the art while whatever may be the present offsetting disabilities of increased equipment costs, these are largely temporary. We are just beginning to make 5000-volt equipments and 3000-volt equipments are not so very old. The history of all electrical development has shown that we may confidently expect improvements in design which will largely or entirely remove such temporary offsetting disabilities if any, as may now exist. One speaker cited the St. Paul Road as an example to prove that a 3000-volt trolley e.m.f. is high enough, concluding therefore that there is no use of trying to use higher pressures. He remarked that only one single 500,000-circular mil feeder is needed throughout the entire length of line. Without pausing to comment on the advisability of letting the entire service of a large railway system depend on one feeder it is interesting to note that a 500,000-circular mil bare copper feeder, 440 miles long, calls for over 3,500,000 pounds of copper, while with 5000 volts and with the same energy loss the investment in over 2,000,000 pounds of this copper would be unnecessary.

I feel very strongly that the Institute should welcome and in no sense attempt to decry any fundamental advance such as is described in the paper of the evening, and we should congratulate ourselves and the successful designers that such progress has been made possible.

While rejoicing at the recent rapid and marked increases in available continuous-current voltages, it is perhaps interesting to ask why this sudden activity—this very material advance after years of practically no progress when the limits seemed to have become rather firmly established? I find the answer largely in the increased demands of the new field of heavy railroad electrification and the development of the single-phase system which threatened to monopolize this field. The stimulus of competition has supplied the needed incentive to greater exertions in the study of continuous-current possibilities. If continuous-current apparatus was to receive serious consideration in heavy railroading it was necessary that every possible reduction in the excessive costs of that system should be made and every advantage taken of simplification of method. These conditions have not changed. It is still necessary for the continuous-current system to be bettered. A 3000-volt trolley is not good enough to more than incidentally share, much less to monopolize the heavy traction field against the alternating current. It is far from clear that even a 5000-volt trolley e.m.f. will be sufficient to prevail over available alternating-current systems but

it is however a long step in the right direction and we should welcome and encourage it in every possible way.

S. I. Oesterreicher: While in Mr. Renshaw's paper only general outlines of the underlying fundamental principles of high-tension d-c. railway practise are discussed, perhaps, it will not be out of place to mention certain details of modern d-c. railroad practise.

Mr. Renshaw does not mention storage batteries in connection with high-tension d-c. railroad work. From this I infer, that Mr. Renshaw does not deem it practical to consider such, for the voltages which are discussed in his paper.

While there are, no doubt, considerable difficulties about a floating battery on a say 3000-volt equipment, however it certainly would be worth while to investigate these difficulties for the sake of the advantages gained from the economic operation of the installation as a whole.

The greatest handicaps for such a storage battery project are purely commercial. Naturally this side of the problem must be determined, from case to case as it is presented, and for which no definite rules can be set down in advance.

From the technical side there can be no question, that it is entirely feasible to build and operate with perfect reliability a storage battery for any reasonable moderately high-tension voltage.

To give this statement some weight, I will cite a 1100-volt d-c. railroad equipment as designed by Mr. Fischer, chief engineer of the Budapest City Railroad Co. This company operated in 1912 about 56 miles of three branch lines, having a total of about 124 miles of tracks.

On one of these lines, with a length of about 30 miles, there are one generating and two substations. Power is generated at 11,000 volts, 42 cycles, 3 phase, and supplied to motor generators in the substations. The generators in the substations generate on this particular line 1100 volts, direct-current.

Upon the d-c. bus is connected a Tudor type 484-cell 1000-ampere-hr. battery which floats upon the system as any other standard battery.

There is nothing remarkable or special about this installation as a unit. The battery is standard in every respect, except the battery room, where the floors and wall are insulated from the building.

Even on a three-wire installation, having as potentials 650 and 1100 volts, there is no difficulty experienced from the battery. The only special auxiliary on this double-voltage equipment is the counter-e.m.f. booster regulator. This set consists of a 600-volt d-c. motor and six generators mounted upon the same shaft. The operation of this set is however standard. Each three generators taking care of one side of the system. The voltage regulation of the booster regulator as well as the load distribution between generator and battery is entirely automatic.

Another interesting feature of this Budapest system is the overhead line construction, with its flexible trolley wire suspension, upon the messenger cable. The trolley wire is allowed to slide lengthwise over the tracks, to adjust itself automatically to the climatic variations, allowing a free contraction or expansion of the wire without additional sagging under the suspension clamps, and from which it follows that sparking is almost entirely done away with. Counter-weights of about 3000 lb. at every mile or mile and a half or so about take care of the even trolley tension over their respective sections.

