THE STORAGE-BATTERY IN SUBSTATIONS.

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The rapid development of interurban electric traction has brought with it a new field for the economic utilization of the storage-battery. Inasmuch as in interurban electric traction it is the practice to develop the energy for the operation of any one system in one or two large generating stations and to distribute this energy to the trains through the medium of substations, in these substations the storage-battery has found a place as an equalizer. The function of the storage-battery is here to take care of the heavy loads or of the peaks of the demands which are made on the substations by the trains; and by absorbing energy from the central station at times of low demand, to smooth out the central station load line, filling up the hollows and cutting off the peaks.

The present paper deals with tests which were made on a large interurban system equipped with nine substations, and the data accumulated shows in a variety of ways the character of the demands which the storage-battery has to meet in substation practice. The data may be said to reveal as many of the faults as of the benefits of the storage-battery in substation practice, and as the intent of all of our engineering investigations is to improve conditions of operation, the faults which have been detected may prove as valuable from having been brought to light as are the measures which are given of the work done by the storage-batteries in improving the general economy of the system.

The tests described were made during the spring of 1902 on

the system of the Union Traction Company of Indiana. This company was organized June 28, 1899, and is the consolidation of the Union Traction Company of Anderson, and the Muncie, Anderson and Indianapolis Street Railway Company. Later by the purchase of the local lines of Marion and the building of inter-

FIG. 1.

urban lines the system has been extended until at the time of the tests it was operating over 160 miles of city and interurban track. About 110 miles of this is interurban road connecting the principal cities of the Indiana gas belt and its location is shown by the

chart of Fig. 1, in which diagrammatical representation is given of the transmitting and distributing lines which connect the distributing substations. At the present time this system is greatly extended over what it was at the time of the tests and represents the greatest interurban property in the world. The main power station at which all the power for the entire system is generated is located at North Anderson, adjacent to the interurban line. The substations have been installed at Lawrence, Ingalls, in the main station at Anderson, at Daleville, Muncie, Alexandria, Fairmount, Marion and Elwood.

At the central station the generators deliver electric energy to the load bus-bars at 400 volts. It is then stepped up to 16,000, and transmitted at this potential to the substations, where it is stepped down to 330 volts. Rotary converters then transform the energy from alternating at 330 volts to direct current at 550 volts, the latter being the pressure used on the trolley system. The substation at Ingalls is 15 miles from Anderson, that at Lawrence 28½ miles. These substations receive energy from the same high-tension feeders. The substation at Daleville is 9 miles and that at Muncie 18 miles from the central station. These two stations are also on the same set of high-tension feeders. Alexandria is 11 miles and Fairmount 21 miles from the central station; the substations at these points receive energy from the same set of high-tension feeders. Marion, which is 33 miles from Anderson, and Elwood, which is 21 miles from Anderson, have substations receiving energy in part over the same high-tension feeders. The feeder system supplying these stations branches at Alexandria, one section continuing north and the other due west.

The several sets of high-tension feeders consist of three No. 5 bare B. & S. wires. The substation equipment at Anderson consists of three 250 k.w. rotary converters, a 20 k.w. booster unit and a storage-battery of 264 chloride cells having a one hour capacity of 400 amps. and an 8-hour capacity of 100 amps. In this substation a portion of the low potential current from the main generators is led to the rotary converters through auto-transformers instead of through the fifteen 250 k.w. static step-up transformers. Of these 15 static step-up transformers only 12 are kept in service, the other three being a reserve. The substations at Lawrence, Ingalls, Daleville, Fairmount and Elwood are each equipped with three 87.5 k.w. static step-down transformers, one rotary converter of 250 k.w. capacity, a battery of

264 chloride cells, having a one hour capacity of 160 amps. and an 8-hour capacity of 40 amps., and one 8 k.w. booster. The remaining substations, namely, those at Muncie, Alexandria and Marion are equipped with four 175 k.w. static step-down transformers (one being held in reserve), two 250 k.w. three-phase rotary converters, one 16 k.w. booster unit and a storage-battery of 264 chloride cells, having a capacity of 320 amps. at a one hour rate and 80 amps. at an eight hour rate.

