THE ENGINEERING PROBLEM OF ELECTRIFICATION

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This is an important contribution to electric railway literature, and, owing to the author's reputation, should attract a great deal of attention. He analyzes the three systems which would be considered for main line electrification, viz., the single-phase alternating current, split-phase alternating current, and high voltage direct current systems, and shows the present standing of each as regards their use on important roads. The list of railways using single-phase and high voltage direct current are impressive, and the fact that so many systems originally equipped with single-phase have now changed to higher voltage direct current, and that no high voltage direct current installations have been changed to any other system speaks more eloquently than words for the good inherent qualities of the high voltage direct current apparatus. The illustration showing the comparative size of the split-phase alternating current and the 2400 volt direct current locomotive will speak more convincingly than many paragraphs of text. The efficiency of the different systems is reviewed from many different standpoints. This paper was read before the Canadian Society of Civil Engineers in Montreal on December 18, 1913.—Editor.

The broad question of whether electrification will show an attractive return upon the large capital investment required can best be determined by a detailed investigation of the local conditions obtaining in any given case. Any estimate of a general character is at best more or less misleading when applied to a specific problem. The electric locomotive possesses many operating characteristics not shared by the steam engine and its introduction opens up possibilities in operating methods that may make it desirable to effect sweeping changes in train operation as now carried on with steam engines. Until one or more engine divisions are electrically operated, perhaps we may not fully appreciate what it means to the railway operator to be relieved of many of the limitations of the steam locomotive.

For example, given an electric locomotive capable of hauling an 800 ton passenger train at sixty miles per hour on level track and without assisting locomotives, haul the same train up gradients of 2 per cent at a speed of twenty-five miles per hour, it is possible to make radical improvements in schedule. When it is considered furthermore that such an electric locomotive requires no stops for fuel and water and can operate 1200 miles or more between inspections, it is evident that electrification calls for considerable readjustment of steam railway traditions.

Failure to fully grasp the possibilities of electrical operation may result in running up the first cost of proposed electrification to an extravagant total upon which no adequate return is possible. So much local color is required to intelligently discuss the question of "will it pay to electrify," that no attempt will be made in this paper to discuss the financial aspect of the matter. The several important installations now under construction and the even larger projects upon which favorable decision has been reached, all point to the fact that electrification must be attractive in some instances at least. There are, however, certain fundamental data governing the operation of all electric locomotives and it is the purpose of this paper to discuss some of the engineering questions involved.

At the outset, it is found that the electrical engineer has perfected several types of locomotives and different methods of distributing electric power to them, thus giving rise to what is known as several different "systems of operation." The term "system" is generally applied to the combination of locomotive and trolley or third rail distribution as the question of power generation and transmission is common to all. While it is true that the single-phase and split-phase locomotives call for a supply of single-phase 25 cycle power, it is only in isolated instances that this kind of electric power can be economically generated and used exclusively by the railway company. Large power installations are now so well equipped to give attractive power rates over extended areas and economical electric power production is so completely an industry in itself, that local conditions must be very favorable to justify the installation of a separate power house devoted exclusively to railway load. Even should such a separate installation be made, it may be considered sound engineering to look to future possibilities and install apparatus similar to that in neighboring systems where the frequency and voltage are standardized. Different frequencies are not as serious as conflicting track gauges, but they do involve the burden of expense and loss in efficiency of frequency changing sets which it may some day be found expedient to install in order to tie the two systems together. Hence the statement is again made that the generation and transmission of power offers the same problem without regard to the system of electrification favored.

It is proposed to replace the steam engine with a type of motive power that offers superior advantages in the hauling of heavy trains. In other words, the electric locomotive itself constitutes the main argument in favor of electrification, and no marked excellence of distribution system can offset the failure of the electric motive power. The steam locomotive it is proposed to replace is a highly developed machine of great reliability and the result of the experience born of a great many failures. It cannot be too strongly emphasized therefore that the electric motive power is the controlling factor in main line electrification, a point of view that is sometimes overlooked.

The three electric systems considered for main line electrification are as follows:

1. Single-phase—alternating current.
2. Split-phase–alternating current.
3. High voltage—direct current.

The single-phase commutating motor has been in operation upon interurban electric railways for some years, and a study of the history of these installations reveals some of the fundamental reasons why this type of motive power has not been more generally adopted. It has been found that the initial expense and cost of upkeep of rolling stock equipped with single-phase commutating motors is fully double that of cars having the same seating capacity and equipped with direct current motors. No new installations have been made for the past two years, and the several single-phase roads are being changed over to direct current as fast as financial conditions will permit. Following is a list of the single-phase installations and on those roads starred the single-phase motors have been replaced with the direct current type.

The introduction of the single-phase system was a result of the success of suburban and interurban electric railway operation and the extension of these lines over large areas, thus bringing into prominence the question of economical power distribution. It was recognized that a voltage higher than the com-

SINGLE-PHASE RAILWAY INSTALLATIONS IN UNITED STATES AND CANADA

Name of Railway	Year
Indianapolis & Cincinnati	1904
* Atlanta Northern Ry.	1905
* Illinois Traction Co.	1905
Long Island R. R.—Sea Cliff Division	1905
San Francisco, Vallejo & Napa Valley, California	1905
* Warren & Jamestown	1905
Westmoreland County Traction, Derby to Latrobe, Pa.	1905
Spokane & Inland Empire R. R.	1906
* Toledo & Chicago Ry.	1906
* Anderson Traction, S. C.	1907
Erie R. R.	1907
Fort Wayne & Springfield	1907
* Milwaukee Electric Railway	1907
New York, New Haven & Hartford	1907
* Pittsburg & Butler	1907
Richmond & Chesapeake Bay	1907
Windsor, Essex & Lake Shore	1907
* Baltimore & Annapolis, S. L.	1908
Chicago, Lake Shore & South Bend	1908
Colorado & Southern:	
Denver & Interurban R. R.	1908
Grand Trunk Ry.:	
Sarnia-Port Huron Tunnel	1908
Hanover & York Ry., Pa.	1908
Shawinigan Ry., Quebec	1908
Visalia Electric Ry., California	1908
* Washington, Baltimore & Annapolis	1908
Rock Island Southern:	
Rock Island to Monmouth	1910
New York, Westchester & Boston	1911
Boston & Maine:	
Hoosac Tunnel	1911