Benjamin F. Wood: I have been connected with a system that has standardization in fact, and lately I have changed to a system that has standardization, to a great extent, in theory. The trolley car man wants everybody to adopt his standard. I noticed in the first picture which was thrown on the screen that there were four or five voltages shown. It does seem that some standardization is desirable, but I think that the electrical man is getting himself into some difficulty with the railroad people when he talks about cost and the little refinements connected with the efficiency of operation. I made some calculations one time on the electrification of a double-track line, 130 miles long, operating 3000 to 3500-ton trains, at twenty minute intervals throughout the day, at a maximum rating of 0.2 per cent, and found that could be done with 600 volts. The difference in cost between the different voltages was comparatively small, only 2 per cent on the total, and the cost of operation would be only a few per cent. When you realize that the total fuel cost on a trunk line is only five or six per cent of the operating expenses, and you have got to sell electric power to the steam railroad at approximately the cost of fuel when you take over that operation by electric service, you will see that when you come to save five per cent, or ten per cent, even, of this fuel percentage, it is of trifling importance when compared with dependability of operation. That is the primary thing. The railroad man wants something he can be sure is going to operate continuously and reliably, and that is the end to which all efforts at standardization should be directed.

Ernest V. Pannell: If I have understood Mr. Renshaw's conclusions correctly, he is strongly in favor of the motor, insulated for 1200 volts and commutating only 600 as opposed to the motor which operates at a terminal pressure of 1200. Now this operation of two motors in series on a 1200-volt trolley has always seemed to me to represent only half a solution of the high-voltage railway problem. It is expedient where a considerable proportion of the running is on the 600-volt trolley but one usually finds that where interurban cars operate within city limits, the switch over from 600 to 1200 volts occurs at the end of the limited speed area so that the motors take up full speed just as soon as full speed is permissible.

The main problems attaching to the design of high-voltage motors are two; those of insulation and commutation. In constructing a motor which will operate in series with another on 1200 volts, the first problems has to be met. Clearances have to be sufficient to take care of flashover, projections in the interior have to be rounded off and extra slot insulation carried. In a recent instance the slot space factor of a 150-kw., 1200-volt motor worked out at 37.5 per cent whereas the corresponding 600-volt design would probably have a value of 50 per cent: in other words an armature of given size has a capacity 25 per cent lower when insulated for 1200 as compared with 600 volts. Now in making the additional modifications for running the motor direct on 1200 volts the commutator bars have to be increased in number, possibly by 100 per cent and the armature, if a two-turn winding reduced to one turn. Simultaneously however the amperes per motor for a given output are reduced by some 50 per cent this makes it possible to shorten up the commutator by a similar proportion. Although on account of the space required for bearings, fan, etc., it is impossible to add to the core-length every inch saved on the commutator, it will usually be found practicable to increase the core by two to four inches and by this means the armature will carry a greater flux. On the foregoing basis therefore, a motor of given weight will actually have a greater output with 1200 terminal volts than where it is one of a pair designed for working in series on this potential.

As Mr. Renshaw implies, the question of dollars and cents will ultimately settle the maximum voltages for railway operation. We do not run our trains at [illegible] miles an hour because the cost of track maintenance and power for operation would be prohibitive. Similarly an economical maximum voltage will be evolved beyond which the extra cost and maintenance of the equipment will outbalance the economy on the line copper. Because 1500 volts is about the maximum which can be applied to a railway motor commutator in service with reasonably satisfactory results I would set the maximum desirable trolley pressure at 3000 volts in the present stage of the art.

A. H. Armstrong: There are two rather positive statements made in Mr. Renshaw's paper and to bring them freshly to mind I will quote. With reference to the use of 2400 volts the author states "From a general standpoint, however, while the results have been welcome as a contribution to the development of the art, suitable applications for this particular voltage are apparently somewhat lacking." On the next page the author goes on to state, "For heavy traction on the other hand this voltage is much too low to solve the problem in a sufficiently comprehensive way to attract the investment of capital in electrification. Even 3000 volts, while overcoming the latter disadvantage to some extent, does not do so completely." The author then goes on to make the suggestion that 5000 volts direct current be adopted and standardized as the proper d-c. voltage for electrification work.