The high-tension lines both at the central station and the substations are protected by high-tension lightning arresters and the static transformers are oil-cooled.

A portable substation, equipped with three 87.5 k.w. static step-down transformers, one 250 k.w. rotary converter and a switchboard, has been built for use in case of an emergency arising from accident to one of the rotary converters, or for temporarily increasing the capacity of any one of the established substations. Track has been laid into the substations so that this portable substation car may be run directly into any one of the converter rooms and its rotary leads connected to the direct-current line in the same manner as are the regular substation machines. At the time of the test the portable substation was in use at Marion, increasing the capacity of the Marion substation, where the load was temporarily in excess of the rated capacity of the equipment. The substation buildings are all of the same construction. In addition to the equipment just specified, the substations contain switchboards of white marble, which consist of one A.C. panel and one D.C. panel for each rotary installed, two battery and booster panels and one D.C. panel for each feeder leaving the station. The station instruments are mounted on the switchboards and consist of three A.C. ammeters, one in each leg of the three-phase lines, one D.C. ammeter, voltmeter and wattmeter for each rotary, one D.C. ammeter and voltmeter for the battery and one D.C. ammeter for each D.C. feeder panel. Automatic circuit-breakers and lightning-arresters are provided for outgoing lines.

The substations were equipped with recording wattmeters, in addition to those permanently mounted on the switchboards. These are indicated in Fig. 1. For instance, the substations at Ingalls, Lawrence and Daleville have a switchboard recording wattmeter (*r*) which registers the rotary output, and a temporary recording wattmeter (*c*) for registering the battery charge and a temporary recording wattmeter (*d*) for registering the

battery discharge. The wattmeters (*c*) and (*d*) were controlled by a switch which connected the pressure-coil of the wattmeter (*c*) in circuit when the battery was charging and connected the pressure coil of the wattmeter (*d*) in circuit when the battery was discharging. A special observer controlled the position of this switch in accordance with the indications of the battery switchboard ammeter. At Anderson one switchboard recording wattmeter (*r*) registered the output of the three rotaries, the battery charge and discharge being determined by two wattmeters in the same way as at Lawrence, Ingalls and Daleville.

As the Anderson substation supplied power to the local lines in addition to the interurban lines, two special wattmeters (*f* and *g*) were placed in the feeders extending east and west from Anderson. At Muncie two switchboard recording wattmeters are supplied for determining the output of the two rotaries in this substation. The battery charge and discharge was determined by two recording wattmeters (*c* and *d*) as at Lawrence, Ingalls and Daleville, with the addition of the recording wattmeter (*e*) which was permanently connected in the battery lead so that it ran forward when the battery was charging and backward when the battery was discharging. The recording wattmeter (*f*) placed in the interurban feeder registered the amount of the output of the Muncie substation which was delivered to the interurban cars. This substation also supplied the cars of the local line with power. At Elwood and Fairmount the rotary output was determined by the switchboard recording wattmeter (*e*) permanently connected in the battery lead. At Alexandria the same conditions existed as at Elwood and Fairmount except that two switchboard recording wattmeters are provided for determining the rotary output. At Marion the same conditions obtained as at Alexandria except that an additional recording wattmeter (*p*) was placed in the portable substation to determine the output of the rotary. In all, therefore, there were twelve switchboard recording wattmeters in use for determining the output of the rotaries and one temporary recording wattmeter for determining the output of the portable substation rotary. Fifteen temporary recording wattmeters were used for determining the charge and discharge of the storage batteries and three special feeder recording wattmeters for determining the proportions of the output of the Anderson and Muncie substations which were delivered to the interurban feeders.