*** Changed from alternating current to direct current motors.**

monly accepted standard of 600 volts was desirable upon the trolley in order to minimize the cost of installing feeder copper and substations. While the single-phase motor was being developed and installed upon interurban railways careful attention was also being given to the question of the possibility of using direct current motor equipments at higher voltages and resulted in the installation of the first 1200 volt road, the Indianapolis & Louisville Traction Railway, operated in 1907. The success attending this operation lead to other similar installations at both 1200 and 1500 volts until it is now generally recognized that the high voltage direct current system is without a competitor for all classes of suburban and interurban electric railways. It is a safe prediction to make that no more single-phase motor equipments will be placed in operation in this country on new roads unless these roads virtually form an extension of existing systems.

Following is listed the several high voltage direct current installations in the United States and Canada.

The history of the battle of the systems and the elimination of the single-phase motor as being unsuitable for the equipment of light electric railways has an important bearing upon the selection of systems for main line electrification. The limitations of the single-phase motor that lead to its failure in the interurban railway field do not appear to be lessened when considering it for locomotive equipment with the result that it is in use on but three of the twelve roads that are truly representative of electrified steam roads operating large electric locomotives.

There are other electrified steam lines but the service on them more nearly approaches that of high class electric interurban railways.

HIGH VOLTAGE DIRECT CURRENT RAILWAY INSTALLATIONS IN UNITED STATES AND CANADA

Road	Voltage	No. of Equipments	Date
Indianapolis & Louisville Trac. Ry. Co., Scottsburg, Indiana	1200	13	Oct., 1907
Central California Traction Co., Stockton, California	1200	22	June, 1908
Pittsburg, Harmony, Butler & New Castle Ry., Bidenau, Pa.	1200	30	July, 1908
Washington, Baltimore & Annapolis Elec. Ry., Baltimore, Md.	1200	47	Feb., 1910
Milwaukee Elec. Ry. & Lt. Co., Milwaukee, Wis.	1200	32	Mar., 1910
Aroostook Valley Ry. Co., Presque Isle, Me.	1200	6	July, 1910
Oakland, Antioch & Eastern Ry., San Francisco, Cal.	1200	25	1910
Southern Cambria Ry. Co., Johnstown, Pa.	1200	10	1910
Shore Line Electric Ry. Co., Saybrook, Conn.	1200	22	Sept., 1910
Southern Pacific (Oakland, Alameda & Berkeley Div.), Cal.	1200	82	April, 1911
Ft. Dodge, Des Moines & Southern Ry., Boone, Iowa	1200	29	Sept., 1911
Southwestern Traction & Power Co., New Iberia, La.	1200	3	May, 1912
Oregon Electric Ry., Portland, Oregon	1200	72	July, 1912
Davenport & Muscatine Railway Co., Davenport, Iowa	1200	7	Aug., 1912
Kansas City, Clay County & St. Joseph Ry., Kansas City, Mo.	1500	22	June, 1913
Piedmont Traction Co., Charlotte, N. C.	1500	43	1913
Nashville, Gallatin Interurban Ry., Nashville, Tenn.	1200	6	April, 1913
Butte, Anaconda & Pacific Ry., Butte, Montana	2400	17	June, 1913
United Railways Co., Portland, Oregon	1200	8	June, 1913
Southern Traction Co., Dallas, Texas	1200	30	Oct., 1913
Pittsburg & Butler Ry. Co., Pittsburg, Pa.	1200	13	1913
Pacific Electric (San Bernardino Division), Los Angeles, Cal.	1200	54	Building
Tidewater Southern R. R., Stockton, Cal.	1200	4	1913
Portland, Eugene & Eastern Ry. Co., Portland, Oregon	1500	38	Building
Southern Illinois Ry. & Pr. Co., Harrisburg, Ill.	1200	5	Sept., 1913
Jefferson County Trac. Co. (Eastern Texas Elec. Co., S. & W.) Beaumont, Texas	1200	7	Building
St. Paul Southern Electric Ry., St. Paul, Minn.	1200	5	Building
Michigan United Traction Co., Jackson, Mich.	2400 1200	20 40	Building Building
Canadian Northern Ry. Co., Montreal, Canada	2400	14	Building
Canadian Pacific Ry. Co., Rossland, B. C.	2400	4	Building

All the above roads are operating with the highest degree of success and no change of type of equipment has been made or any such contemplated.

MAIN LINE ELECTRIFICATION—UNITED STATES AND CANADA

Installation	Year	Type Locomotive	System	Voltage
St. Clair Tunnel	1908	Geared	Single-phase alternating	3300
N. Y., N. H. & H.	1907	Gearless	Single-phase alternating	11000
Hoosac Tunnel	1911	Geared	Single-phase alternating	11000
Cascade Tunnel	1909	Geared	Three-phase alternating	6600
* Norfolk & Western	1914	Geared side rod	Split-phase alternating	16500
Baltimore & Ohio Tunnel	1895	Geared	Direct current	600
New York Central	1906	Gearless	Direct current	600
Detroit Tunnel	1910	Geared	Direct current	600
Pennsylvania Terminal	1910	Side rod	Direct current	600
Butte, Anaconda & Pacific	1913	Geared	Direct current	2400
* Canadian Northern	1914	Geared	Direct current	2400
* Canadian Pacific	1914	Geared	Direct current	2400

* Under construction.