A number of years ago on the floor of this Institute the suggestion was made to standardize the 15-cycle a-c. single-phase motor system as the standard equipment for steam railway electrifications. At that time not a single 15-cycle a-c. motor was in operation in this country, and but one installation has been made in the many years which have since passed. To-night we have the suggestion that 5000 volts direct current be standardized although there is only one experimental car equipped with 5000-volt d-c. apparatus which has been in intermittent experimental service for a period of a few months.

There are in operation in this country three very extensive railway systems using d-c. motor equipments of 2400 to 3000 volts, and contracts have been let for similar apparatus for two other installations also of some magnitude. In view of these facts it therefore seems pertinent to approach the proposal to standardize 5000-volt d-c. apparatus by asking two questions.

1. What facts are behind the two statements made by Mr. Renshaw in which he broadly discredits 2400 and 3000-volt apparatus as being applicable to main line electrification?

2. What experience is behind the suggestion that 5000 volts be adopted as a standard d-c. potential and what advantages does it offer?

The sweeping statements that 2400 and 3000 volts direct current "are much too low to solve the problem," cannot be accepted without advancing sufficient facts to disprove the economic fitness of the apparatus now operating successfully on three railways and under construction for two more. Especially is this so when one electrification at 3000 volts has a route mileage greater than the combined length of all the electrification thus far completed in this country to date. It is therefore impossible to let go unchallenged the broad statement that potentials considerably higher than 3000 volts direct current must be resorted to in order "to attract the investment of capital in electrification." In the absence of any facts supporting the claim that 3000-volt d-c. locomotives cannot successfully meet the requirements of heavy traction service, it is not out of place to refer to some of the fundamental features of the C. M. and S. P. electrification operating at that potential.

This electrification extends over four steam engine divisions, a total of 440 route miles across three mountain ranges, the Belt, Rocky and Bitter Root mountains, and presents all the problems confronting operation over a broken profile from level track to long sustained grades of 2 per cent. This 440 miles of track is fed from 14 motor-generator substations having an aggregate installed capacity of 59,500 kw. full-load rating. In each of these substations there is one motor-generator set serving as a complete spare so that in normal operation of the road the aggregate substation capacity running is limited to 33,000 kw. The total d-c. load on the 14 substations will probably be less than 14,000 kw., giving a load factor of over 40 per cent of the aggregate running capacity of the substations. This remarkably high load factor is secured by spacing the substations some 32 miles apart as permitted by trolley distribution at 3000 volts direct current. This substation spacing is obtained in most cases with only one 500,000-circular mil feeder reinforcing the two 4/0 contact trolley wires, the exceptions being the 2 per cent grade over the Rocky Mountains and the 1.7 per cent grade over the Bitter Root Mountains, in which locations 1,400,000-circular mil and 1,000,000-circular mil feeder cables respectively reinforce the trolley.

We have then in the St. Paul electrification a good example of what can be done with 3000-volt trolley distribution and the above statement gives evidence that substation spacing is approximately 32 miles, the feeder copper installed is entirely reasonable and furthermore the load factor of the motor generator sets running in the substations under normal service is very good indeed. Furthermore, the 33,000 kw. running in the 14 substations furnish power to 12 main line locomotives and 2 switch engines having a combined continuous rating of 127,000 h.p. or 95,000 kw. which is further proof that the substation spacing is sufficiently great to profit to a large extent in the matter of diversity factor of the several locomotives operating and assigned to each division. A statement of the Butte, Anaconda and Pacific Railway operating at 2400 volts direct current would add further facts to those cited in the case of the C. M. and S. P. and these facts are submitted as substantial evidence that 2400 and 3000-volt direct current are sufficiently high to adequately take care of the demands of main trunk line electrification. The train weight on the St. Paul totals 3500 tons gross including locomotives, and these heavy trains operate against a 2 per cent grade at 15 miles per hour. On the Butte, Anaconda and Pacific trains of 5000 tons gross are being operated against a lesser gradient and the average drop in trolley feeders and ground return on either road will be found to be less than 10 per cent under the average traffic demands and possibly 20 per cent maximum under certain conditions of operation.

It may seem attractive to always consider the use of still higher voltages, but it must be recognized that very high voltages impose their burden of expense and complications upon the motive power and substation apparatus until a point is reached where these costs become so excessive as to more than offset the reduction in feeder copper and other advantages of a high distributing voltage. There is nothing inherently inexpensive in a high-voltage locomotive and there is little saving in the first cost of the entire installation by transferring a certain portion of the initial investment in copper to a corresponding increase in the cost of locomotives which is the result of going to higher potentials.