During the tests the d.c. instruments which have been men-

tioned, except the feeder ammeters, were read in all of the substations every fifteen minutes. Simultaneously with these readings a polyphase recording wattmeter, which registered the central station output, was read and readings were also taken from recording wattmeters placed in each one of the interurban cars plying between Indianapolis and Muncie.

All of the instruments used in the test were carefully calibrated by being compared with standards. The method of calibrating the recording wattmeters was as follows: the time was taken during which a certain number of revolutions of a wattmeter-disc were made, while during the same time rapid observations were made of the current and voltage fluctuations. From the latter the average of the current and voltage during the time the revolutions of the wattmeter disc were being made were determined. The constant of the wattmeter is found by the formula:

$$K = \frac{\text{Watt hours}}{\text{revolutions}} = \frac{E \times I \times T}{3600 \times R}$$

Where E is the average voltage,

I the average current,

T the time in seconds,

and R the number of revolutions of the disc.

The wattmeters were all calibrated while connected in with the service lines. The constants determined for many of the wattmeters differed widely from those given by the manufacturers. This is probably due to the fact that in many cases the wattmeters ran far below their rated current capacity. This was unavoidable on account of the fact that the capacity of the wattmeters had to be sufficient to take the peak loads. Where the wattmeter was permanently connected in the storage battery leads, as at Muncie, Alexandria, Fairmount, Marion and Elwood, so that it ran both forward and backward, the instrument had to be calibrated for both methods of operation. It was found that the constants of these instruments when running forward were quite different from the constants of the instruments when running backward.

The polyphase wattmeter at the power house was also calibrated, and as the calibration showed its error was probably not greater than those of observation, its readings were assumed to be correct.

EFFICIENCY OF HIGH AND LOW-TENSION DISTRIBUTION LINES.

The arrangement of the high-tension feeders between the

central station at Anderson and the several substations has already been described. In determining the efficiency of the high tension distribution system recourse is had to the central and substation records. In Table I. the total outputs of the rotaries in the different substations for the different days of the test are recorded. In Table II. that part of the total output of the main generating station at Anderson is recorded which was delivered to the primary windings of the high-tension transformers. These values are equal to the total output of the generating units as given by the recording wattmeter on the load panel, less the power taken from the primary bus-bars by the rotaries located in the generating station. Table II. also records the total power delivered to the low-tension feeders by the substations which derived their energy from the high-tension system. The d.c. output of Table II. is therefore the sum of the readings of all the rotary wattmeters less the output of the rotaries in the Anderson substation, as these were fed directly from the generating station bus-bars through auto-transformers and not through the high-tension lines. The all-day efficiencies obtained run very close together, averaging $73\frac{1}{2}$ per cent.; this is the efficiency of the high-tension distribution from the low-tension bus-bars in the generating station to the direct current terminals of the rotaries.

In determining the efficiency of the high-tension transmission lines, the amount of energy lost in the raising and lowering transformers, as well as in the rotary converters, had, of necessity, to be determined. The transformers were not worked up to their full capacity; the load on the single, or A and E. stations, Fig. 1 averaging about 40 per cent., the load on the Muncie station averaging about 34 per cent. and that on the Alexandria and Marion stations but 30 per cent. of the total full load capacity of the transformers. By an inspection of the transformer efficiency curve supplied by the manufacturers, it is estimated that the average efficiency at which the transformers worked is not far from 95 per cent. and, as recorded in Table IV., this value has been used. To obtain the average working efficiency of the rotary converters, a special test was made on the rotaries in the Alexandria substation, beginning on April 27th and ending on April 30th. In arranging for this test an alternating current recording wattmeter was connected in each of the three alternating current leads of one of the rotaries. The sum of the readings of these wattmeters gave the rotary input, while the output was given by the regular direct current station recording wattmeter:

the instruments were read every hour. From these two sets of readings the efficiency was estimated by determining the ratio of the output to the input of the rotaries over selected periods of one, six and twelve hours; the results of these efficiency determinations are given in Table III. and plotted in Fig. 25. It will be observed that the load on the rotary under test varied from 23 to 54 per cent. of the capacity of the rotary, and that the average of the efficiency record is practically 88 per cent.; and since all of the rotaries installed are identical in design and construction, it may be safely assumed that the efficiency as determined above for one rotary is applicable to all the rest of the rotaries. Further, the average load on the substations varied between 30 and 40 per cent., of the capacity of the rotaries in the several substations, and, therefore, the records in Table III. show that the rotary under test was subjected to an average degree of loading. The figure, 88 per cent., has been used, as recorded in Table IV., in determining the energy lost in the rotaries.