Also there are interurban systems where electric locomotives of considerable capacity are operated, but the class of service does not approach the exacting demands of main line passenger and freight operation. The above table, however, comprises converted steam lines where the service consists of hauling main line passenger and freight trains behind electric locomotives of large capacity.

It is a noteworthy fact that the use of the single-phase motor has not extended beyond the two original roads installing this type of equipment, the Grand Trunk and New York, New Haven & Hartford (including Hoosac Tunnel) whereas direct current motors have been universally adopted in all the more recent electrifications with the single exception of the proposed split-phase installation on the Norfolk & Western Railway.

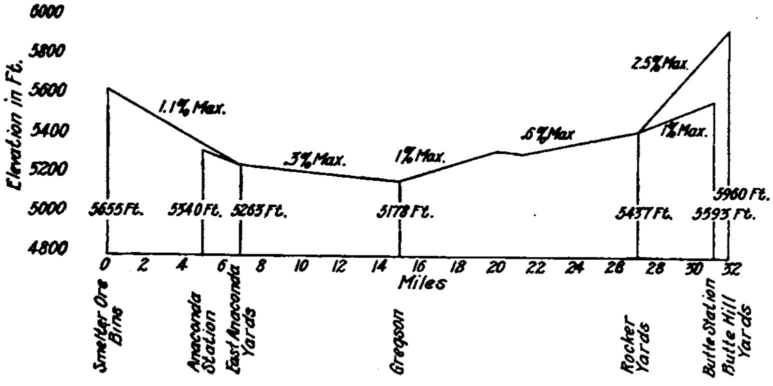

Fig. 1. Profile of Butte, Anaconda & Pacific Railway

The so-called "split-phase" system is a comparatively new comer in the electric traction field and it has not yet been subjected to the test of actual operation. The proposed system offers many attractive features, however, and it is worthy of careful study in order to understand its fitness for heavy electric railway service. From experimental tests made, it seems reasonably certain that the split-phase locomotive can meet the demands of commercial operation with satisfactory reliability.

The split-phase locomotive was first described by E. F. W. Alexanderson, and reference is made to his articles for a full understanding of its underlying principles.*

Confronted with the problem of main line electrification and the demand for a distributing system which would provide for the economical distribution of large units of power over an extended area, the need of higher direct current voltage was appreciated and resulted in the first installation of 2400 volts direct current upon the Butte, Anaconda & Pacific Railway, first operated May 28th of this year. This installation marks an epoch in electric railway progress, as its success offers substantial proof that direct current motor equipments can be constructed at a reasonable cost and operated in an efficient and reliable manner with trolley potentials as high as 2400 volts.

It has been characteristic of the installations operating at 1200 and 1500 volts that

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* A.I.E.E. Proceedings, 1911, Induction Machines for Heavy Single-Phase Motor Service. G. E. Review, October, 1913. "The Split-Phase Locomotive."

the reliability of the direct current motive power has been in no way impaired by reason of using a higher trolley voltage, in fact, the maintenance of 1200 volt motor equipments shows no increase over that of 600 volt equipments. A brush life of over 150,000 miles gives evidence of good commutator performance with practically no wear and the increased insulation and creepage distance provided has been ample to ensure reliability and low cost of maintenance.

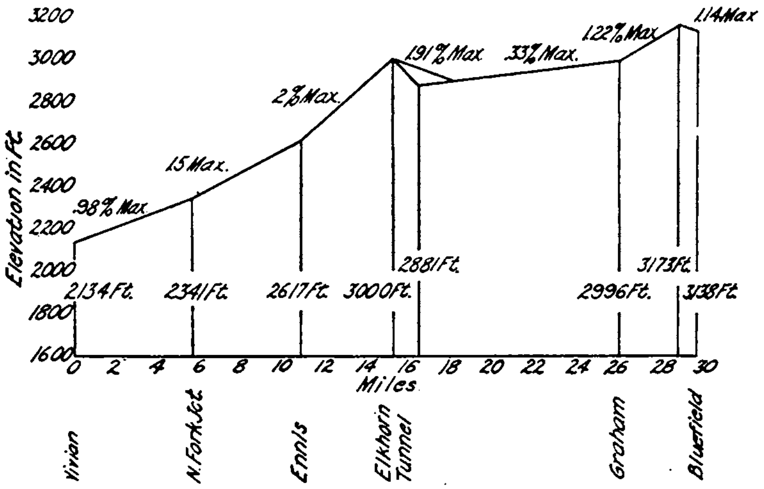

Fig. 2. Profile of Norfolk & Western Railway—Elkhorn Division

The transition from 1200 to 2400 volts direct current has also resulted in completely successful operation at this potential. The operating record of the Butte, Anaconda & Pacific 2400 volt direct current system has been truly remarkable and can best be expressed by quotation from letter published in the Electric Railway Journal by Mr. H. A. Gallwey, General Manager.

"To the Editors:

"In reply to your inquiry I would say that on Oct. 1, 1913, the Butte, Anaconda & Pacific Railway established regular electric passenger service between Butte and Anaconda. For approximately four months previous to this the freight service between East Anaconda yards and the smelter had been handled electrically. During this period electric locomotives have made approximately 55,000 miles and have delivered to the smelter about 1,500,000 tons of ore. Since starting the electric service there has been no failure of any of the electric apparatus and no delay in any way attributable to electric operation.

"The substation at Anaconda has been in continual service twenty-four hours a day with no more than ordinary care and without replacement of any parts. The locomotives have been operated by the steam locomotive enginemen and have been maintained by the regular shop force with the addition of one man experienced in electric operation. They have met every requirement and there has been no failure or replacement of locomotive parts.