Referring again to the proposal to standardize 5000 volts direct current, I do not share with Mr. Renshaw the conclusion that this potential is a natural selection or in any way represents the last word in the development of d-c. locomotive equipments Before the decision was made to adopt 3000-volt d-c. apparatus for the C. M. and S. P., exhaustive experiments were carried out at Schenectady with d-c. apparatus operating as high as 6000 volts with an idea of determining if possible the limiting potential of d-c. apparatus. No such limits were discovered, as with the hastily constructed apparatus tested, it was found possible to successfully open 6000 volts on contactors, circuit breakers and fuses assembled for the purpose and furthermore the current used was obtained from motor-generator sets and was of sufficient volume to demonstrate the successful operation of d-c. apparatus at this potential in commercial service. To my mind therefore it is not a question of the feasibility of operating d-c. equipment at higher than 3000 volts, but rather what advantage either in first cost, cost of operation or increased facilities does the adoption of a higher potential offer.

The 5000-volt car fed from a mercury rectifier tube referred to by Mr. Renshaw constitutes a most interesting experiment but in no way forms a sufficiently solid basis for a recommendation to adopt 5000 volts direct current for heavy traction electrification. If facts can be disclosed which will discredit 2400 and 3000 volts direct current then it will be time to consider the initial installation of d-c. apparatus at a higher potential, and its successful performance perhaps in time may lead to the adoption of a general standard d-c. potential higher than 3000 volts. With the facts at hand, however, I see no reason to go to a higher potential than 3000 volts even to meet the requirements of the heaviest kind of trunk line service. In fact there is much more reason to suggest standardizing this potential with the weight of experience behind it than to blindly adopt a higher potential not yet in commercial service on any scale commensurate with the problems to be solved.

Selby Haar (by letter): I should like to have Mr. Renshaw give his reasons for preferring 5000 volts as the standard. Viewed as a multiple of 1200 and 2400 volts it should, apparently, suit him less than 6000 volts, which is derived from 1500 and 3000 volts. Furthermore I do not see that it is obtained by rectification of a-c. voltage or potential any more conveniently than some other potential of the same order of magnitude.

Carl Schwartz (by letter): Mr. Renshaw's paper in calling attention to the successful application for railway operation of direct current of sufficient voltage to compare in economy of transmission favorably with single-phase alternating current suggests a potential of 5000 volts as a standard operating voltage.

Without desiring in any way to detract from the value of standardization, I would like to caution against prematurely adopting a standard high d-c. voltage for railway work.

We have in operation a variety of systems with different pressures so that the ultimate loss on account of lack of standardization should not be materially increased if standardization was deferred until we are able to foresee more definitely what the future will bring us in new developments and experience.

Practically all standards are the result of gradual development to a degree where a further increase in perfection or efficiency is either impossible or unnecessary and it seems questionable whether we have reached this point as far as voltage for electric train operation is concerned. Standardization if adopted too early either means a check in progress or if progress is not stopped standardization automatically fails.

The paper further permits the conclusion that if high-voltage direct current is as successful as it promises to be, the future standard system, if such a thing is possible, has increased chances to be direct current rather than single-phase alternating current.

The writer has refrained from taking part in discussions concerning the relative merits of single-phase alternating current as compared with direct current for electric traction. There is one feature in his mind, however, for many years and that is the difficulties connected with the generation of single-phase alternating current. These difficulties are usually reflected by appreciably higher cost of current and greater chance of disturbances in the generating station.

If these difficulties can be eliminated by the use of direct current, still retaining essentially the advantages of single-phase a-c. transmission, a long step in advance will be made.

The principal reason for the relatively limited electrification of steam railroads is not that steam railroad men have failed to appreciate the advantages of electric operation but rather the fact that so far the investment required for all of the electric traction systems has been so high that it was in most cases hopeless to expect a saving in operating expenses to pay for the additional fixed charges.

Mr. Renshaw's paper indicates that this handicap shows signs of becoming materially reduced.

N. W. Storer: The point in Mr. Renshaw's paper that should appeal most to the railway engineer is the portrayal of the great progress that has been made in the car and locomotive equipments for operation on increasingly high d-c. voltages, culminating in the 5000-volt car equipment that has been in operation during the past year at Jackson, Mich. The operation of this equipment has been a revelation to all concerned and it may be interesting to discuss briefly the main points of interest in it, even though it has been partially described in the technical papers.