Having the transformer and rotary efficiencies estimated with a fair degree of accuracy, it was a simple matter to determine the input to the high-tension line from the input to the step-up transformers, and the output from the high-tension line from the output of the rotaries. Taking the ratio of these values we find that the average efficiency of the high-tension distributing system is 93 per cent., being practically constant for the three days. This result indicates that the efficiency of the high-tension system in operation is somewhat less than the efficiency for which it was calculated. When installed it was estimated that the high-tension lines would absorb 7 per cent. of the energy transmitted when the system was working under full load; inasmuch as the average load was not in excess of 40 per cent. of the capacity of the system, the efficiency shown by the test is lower than what would be expected.

In determining the efficiency of the low-tension distributing system, the ratio is taken of the total power delivered to the cars to the total power delivered into the low-tension feeders from the substations. The determination of the amount of power supplied by the substations to the low-tension distributing system is given in Table V. Owing to the fact that it was only possible to equip the interurban cars plying between Indianapolis and Muncie with the recording wattmeters, the efficiency of only this portion of the low-tension transmission system was made. On account of the fact that the Muncie substation supplied the

power for the local cars in Muncie, it was necessary to install a special recording wattmeter in the interurban feeder from the Muncie substation. The Anderson substation also supplied power for the operation of the local cars in Anderson; and accordingly a wattmeter had to be placed in the feeders which run East and West from the Anderson substation supplying power to the interurban cars.

Circuit-breakers were inserted at the city limits in Muncie and in Anderson. This arrangement effectively prevented any error entering into the efficiency determinations, inasmuch as the wattmeters on the interurban cars were read whenever these circuit-breakers were passed. In determining the power delivered to the low-tension distributing system from the substations, the battery charges were in each case subtracted from the sum of the rotary outputs and the battery discharges, except in the case of the Anderson and Muncie substations where the results were obtained directly from the feeder wattmeters. The results of the efficiency determinations show that the efficiency of the low-tension distribution system over the Anderson-Muncie division is about 5 per cent. higher than that over the Indianapolis-Anderson division. The loss of the former amounts to about 22 per cent. and that of the latter about 28 per cent. of the energy delivered to the low-tension feeders. The average efficiency of the low-tension transmission for the three days of the test over the Muncie-Indianapolis lines was $74\frac{1}{2}$ per cent., which shows a loss in the distributing system of $25\frac{1}{2}$ per cent. of the energy delivered by the substations to the feeders.

STORAGE-BATTERY TESTS.

Having obtained a fair understanding of the conditions which existed over the system, we can now profitably turn to the records which were made of the storage-battery performances in the various substations. The connections in the substations are shown in Fig. 26. From these it will be seen that the booster is so connected in the battery circuit as automatically to adjust the battery voltage to the demand on the substation; in other words, the battery charges and discharges automatically, feeding out to the line when the demand is above a given amount, and being charged by the rotaries when the demand falls below that amount. The potential at which the battery will float on the system, or the demand on the system corresponding to which the battery is inactive, can be adjusted at any desired point by the switchboard attendant; this fact is to be remembered in connection with the data which is presented.

Prior to the main test, a special test was made of the storage-battery in the Ingalls substation on the 23d of March, 1902, between 8:15 A.M., and 8:00 P.M. The record of the rotary output during this time is given in Fig. 2; the battery current and the battery and line voltage are not plotted in Fig. 2, but these quantities are given in Fig. 3 for the period of the test between 5:00 and 7:00 o'clock. The results are plotted to a much larger time-scale in Fig. 3 than in Fig. 2 and more perfectly show the load variations.