"The overhead contact system has been highly successful, and there have been no failures and no accidents. The wear of the contact wire is inappreciable. The original pantograph rollers on the locomotives are still in use and show very slight wear notwithstanding the severe conditions imposed by the smoke and soot deposited on the wire from the steam locomotives during the several months of construction. Our experience up to the present time indicates the complete success of our electrification and justifies the existing optimism and enthusiasm for heavy railroad electrification.

"(Signed) H. A. Gallwey,
"General Manager."

The success of high voltage direct current installations has not been marred by a single instance of failure due to fundamental defect in the type of apparatus used, and justifies the conclusion that the 2400 volt, 1200 volt and the 600 volt direct current equipments are all part of the same general direct current system, and that the only difference is the need of more insulation in one case than in the other. The 2400 volt direct current installation of the Butte, Anaconda & Pacific cannot be looked upon therefore as in any way constituting a new "system" of electrification, but rather as a natural development along the lines of higher voltage of the same well known direct current system which has rendered such excellent account of itself in the past on all our city and practically all of our suburban and interurban electric lines. This has an important bearing upon the general electrification of the steam roads, as it places the status of the direct current system as applied to such service.

Fully appreciating the grave responsibility of selecting a type of motive power for a proposed electrification that holds promise of special fitness for the immediate service contemplated and also is capable of meeting the demands of unlimited future extensions, this paper will briefly touch upon the comparative characteristics of the split-phase and 2400 volt direct current systems of operation. The choice seems to lie between split-phase and direct current inasmuch as the history of the single-phase motor equipment does not seem to justify its further consideration for heavy electric railroading.

The general scheme of distribution to the split-phase locomotive is shown in Fig. 5 which has special application to western railways where 60 cycle power supply is universally standardized. A corresponding diagram of the 2400 volt direct current system is shown in Fig. 6, this also being adapted to 60 cycle power supply.

Starting first with a comparison of the two types of locomotives it is necessary to make some general assumption as regards service conditions in order to draw conclusions as to relative locomotive characteristics. The electric locomotive is capable of being constructed in very large units, but convenience in shopping and simplicity in construction both point to a unit of approximately 100 tons total weight on drivers. These 100 ton units can be coupled together and operated as a single locomotive of any desired capacity, though probably a two unit locomotive weighing 200 tons and giving a starting tractive effort of 120,000 lb. is as large as the draft gear will stand.

Experience with steam locomotive practice seems to point to a locomotive rating on ruling grade that calls for a tractive effort corresponding to approximately 18 per cent coefficient of adhesion on drivers. Thus the conditions obtaining upon a 2 per cent ruling gradient will be as follows:

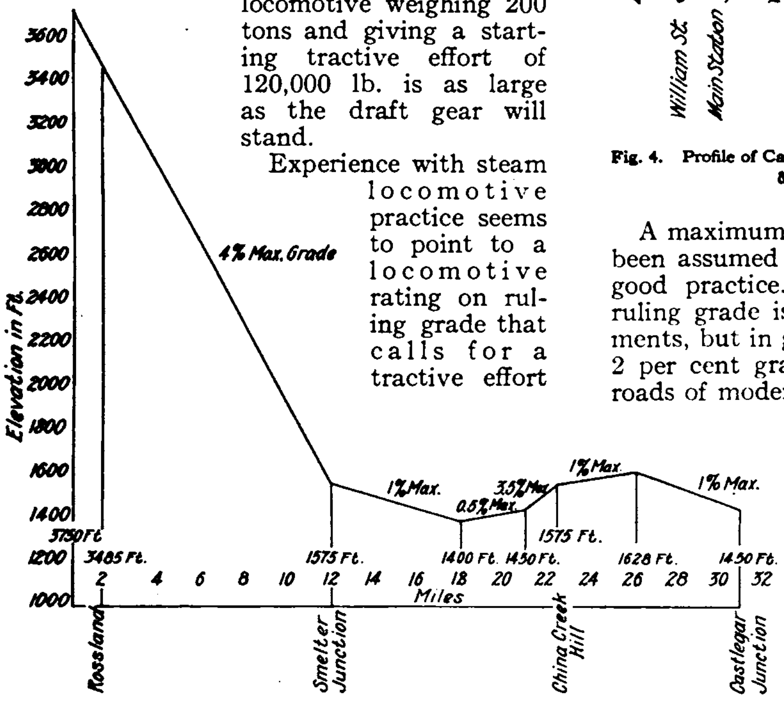

Fig. 3. Profile of Canadian Pacific Railway—Rossland Subdivision

Tractive effort due to 2 per cent grade	40 lb.
Tractive effort due to train resistance	6 lb.
Tractive effort due to curve resistance	2 lb.
Total per ton	48 lb.
Total weight on drivers . .	200,000 lb.
Rating at 18 per cent coefficient of adhesion	36,000 lb.
Gross train weight	750 tons
Trailing train weight . . .	650 tons
Speed	15 m.p.h.
Net output at drivers . . .	1450 h.p.

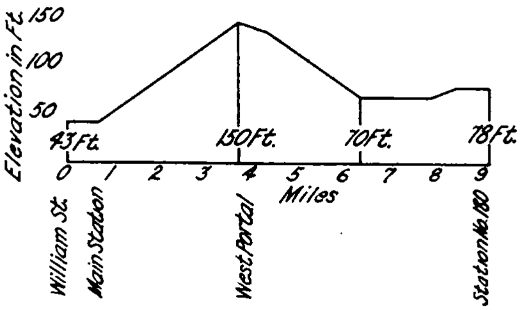

Fig. 4. Profile of Canadian Northern Railway—Montreal Tunnel & Terminal Electrification

A maximum load of 50,000 lb. per axle has been assumed as being within acceptance of good practice. The question of speed on ruling grade is one subject to local requirements, but in general a speed of 15 m.p.h. on 2 per cent grade is as high as desirable on roads of moderate tonnage.