The development of this equipment was carried out in pursuance of a settled determination to find, if possible, a limit to d-c. voltage for railway purposes, or at least to see if it is possible to arrive at one which would be high enough to meet the requirements of heavy electric traction in extreme instances, and to do this economically. The development of 5000-volt apparatus was started several years ago at a time when 2400 volts was the maximum d-c. potential that had been installed on any line in this country. It was known that an experimental line was in operation in England at 3500 volts, d-c., but no information concerning it was available at that time. Since then, I have had the pleasure of riding on this 3500-volt car and have inspected the equipment. Owing to limitations in the substation generator; the equipment has been operated most of the time with the motors all in series giving half voltage and half speed. However, the commutation of these motors was excellent at full voltage and practically no trouble had been experienced with any part of the equipment, except the dynamotor which was used for furnishing power for lights, control and compressor.

This experience corresponds closely with that of the 5000-volt equipment, except that the latter has no dynamotor.

Any system of electrification, or any voltage that is applied to the electrification of a heavy traction line, should be suitable not only for locomotives, but for multiple unit cars as well. Since the 5000-volt equipment, which has been in operation, consists of four motors of only 100 h. p. each, this can be safely said to be suitable for multiple-unit car operation. In view of the fact that many of the limitations to the voltage of a small motor are much greater than in a large motor, it would appear that it would be still easier to build larger equipments and locomotives, at least the problems of insulation and commutation should be easier.

From Mr. Armstrong's discussion, it may be inferred that he thinks this is a freak construction. Certainly, the designs of the motor and switch groups are quite different from the ordinary types of motors and switch groups for car purposes. However, a careful examination of the equipment will show that the principles are identical with those of the standard well-known types and that the difference is in appearance only; the voltage between commutator bars is no higher than on the ordinary 600-volt motors; the voltages between the upper and lower layers of the armature winding are no greater than with any 1200-volt armature; the number of field coils is less than on the ordinary four-pole motor; in fact, throughout practically the entire motor, the construction is simpler than that of the ordinary 600-volt motor. Practically all that has to be given special care is the insulation of the armature windings from ground. How well this was done may be inferred from the fact that after the car had run over 30,000 miles, one of the armature leads, leading from the coil to the commutator bar, broke off and a hole about 1½ inches in diameter was burned through the armature hood. This armature stood a test of 12,000 volts a-c. to ground without a sign of distress. The commutation has been as near perfect as that of any 600-volt motor, and while there have been cases

of flashing in the motor, they have, without exception, been due to abnormal causes, such as reversed commutating fields or broken brush-holder cable, and in no case has there been any damage resulting from this.

The operation of the switches with the arc splitters has been so successful that there appears to be no difficulty whatever in designing switches to handle any reasonable amount of power at this voltage. The arc splitters serve to greatly increase the length of the arc, as well as to chill it. The insulation of the switch group was so perfect that although the switch group frames were grounded to the car structure, there was no case of a breakdown in the insulation until after a 44,000-volt transmission line had dropped on the trolley wire. Then a short time later, one switch insulator and one motor armature were grounded.

The auxiliaries are very well taken care of by the storage battery, which is connected between the main motors and rail. Since the operation of the compressor is delayed until the car starts, the battery is not required to furnish very much of the power for the compressor motor which operates from the current through the main motors. The battery absorbs the excess or furnishes any current that is required above the main motor current. The duty on the storage battery is, therefore, very light. Test on this equipment shows beyond question the possibility of operating satisfactorily with 5000 volts in light service. There would appear to be no reason to doubt that it will operate at least as well in heavy service.

As to the question of standardization, I do not think that we need to feel that Mr. Renshaw had any intention whatever of starting out to show that 5000 volts could be at once adopted as a standard. It is a point to aim at, and it certainly seems more logical to undertake the development of apparatus for a voltage which it is recognized would be high enough to handle any kind of traffic with a very economical distribution system, than to proceed by the small steps which have thus far been made. As a matter of fact, it is recognized that 5000 volts would not be at all suitable for standardization if it could not be made thoroughly reliable. It has not, of course, yet received a test under conditions which would warrant adopting it for general use, or to replace other established systems, but it is certain that a new "bogie" has been established, and it is a voltage beyond which it appears scarcely worth while at this time to go. To be sure, this same equipment was operated at as high as 7000 volts experimentally with entire satisfaction, but this simply shows the factor of safety which the present equipment has.