The records in Fig. 2 are given to show the load cycle on the Ingalls substation. The cycle is caused by the manner in which the local interurban cars and the limited interurban cars pass the substation. At the even hour the local interurban cars running both East and West are so far from the station as to make but a slight demand upon it for power; however, at twenty-five minutes past the hour a local interurban car passes going East and at thirty-five minutes past the hour another passes going West; this cycle was repeated each hour. The limited interurban cars approach and pass the station just before and just after the even hours every third hour, *i.e.*, at five minutes to twelve a limited car passes the station, going East, and at five minutes past twelve a limited car passes the station, going West at five minutes to three another limited passes the station, going East, and at five minutes past three a limited passes the station, going West. By the letters I E for the local interurban going East and I W for the local interurban going West, by L E for the limited interurban going East and L W for the limited interurban going West, the times at which the interurban cars pass the Ingalls substation are indicated on Fig. 2. It will be noted that the points of maximum demand usually fall about the time (according to the schedule) the cars should be passing the substation.

The maximum capacity of the rotary of this substation is 500 amperes, and it will be noted that the load on the rotary during the twelve-hour test rarely exceeded this maximum amount, the average load being between 200 and 250 amperes. The readings from which these curves are plotted were taken with great care, Fig. 2 being plotted from readings taken at thirty-second intervals and Fig. 3 from readings taken at fifteen-second intervals. In Fig. 3 the battery current and the rotary current are shown by full lines. The algebraic sum of the battery and rotary currents give the dotted line which crosses the rotary current line; this

dotted line shows the total demand on the substation by the trains. The line voltage is shown by a full curve at the top of the chart, the dotted curve being the battery voltage. The maximum discharge rate for one hour of the battery in the Ingalls substation is 160 amperes. The maximum demand made upon the battery in one instance was as high as 270 amperes and in another ran up to 175 amperes; in general, however, the demand upon the battery was not especially heavy, not often exceeding 100 amperes, and, frequently for a considerable period of time falling within the eight-hour discharge rate of 40 amperes. The greatest instantaneous demand on the station recorded in Fig. 3 occurred at 6:55 P. M., when the load momentarily ran up to 700 amperes. The accuracy of the results plotted in Fig. 3 is indicated by the fact that when the battery is discharging the battery voltage always drops below the line voltage, and, that when the battery is charging, the battery voltage runs above the line voltage.

The curves of Fig. 3 have been made chiefly useful in determining the "*efficiency of equalization*," of the battery in this substation. The efficiency of equalization designates the extent to which a storage-battery is successful in maintaining the demand on a rotary converter or generator at the true average of the load under the variable conditions of service. If a line be drawn that represents the average load on a station and the rotary load curve coincides with it, the battery may be said to have an "*efficiency of equalization of 100 per cent.*"; *i.e.*, it performs its function as an equalizer perfectly. On the other hand, if the rotary curve follows the line load-curve, the battery is obviously inactive, and, therefore, its efficiency of equalization is zero. The efficiency of equalization may then be defined as the ratio of that portion of the rotary load-curve that is above the average load curve to that portion of the line load-curve that is above the average load-curve. In the present instance the efficiency of equalization of the battery works out to be 11.9 per cent.; *i.e.*, the battery only reduces the irregularities in the demand on the substation from the line by 11.9 per cent of what the demand on the rotaries would be if the battery so equalized the load that the rotaries worked constantly under a load equal to the average of the variable demand made upon the substation by the cars.

The result of these considerations indicates that the adjustment in the substation was somewhat faulty; the booster and battery are not so arranged as to enable the battery to respond with sufficient promptness in taking care of variations in the load

which occur. It is not a case of the battery not having sufficient capacity for the duty which it is called upon to perform, as the maximum variations in the load seldom exceed 250 amperes and more frequently run within 150 amperes. No attempt was made to remedy the faulty action of the booster set, as until the recorded data could be worked up no estimate could be made of the performance of the battery in this particular.