As ruling grade generally extends unbroken over comparatively short distances, it is possible to take advantage of this fact in electric locomotive design and proportion the motive power for a continuous capacity of say 16 per cent coefficient of adhesion without danger of exceeding safe temperature limits in operation. The continuous capacity of the 100 ton unit would therefore be 32,000 lb. tractive effort at somewhat more than 15 miles per hour, based upon 16 per cent coefficient of adhesion of the weight upon the drivers.

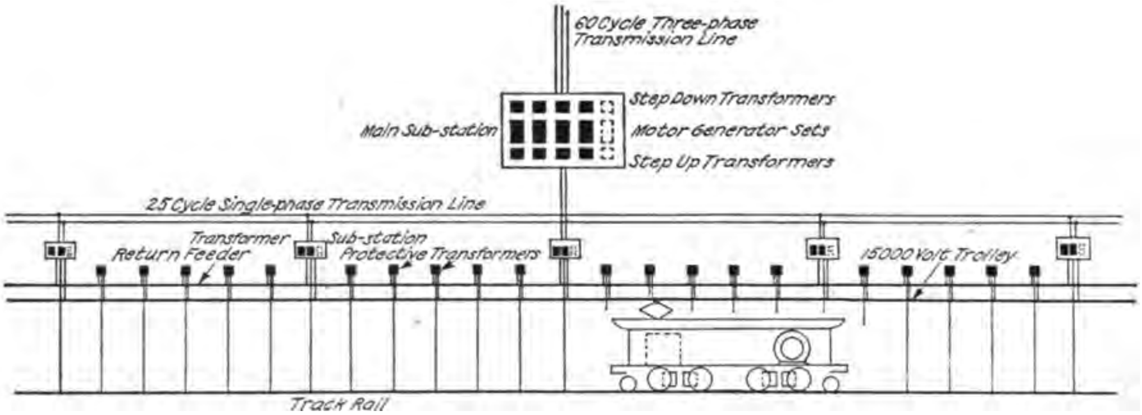

Fig. 5. General Scheme of Split-phase Alternating Current System

Owing to the moderate speeds at which a freight locomotive will operate, it is entirely feasible to consider a construction wherein the motors are geared direct to the driving axles by twin gearing, in this respect following the practice of the Detroit Tunnel, Cascade and B. A. P. locomotive which has proven very successful.

For the purpose of this comparison, it is assumed that both split-phase and direct current locomotives will be of similar construction and employ twin geared motors of equal weight and efficiency. A comparison of weight distribution in the two types of locomotives is presented herewith. See page 69.

As the direct current locomotive of 100 tons carries no ballast, it is evident that the 40,000 lb. comprising the phase converter and transformer of the split-phase locomotive must be carried on idle wheels together with the additional weight of cab and running gear required to carry this excess weight. The net result is a split-phase locomotive of fully 35 per cent more weight than a direct current locomotive of equal capacity and of similar construction. This weight comparison is based upon the assumption that 50,000 lb. per axle constitutes the limit allowable, thus forcing the introduction of guiding axles to carry the excess weight of the split-phase equipment. For locomotive construction of less capacity, permitting the split-phase to come within axle weight limits, both types of locomotives would comprise four axles with no guiding wheels and the split-phase locomotive may not total more than 20 per cent more weight than the equivalent direct current type.

It is evident that the split-phase locomotive is not only considerably heavier for equal capacity, but also more complicated and inefficient than the direct current locomotive.

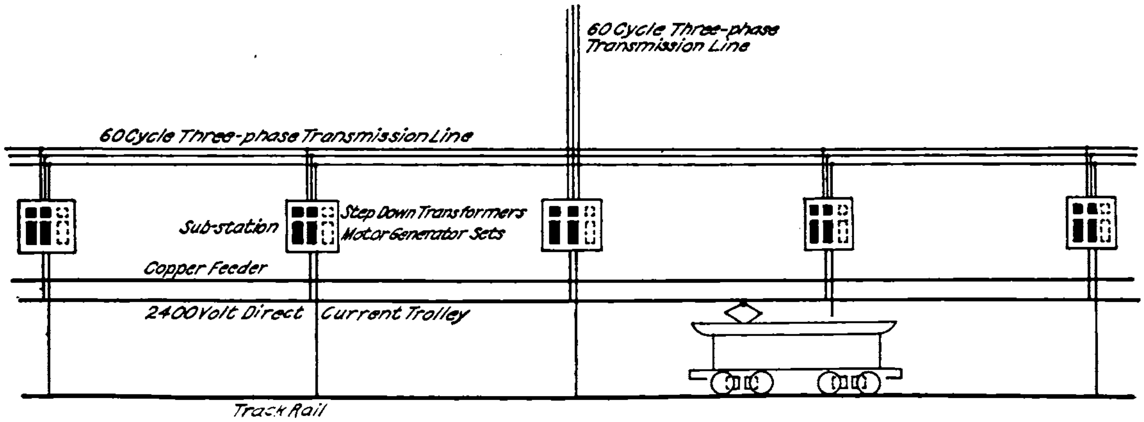

Fig. 6. General Scheme of 2400 Volt Direct Current System

The power from the trolley must in turn pass through transformer, phase converter, control, motors and gears. The efficiency of the complete locomotive in operation will depend upon its output and hence in the following comparison, efficiency has been computed for operation on both ruling grade and level track. The average efficiency of a day's run will obviously lie somewhere between these values, assuming that portion of the run when the locomotive is taking power.