There has been some doubt expressed by several of the speakers as to the economy of any higher voltage than 3000. The answer to this question depends solely on the cost of substations and locomotives. If the increase in the cost of locomotives is going to be a large percentage of the cost of 3000-volt locomotives, the limit would be very soon reached, but this depends entirely on the type of locomotive that is adopted, and the use of the twin-armature bi-polar motor places a very different light on this question of cost from what would appear with the older forms of motors. As a matter of fact, it appears that the additional cost of a locomotive designed for 5000 volts over that for 3000 volts will be a very small percentage of the total cost, while the decrease in the cost of substation and feeder copper will be a very considerable proportion. It, therefore, seems inevitable that a higher voltage than 3000 will be utilized in the near future, and whether this voltage will be 5000, 4200 or 6000, is, to a certain extent, immaterial.

The advantage of a standard which can be adopted by universal consent is so great that I feel that every effort should be made to reach one at the earliest possible date. If we can get together and decide on something which we feel will be proper and fundamental, as Mr. Townley has expressed it, we will be doing far better than by trying so many steps along the line.

In a paper which I recently presented in England, I stated that in a country where there is an autocratic government, one man can decide on what is going to be the standard. In another country, where there is absolute independence and individual initiative, there may be a hundred different things proposed and used to accomplish the same purpose. In the first case while the man may not decide on the best system, it would probably nevertheless operate more satisfactorily than in the latter case where there are so many different schemes, because the cost of manufacture in the first case will be very much less and everyone will become familiar with the one system and kind of apparatus, and the operation will undoubtedly become satisfactory even though there may be some other system which would have been a little cheaper under the same conditions. At present, we are required to design apparatus to meet many different systems which are really intended to perform the same work. In this way, the cost of development and manufacture runs up to an enormous figure, which the operating companies must eventually pay for.

Mr. Sprague has, as usual, given a spicy addition to the discussion of the paper, although one must search a long time before finding wherein it applies to the subject under discussion. It would appear that he assumes from the fact that Mr. Renshaw, who represents the company which has been responsible for practically all of the successful single-phase installations in this country, has presented a paper outlining the possibilities of high-voltage d-c. apparatus, that the single-phase system is, therefore, dead. A little further investigation of the question will prove to Mr. Sprague's satisfaction that the single-phase system is very much alive.

Mr. Sprague has quoted one of my previous statements in regard to the influence of cost on the system of electrification.

I still hold that the ultimate decision will be based on the first cost and the cost of operation, provided the systems are equally reliable. It is certain that reliability is going to be a prime factor, but reliability is a relative term. There are many things on a railroad which cause delays to traffic. If the number of delays incident to matters entirely apart from the power system is very large in comparison with the number due to the electrical equipment, the question of reliability of the latter becomes of less importance. 600-volt apparatus would doubtless be more reliable than any of the so-called high-voltage or single-phase systems, but the value of the small additional reliability would be far less than the extra cost of electrifying a long line with this voltage.

C. Renshaw: Mr. Sprague's principal point of disagreement, if I understand him rightly is that my simile was somewhat overdrawn, when I asserted that it was practically a universal belief, ten years ago, that 600 volts was the maximum d-c. railway potential, since even at that time he had predicted some of the things which have now come to pass. Aside from this minor point, however, I judge from his remarks that he agrees substantially with the ideas I have expressed.

Mr. Davis points out that with a given train unit the problem of distribution is simplified as the number of tracks increase. A certain minimum size of trolley wire must be used over each track for mechanical strength and with two or three or four tracks, the combined conductivity of the several trolley wires and of the various rails in parallel necessitates a less amount of auxiliary feeder than if only a single track were electrified. Stated in another way, with a fixed amount of auxiliary feeder, the greater the number of tracks the lower the voltage which can be used with a given economy of distribution.

While it might be inferred from Mr. Davis's remarks that in view of these facts, he would advocate selecting the voltage for any given electrification according to such circumstances and thus perhaps using 1200 volts in one case, 1500 volts in the next, 2400 volts in a third, 3000 volts in a fourth, etc., I believe that he merely wished to call attention to the principle rather than to advocate such a multiplicity of voltages for future heavy electrifications.

Mr. Davis states also, that since motor-generator sets and synchronous converters are usually designed to stand three times normal load for short periods, there will be no saving in the total amount of substation apparatus by increasing the load factor beyond 33 per cent. This analysis, however, overlooks the fact that the machines which have been designed to stand three times normal load have been made in this way to suit the loads which they must carry and not because such designs give the most desirable or the least expensive machines.