In order to determine the duty performed by the boosters in the substations, a determination has been made from the readings taken in the Lawrence substation during the main test of the average amount of boosting done by the booster during each of the three days. On the first day, April 17th, the line voltage averaged 15.5 volts higher than the battery voltage; on the second day, the line voltage averaged 31 volts higher than the battery voltage and on the third day 10.6 volts higher than the battery voltage. The Ingalls and Lawrence substations, as indicated by Table I., have about the same rotary output in k.w. hours per day. The average current demand made on these substations is not far from 175 amperes and, consequently, the normal demand made upon the boosters is from 1.75 to 5.25 k.w. The capacity of the boosters in the Ingalls and Lawrence substations is 8 k.w., and it is probable that very frequently so heavy a demand is made upon the boosters that they have not the capacity to enable them adequately to meet the demand. If the boosters had been equipped with a heavy flywheel, the chances are that the "efficiency of equalization" of the storage-battery would be very greatly improved over what the results recorded make it possible to report.

At the time of planning for the tests which were made on the storage-battery it was hoped that data would be accumulated which would make it possible to determine the exact commercial efficiency of the storage-battery equipments of the various substations. When, however, it is remembered that it was not possible to subject the storage-batteries to any definite cycle of loading, and that it is extremely difficult when a definite cycle of loading does not exist to keep a sufficiently accurate hold on the battery to admit of its being brought to the same condition once in 24 hours, the difficulties in the way of obtaining any accurate efficiency estimates are at once apparent.

In scanning the records, efforts were made to obtain efficiency indications by a comparison of wattmeter readings made at times when the battery current was zero and the voltage the

same, on the assumption that within reasonably short periods of time the variations in the battery-solution would not be sufficient to affect the results materially. Inspection, however, proved that the variations which took place in the load upon the battery were entirely too rapid for the voltage record to be sufficiently reliable for the purpose contemplated, and, therefore, all attempts to determine the performance of the batteries in terms of commercial efficiency were abandoned. In lieu of these determinations an effort has been made, by virtue of the presentation of the recorded data which is given in Figs. 4 to 23, to throw some light on the service which the different batteries were required to render.

Figs. 4, 5, 6 and 7 relate to the battery in the Lawrence substation. Fig. 4 is the load-curve for the three days of the test on this battery. The ordinates represent the k.w. hour load for 4-hour periods plotted above the mean time of the period. For instance, the ordinate which determines the peak in the afternoon of the third day gives the k.w. hour output of the substation between 4 and 8 P. M., and is plotted over the 6 P. M. abscissa. The curves of Fig. 4 therefore indicate the demand made on the substation by the cars during 4-hour periods. In Fig. 5 the charge and discharge of the Lawrence substation battery is also shown for 4-hour periods. For instance, during almost any period of four hours the battery is both charged and discharged and the total charge and discharge values common to a 4-hour period are plotted over the center on that period. For instance, the charge between 12 and 4 P. M. of the second day was 26 k.w. hours and the discharge during the same period was 19 k.w. hours.

The curves of Fig. 6 show the excess of the charge over the discharge or of the discharge over the charge in k.w. hours for 4-hour periods. In other words, the areas of Fig. 6 are the algebraic differences of the charge and discharge areas of Fig. 5. From these, therefore, we can determine the total charge or discharge over the discharge or charge for any 4-hour period. For instance, between 8 and 12 P. M. of the second day the battery had an excess of charge over discharge equal to 40 k.w. hours, while between 12 and 4 A. M. of the third day the battery was discharged more than it was charged by an amount of 30 k.w. hours. Fig. 7 shows the rate at which the battery was charged or discharged in excess of the discharge or charge during any 4-hour period. For instance between 8 and 12 P. M. of the third day the battery

received a charge eight times greater than the discharge which occurred during this 4-hour period, while between 12 midnight and 4 A. M. of the third day the battery received a discharge which was eleven times greater than the charge which it received during the same period.