COMPARATIVE WEIGHT OF LOCOMOTIVE
CONTINUOUS CAPACITY, 32,000 LB.–15 M. P. H.

	Split-Phase	2400 Volts Direct Current
Four motors	44,000 lb.	44,000 lb.
Control apparatus complete	17,000 lb.	27,000 lb.
Air compressor	4,000 lb.	4,000 lb.
Air brake equipment	3,000 lb.	3,000 lb.
Miscellaneous	2,000 lb.	2,000 lb.
Phase converter	22,000 lb.	......
Transformer	18,000 lb.	......
Cab and running gear	160,000 lb.	120,000 lb.
Total	270,000 lb.	200,000 lb.

FREIGHT LOCOMOTIVE EFFICIENCY
DETAILED COMPARISON

	SPLIT-PHASE		2400 VOLTS DIRECT CURRENT	
	Ruling Grade	Level	Ruling Grade	Level
	Per Cent		Per Cent	
Motors and gears	89.3	86.0	89.3	86.0
Blower	97.8	95.8	97.9	95.9
Starting resistances	98.6	98.0	99.2	99.4
Phase converter	96.3	94.7	....	....
Transformer	98.0	97.0	....	....
Wheel correction	98.0	98.0	....	....
Weight efficiency	95.0	97.0	....	....
Combined efficiency	75.7	70.5	86.6	82.0
Average of grade and level	73.1		84.3	

Motor and gears are assumed to be of equal efficiency for both split-phase and direct current, as the advantage of one type motor over the other will be small at best and will not materially affect the values given.

Blower efficiency is based upon the fan blower required to cool the motors and auxiliaries taking 30 kw. split-phase and 25 kw. direct current.

Starting resistances consume a portion of the power required to start the train, and efficiency of the locomotive is based upon the assumption that the train is started from rest once in two hours. This starting resistance loss is greater with the split-phase than with the direct current locomotive, being twice as large up to speeds of 15 miles per hour on ruling grade and four times as large up to speeds of 30 miles per hour on level track.

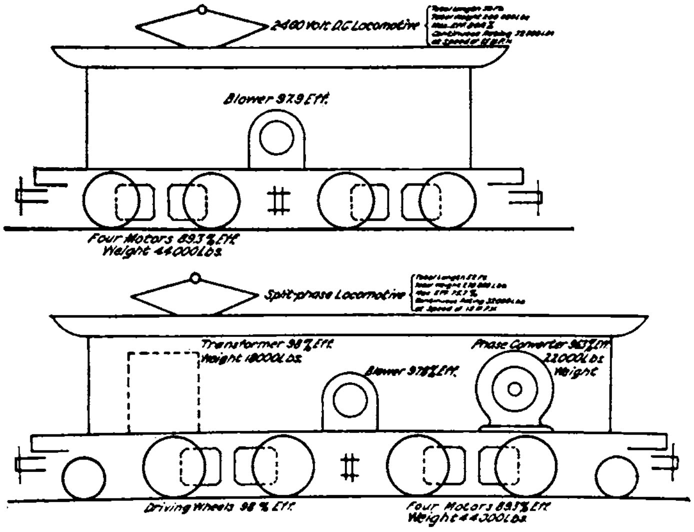

Fig. 7. Comparative Elevations of Split-phase and 2400 Volt Direct Current Locomotives of Equal Capacity

Phase converter efficiency is determined by assuming that the capacity of the converter will approximate 75 per cent of that of the four motors it controls.

Transformer efficiency values given require no comment.

Wheel correction is determined as follows:

Induction motors run at nearly synchronous speed, the slip being proportional to the total secondary non-inductive resistance, hence all wheels upon the same locomotive must be very closely of the same diameter in order to ensure equal loading of the several motors. When one pair of wheels is turned, all must be turned equally. This would not be a very serious handicap were it not for the fact that several locomotives will operate in the same train thus necessitating equal wheel diameters on all such locomotives. It is therefore evident that all locomotives must be interchangeable and any group of two or more be capable of running in the same train or the operating department will be seriously handicapped.

The diameter of new and turned wheels may vary fully 4 per cent, an amount sufficient to cause a prohibitive load distribution between motors. Hence it is proposed to install a variable secondary resistance and so adjust this resistance in the several motor secondaries that all wheel peripheral speeds will conform to the average diameter of new and worn wheels. This will entail an average loss of say 2 per cent when operation has continued long enough to require turning wheels to the minimum diameter allowable. Direct current motors have such a variable speed characteristic as to require no adjustment for varying wheel diameters.

Weight efficiency is a relative value based upon comparison with the direct current locomotives taken at 100 per cent.

COMPARATIVE WEIGHT EFFICIENCY
FREIGHT LOCOMOTIVES

	Split-Phase	2400 Volts Direct Current
Rated t.e. on ruling grade	36,000 lb.	36,000 lb.
Gross train weight	750 tons	750 tons
Trailing train weight	615 tons	650 tons
Per cent trailing to gross	82%	86.7%
Weight efficiency	94.7%	100%

On level track it is assumed that pushing locomotives will be dropped and train weight per road locomotive will be double the ruling grade values. On this basis the split-phase locomotive weight efficiency will be 97 per cent for level track runs. Both values of split-phase locomotive weight efficiency are based upon the assumption that locomotives will be loaded to 100 per cent capacity on ruling grades. As such will not always be possible in regular operation it is evident that the values quoted above will be lower under actual service conditions.

The combined efficiency of the complete locomotive shows that the split-phase freight locomotive will demand 15 per cent more power input from the trolley than a direct current locomotive of equal hauling capacity and similar mechanical drive.