Finally, Mr. Davis states that as a rule the cost of the locomotives for any given electrification will approximate one-third of the total cost and that if there is a material increase in the cost per locomotive for a higher voltage as compared with a lower one, this increase might prove the determining factor. This fact is so obviously true that I thought it unnecessary to mention it. The cost of equipments for 1200 volts, however, is but little more than that of similar ones for 600 volts. Presumably, also, the cost of locomotives for 3000 volts has not proved materially greater than that of equivalent ones for 2400 volts. It seems probable from careful estimates that in view of the improved types of construction that are available, locomotives for 5000 volts can be built so as to cost but little more than if made for 3000 volts, and all of the statements in the paper with regard to the use of 5000 volts have been based upon this idea.

Mr. Potter agrees that my comments on the unfortunate circumstances that have given us electrifications at *both* 2400 and 3000 volts are in the main well taken, and this broad-minded position on the part of a man of Mr. Potter's ability and attainments is the most hopeful sign in the entire discussion. With this point appreciated, everyone must surely see the desirability in future of avoiding similar multiplications of voltages as far as possible, and as it was to point out this fact that the paper was primarily written, I feel decidedly encouraged by this statement from Mr. Potter.

Mr. Potter suggests a change in the last sentence of the paper where I said that if 5000-volt apparatus were "commercially available" such and such would be the case. He suggests the words "commercially economic," instead of commercially available. Such a change, however, would not in any way affect the meaning which I intended the sentence to convey, for to my mind, the apparatus which is out of line in cost, is not commercially available.

Another portion of Mr. Potter's remarks which appealed particularly to me was that in regard to the collection of current. After saying that this had seemed to be a great problem and that some years of study had been given to it, he adds "The solution was found to be rather simpler than anticipated." This sentence appealed to me because I believe that some day I will have the pleasure of hearing Mr. Potter, and some of the other gentlemen who have commented upon the paper, use these same words in regard to the employment of apparatus for 5000-volt direct current and the standardization of voltages for heavy electric traction.

Mr. Townley agrees that a potential of 3000 volts is not high enough to hold the field of heavy electric traction, but he is not sure that even 5000 volts will do this. He announces, also, that he is against standardization, seemingly because he believes standardization tends to discourage advances in the art.

With regard to the last idea it seems to me that just the opposite is true. Nothing tends to encourage the development of an industry so much as a semi-permanence and general interchangeability of the apparatus for carrying it on, and no class of apparatus can be really developed on a commercial basis unless its use for a reasonable term of years is assured. I believe therefore that it would be much more encouraging to the art of heavy electric railroading if, instead of employing a little higher voltage in each successive case, where d-c. apparatus is used, some definite voltage, sufficiently high to meet all reasonable requirements, was generally recognized as being standard.

Replying to Mr. Oesterreicher, I had not mentioned storage batteries in connection with high-voltage d-c. roads, since as far as I know it has never as yet been necessary to consider their use seriously on such roads in America. I see no reason, however, why batteries could not be arranged for 5000-volt direct current if this was necessary.

Mr. Wood has made a good point by indicating that it is not so much the *cost* of electrical apparatus as its *worth* which concerns the railroad man, since the cost of the electrical part of the system is a comparatively small part of the total. "The railroad man", he says, "wants something he can be sure is going to operate continuously and reliably and that is the end to which all efforts at standardization should be directed."

It is obvious that if the skill of the various available designers can be constantly applied to perfecting the details of any given apparatus, rather than to changing its fundamental character, the results Mr. Wood is looking for are more likely to be secured. If the railroad man, also, is offered something that is already in use he can be much more certain of the results he will obtain. I believe Mr. Wood's remarks therefore are strongly in favor of the policy I have been advocating, of choosing the right thing for any given class of work as quickly as possible and then sticking to it.

Mr. Pannell, in advocating the use of motors wound directly for 1200 volts rather than of two 600-volt motors in series, in cases where the cars are not required to run at full speed on 600 volts over part of their route, has overlooked one important fact. Where a manufacturer builds motors for operating on 600 volts, as well as for 1200 volts, a considerable investment in drawings, patterns, tools, etc., can be saved by the use of the same motors with minor changes for the two voltages, instead of radically different designs. In arguing that 1500 volts is about the maximum potential which can be applied to a railway motor commutator in service and that to allow not more than two motors in series he would therefore set the maximum trolley potential at 3000 volts, he has apparently forgotten the double armature motor which Mr. Storer described and which with 1500 volts per commutator and two motors in series would permit a trolley voltage of 6000.

Mr. Haar inquires why the particular voltage of 5000 was chosen, since it is not a direct multiple of 600, 1200, or 1500.

In undertaking to produce d-c. apparatus for a voltage high enough to be suitable as a standard for a reasonable period of years, we started to design our apparatus for 4800 volts, or double the value of 2400 volts, then the maximum contemplated. This was later raised to 5000, however, since it had a more euphonious sound than 4800. As a matter of fact our experimental line has been operated at about ~~5300~~ volts and the apparatus was tried on the test track with voltages up to 7000.

I am not particularly concerned with the exact value of the voltage chosen, whether this be called 4800, 5000, 5500, or 6000, since by the term "5000 volts" in the paper, I have intended to include anything in this range. The fundamental point which I have been trying to make, is that *some* voltage in the neighborhood of 5000 should be generally recognized as a standard for heavy electric traction so that d-c. electrifications can be installed with some degree of uniformity, instead of on a basis which will give each one a voltage just enough higher than its predecessor to be different without being sufficiently high to be adhered to in the next case.

Mr. Schwartz is apparently possessed by the same fear which Mr. Townley has expressed, that standardization tends to limit progress. I believe I have covered his points sufficiently in replying to Mr. Townley's remarks.

In referring to the discussion presented by Mr. Armstrong the first thing to be done is to free oneself from the confusion created by his way of grouping 2400 and 3000 volts together as though they were one and the same, instead of being different systems, sufficiently far apart to be entirely distinct and yet so close together that, as emphasized by Mr. Potter, it is unfortunate that we have both of them. Taking up his question, then, as to what has discredited these two systems for heavy electric traction, I would reply that as far as the 2400-volt system is concerned, Mr. Armstrong himself discredited it by ruthlessly abandoning it in favor of 3000 volts when the first real railroad was presented to him for electrification.

As to the 3000-volt system, nothing has as yet "discredited" it. The St. Paul electrification at 3000 volts is a magnificent piece of work, but so is the New York Central electrification at 650 volts, and there is no more reason to suppose now that the former represents the magic limit of voltage for minimum cost than there was a few years ago to suppose the same thing about the New York Central. I believe, in fact, that if Mr. Sprague would hunt up the bibliography with even a small part of the assiduity he has used in preparing his discussion, he could show that only a few years ago Mr. Armstrong himself was just as positive that the 650-volt system was the only rational way to electrify a railroad, as he now is that there is no possible reason for using more than 3000 volts. I have great hopes, therefore, that Mr. Armstrong will keep on raising his voltage and that if we give him sufficient time, it will sooner or later reach 5000. I will hence waste no effort in trying to convince him now.

While it is true that the operation of one 400-h. p. car for 35,000 miles constitutes the sole commercial experience with 5000-volt direct current, this is a much greater experience than was available when the first line was built to operate at a voltage of 1200 instead of 600, or when the first electrification was undertaken using 2400 volts instead of 1200. From this standpoint, therefore, the matter seems in reasonably good shape.

"It may seem attractive", says Mr. Armstrong, "to always consider the use of still higher voltages" but to me it decidedly does not seem attractive and it is in the effort to set others thinking of the obvious disadvantage of such a procedure that all of my energies have been directed. In the period referred to in the beginning of the paper, 600 volts was the established standard for electric railways, so that "an electric railway" meant a 600-volt d-c. electric railway. This particular standardization on 600-volt direct current, was not brought about by action of the A. I. E. E., or any similar body, but by general recognition of the merits of the case by manufacturers and users of the apparatus. It was nevertheless very effective. When it was proposed to build or equip a given line in those days there was no question as to voltage, or system, to confuse the main issue of whether the work should or should not be undertaken, and it was during this period that most of our present city and interurban railways were built.

To establish the same conditions in the field of heavy traction at this time, is of course a much more difficult matter, but there is no question that the advantage to all concerned would be equally great could this be done. It is not my idea that such a standardization could be brought about by any resolution or recommendation of the Institute, and in suggesting the adoption of a standard I had no such action in mind. If standardization comes, it must be by a general consensus of opinion, as in the case of 600 volts, and my real object has been to start such an idea.

Most of the speakers who took part in the discussion seem to have allowed themselves to be misled by the difficulty of the problem. Not seeing any way to bring about such a standardization of voltage immediately, they have felt forced to speak against the necessity or the desirability of it. No great work is ever accomplished, however, without a great deal of thought and planning and dreaming long in advance of the realization, and if I have succeeded in starting some of this thought or planning or dreaming, I will feel that the first steps have been taken.