For passenger service it is reasonable to expect the locomotive running gear to be so constructed as to permit maximum speeds approaching 75 miles per hour without danger of derailment or exceeding safe limits of motor and drive construction. Neither of the forms of construction in Fig. 7 are well adapted for very high speeds, and to secure good running qualities it is probably necessary to adopt different types of construction for freight and passenger locomotives however desirable it may be from an operating standpoint to have them interchangeable.

With direct current motors several forms of construction are available that will all operate successfully at high speeds. The most efficient construction is unquestionably to mount the motor armatures upon the driving axles and eliminate the losses, weight and complications of any form of mechanical drive. It is assumed in this comparison that gearless construction will be adopted for direct current high speed passenger locomotives.

The split-phase locomotive motor is of the multiphase induction type and not adapted to gearless construction except by the introduction of quills and springs. This form of construction has not been so successful in operation as to justify considering its general adoption. It is assumed therefore that in order to get a locomotive of good riding qualities at high speeds, it is necessary to resort to side rod drive from a jack shaft and house the motors in the cab. In this comparison it is assumed that motors drive the jack shaft through gears rather than by rods as offering a lighter form of construction requiring less space. The same form of drive is equally available with direct current motors, but gearless construction offers great advantages such as extreme simplicity, accessibility and high efficiency so that comparison will be based upon geared side rod split-phase and gearless direct current motor locomotives.

It appears reasonable to expect the efficiency of mixed passenger and freight locomotive operation to approximate 85 per cent for direct current and not much exceeding 68 to 70 per cent for split-phase locomotives.

PASSENGER LOCOMOTIVE EFFICIENCY
DETAILED COMPARISON

	SPLIT-PHASE		2400 VOLTS DIRECT CURRENT	
	Ruling Grade	Level	Ruling Grade	Level
	Per Cent		Per Cent	
Motors and gears	89.3	83.0	87.5	94.0
Blower	97.8	84.8	97.9	95.5
Starting resistances	98.6	97.8	99.2	99.3
Phase converter	96.3	94.0	....	....
Transformer	98.0	96.0	....	....
Wheel correction	98.0	98.0	....	....
Weight efficiency	92.5	92.5	....	....
Jack shaft	97.0	93.0	....	....
Side rods	97.0	93.0	....	....
Combined efficiency	69.3	54.5	85.0	89.2
Average of grade and level	61.9		87.1	

This efficiency in each case is based upon that portion of the run during which power is delivered to the locomotive. If transformer, phase converter and blower are kept running during coasting periods or when standing, the standby losses thus introduced will seriously reduce the all day efficiency in commercial operation. It is evident that such standby losses are much greater in the split-phase than in the direct current locomotive and the 20 per cent saving in power for mixed freight and passenger service credited to the direct current motive power may be materially increased in actual service.

Before concluding the general discussion of the locomotive it is necessary to touch upon the question of braking. One of the strongest arguments advanced for the adoption of the induction motor locomotive is that this type of motor offers an ideal electric brake by reversing its function on down grade and returning power to the trolley circuit. A regenerative braking method of control has been perfected for use with the direct current motor which offers even greater advantages in service operation than induction motor braking. Just as the direct current locomotive is the more efficient in hauling a given trailing tonnage so also it will return to the system a larger percentage of the mechanical power given the locomotive by the descending train. Hence whatever claims are advanced for regenerative electric braking with the split-phase locomotives are even more applicable to the direct current type.

Referring again to Figs. 5 and 6, showing the general plan of distribution respectively for the split-phase and direct current systems, it is of interest to compare the two in order to see how much of the split-phase locomotive loss is recouped by its more efficient distribution system. The following comparison is therefore submitted.

EFFICIENCY OF DISTRIBUTION SYSTEM
DETAIL COMPARISON

	Split-Phase	2400 Volts Direct Current
	Per Cent	Per Cent
Step-down transformers	97.5	96.5
Motor-generator sets	87.0	81.0
Step-up transformers	97.5	....
Railway transmission line	96.0	96.0
Line transformers	96.0	....
Protective transformers	96.0	....
Trolley, track and feeders	96.0	88.0
Combined efficiency	70.5	66.0

Protective transformers appearing in above table are for the purpose of neutralizing the inductive disturbance caused by single-phase trolley upon neighboring telephone, telegraph and signal circuits.

There is every reason to expect that the split-phase system will demand fully 15 per cent more power input than the direct current system of 2400 volts for equal trailing tonnage movement, actual figures depending upon the proportion of freight and passenger tonnage. This figure is based upon 60 cycle power supply for the reason that many of the immediate electrification projects under construction or contemplated are located in territories where this frequency is firmly established.

TOTAL EFFICIENCY
DISTRIBUTION SYSTEM AND LOCOMOTIVE

	Split-Phase	2400 Volts Direct Current
	Per Cent	Per Cent
FREIGHT SERVICE		
Distribution	70.5	66.0
Locomotives	73.1	84.3
Combined efficiency	51.5	55.7
PASSENGER SERVICE		
Distribution	70.5	66.0
Locomotives	61.9	87.1
Combined efficiency	43.6	57.5

Where 25 cycles is available, single-phase power may be taken direct from the three-phase supply provided phase and voltage balance is maintained by suitably located substations containing step down transformers and phase converters. Direct current supply will be more efficiently obtained through rotary converters in place of motor-generator sets. The efficiency of the distribution system, as given above, will therefore need correction for 25 cycle power supply but will result in no material change in the relative efficiency figures quoted for the two systems.

Installing a power house to generate single-phase current at 25 cycles or less introduces all the serious handicaps encountered in single-phase generation as well as raises questions of general expediency and adequate return on the capital invested in a power plant devoted to supplying railway load only. Advocates of single-phase trolley distribution have sometimes failed to fully consider the question of power supply available as having any bearing upon the broad question of electrification. Not every railway is so situated by reason of character of load, cheap fuel or other favoring local conditions as to justify the large expenditure for a generating station containing ample reserve capacity. The somewhat higher efficiency of the distributing system alone in cases where single-phase power is available is so relatively unimportant that it may be looked upon as a special condition applying only to favored and restricted localities.

A study of the general plan of distribution as given in Figs. 5 and 6 discloses the fact that where 60 cycle power supply is available at attractive rates, the general statement can be safely made that the total amount of electrical apparatus is greater and therefore the first cost higher and efficiency lower with the split-phase than with the direct current locomotive system. Nor is this statement modified to any extent in the event that power supply is obtained from a 25 cycle three-phase source, as it will be the exception rather than the rule that any power company will be found willing to furnish single-phase power from its balanced three-phase circuit when the pernicious effect upon the general distribution system of a violently fluctuating low power-factor single-phase load is fully understood. Some corrective device like a phase converter must be introduced and its first cost and efficiency are both comparable to the rotary converters which are permissible with 25 cycle supply to secure direct current. It would seem therefore that the complication of the split-phase locomotive system renders it inherently more expensive to install and less efficient to operate. This is due largely to the fact that substations containing moving machinery are required both on the ground and also in the locomotive cab itself.

The single-phase trolley circuit, irrespective of the type of locomotive it may supply, constitutes in itself a most serious handicap to the adoption of any type of alternating current locomotive. Neighboring circuits of all kinds are practically put out of commission by static and inductive disturbances unless adequate protective measures are introduced. No method of complete protection has as yet been perfected although many schemes have been proposed that are partially successful. The elaborate and expensive apparatus now being installed upon one of our most important single-phase railways will soon be in operation and it is expected to give relief from the present serious condition obtaining. As the inductive interference of the single-phase trolley is proportional to the intensity of the current and distance it is transmitted, it is to be expected that a maximum disturbance will result in the case of mountain grade divisions where the current input to trains approaching 3000 tons gross weight is several times that thus far met with in any single-phase trolley installation now operating. No cost estimate of single-phase trolley systems is therefore complete without including a liberal allowance for telephone and telegraph protective devices. This cost will probably not be less than $2500.00 per mile of route and may even greatly exceed this figure. Even with such an expenditure, no assurance is at hand that hazard to employees and interference with service will be entirely eliminated, and until more exact knowledge of this whole situation is available, single-phase trolley interference constitutes a most serious handicap to the adoption of any alternating current locomotive system of operation.

This paper is largely devoted to a comparison of alternating and direct current motor locomotives, as lack of appreciation of the fundamental facts involved has perhaps been the basis of the false hopes raised as to the possible advantages resulting from the installation of the single-phase trolley. It surely does look attractive to install a system employing 15,000 volts on the trolley, no feeder copper and no rotating substation apparatus. But investigation and experience discloses the fact that the single-phase trolley is a decided menace to neighboring circuits, feeder copper is required for return circuit, substations are comparable as to first cost and efficiency with direct current substations and finally, the alternating current locomotive of the most promising type, the so-called split-phase combination of induction motors, transformer and phase converter is heavy, expensive, complicated and inefficient to a degree that would not be tolerated in direct current construction. Assuming that the favorable results of factory experiments are borne out in the success of later commercial operation, there appear to be no controlling advantages of alternating current locomotive traction which cannot be secured at less expense and with greater reliability in operation with direct current motive power.

Until the adoption of the inter-pole motor construction made it entirely practicable to build direct current motors for high potentials, there was some justification for considering alternating trolley systems as offering the best means of changing from steam to electric motive power at a reasonable first cost. The high voltage direct current motor has now been developed, built and proven completely successful under the most exacting service conditions. The trolley potential has been raised to 2400 volts which seems sufficiently high to ensure a distribution system of reasonable first cost and not too high to handicap the locomotive as regards its first cost, reliability and operating efficiency. Experimental results already obtained with direct current apparatus tested at potentials higher than 2400 volts indicate that no constructive difficulties apparently exist and the installation of a higher voltage becomes an economic question rather than an engineering problem.

With 2400 volts direct current both protected third rail construction and multiple unit car operation are feasible. The third rail offers advantages in accessibility and low cost of maintenance on single track roads and multiple unit car operation is without question the proper way to take care of local traffic. Furthermore, 2400 volt equipments can be successfully operated upon the lower voltage terminal zone that local restrictions may make necessary.

It is popularly supposed among electrical engineers that the cause of electric traction is retarded by an openly expressed divergence of views as to the relative merits of different systems of electrification. The opinion is advanced on the contrary that a free presentation of the facts available, but not always made public, will do much to clarify the situation. No one contributing cause has done more to hurt the electric railway industry than the failure of the single-phase system to make good the too optimistic claims of its early advocates, and no such open presentation of installation and operating costs has ever been made public on any alternating current installation in operation in this country or abroad, as has been published by Mr. B. F. Wood in a paper before the A.I.E.E. on the West Jersey & Seashore Railway.

This paper has been purposely restricted to a discussion of engineering questions entering into the electrification problem as having a fundamental bearing upon the all important matter of first cost and cost of operation. Such estimates are readily prepared for any local conditions obtaining provided there is no serious conflict of engineering opinion regarding engineering details as exist today. The direct current motor is fully able to meet all the requirements of the heaviest passenger and freight train operation as proved by the entirely successful installations now running and which afford the convincing facts upon which statements of cost and operation are based. No such condition exists with any alternating locomotive system and such operating facts as are obtainable are not of such a nature as to inspire confidence in selecting such a system to meet the exacting requirements of heavy electric railroading. The engineering facts presented herewith are offered with the purpose in view of clearing the engineering atmosphere preparatory to the serious work that seems to lie immediately before us, that is the problem of where and to what extent it will pay to replace the steam engine by the electric locomotive.