An interpretation of Curves 4, 5, 6 and 7 considered collectively indicates with a good degree of accuracy the kind of service which the Lawrence substation battery rendered during the three days of the test. On the first day in the forenoon the battery was discharged more than it was charged, but the rate of discharging in the morning of the first day was not great. Early in the morning of the third day the battery received about the same discharge and was charged during the same period only a very little, so that the rate of charge for this time was quite high. Between 8 and 12 P. M. of the second day, as shown by Fig. 5, the battery received a charge of 50 k.w.h. and was discharged 10 k.w.h. The ratio of the charge to the discharge is in this case a little over 5, whereas in the early morning of the same day, although the charge was only 12 k.w.h. the discharge was 3 k.w.h. and therefore the rate of charge over discharge a little over 4. The value of the ratio curves is in determining the accuracy with which the switchboard attendant adjusts conditions in his substation to meet the average demand from the line. If we assume that during any four hour period the charge and discharge of a battery is such as to maintain the battery in the same average condition during this time, the ratio curve will be a straight line displaced $1\frac{1}{4}$ points above the zero line, if the commercial efficiency of the battery is 80 per cent.

Figs. 8, 9, 10 and 11 are plotted from the data obtained from the test of the Ingalls substation in the same manner as were the curves for the Lawrence substation just discussed. However, Table VII. indicates that the battery in the Ingalls substation was worked a little harder during the three days than was that in the Lawrence station. The working conditions in the Ingalls substation are very good. It will be noted that the ratio curve during most of the time runs along between the positive value of one and two, indicating that during any 4-hour period the battery was made to charge slightly more than it discharged. The performance for the three days as shown in Fig. 7 indicates an efficiency of 74 per cent. for the battery; this efficiency being taken as the ratio of the charge to the discharge during the three days. Had the switchboard attendants been a little more careful

the battery could have been carried through the test working on a maximum efficiency basis. The term maximum efficiency is here used to indicate the best efficiency at which the battery can be operated.

The 4-hour period which has been made the basis in this discussion has been assumed arbitrarily, for the reason that it seems long enough to insure a proper gauge of the average performance and not too long to obscure it. The average performance of the Ingalls substation battery for the three days is more nearly what it should be than that of any other of the stations tested. The station shows an efficiency for the three days of 88 per cent., which is 3 per cent. above the efficiency claimed for the batteries by the manufacturers. The ratio curve maintains a good positive value which would have been greatly improved had not the two discharge peaks between 12 and 4 A.M. of the first and third days occurred.

Figs. 12, 13, 14 and 15 are plotted from the data at the Anderson substation. These curves indicate the extremely variable conditions which exist at this substation owing to the fact that local and interurban cars bring about very irregular conditions of load. In spite of the fact that this battery shows heavier charge and discharge periods of long duration than that of any of the other substations, the ratio curve is comparatively good, being in fact as good as any, and much better than the ratio curve of the Daleville substation, in which the tax upon the battery was much less marked. The Daleville curves which are shown in Figs. 16, 17, 18 and 19 indicate quite clearly that the battery was practically floating on the system most of the time, as during no 4-hour period did its discharge over its charge exceed 14 per cent. of the 4-hour discharge rating of the battery. The efficiency of the battery for the three days is 76 per cent.

The substation at Muncie, next to that at Anderson, shows the largest output of any of the substations for which curves have been plotted. As indicated by the ratio curve of Fig. 23, the discharge of this battery was very much in excess of the charge and in fact for the three days the station shows an efficiency of 112 per cent. As at Anderson so at Muncie the local street railway cars make an irregular demand upon the station. This largely accounts for the fact that no special discharge cycle is noticeable. The charge cycle, however, is fairly regular as shown by Fig. 21. Most of the substations have a fairly uniform charging cycle. This cycle is particularly well brought out in the case of the

Lawrence substation on the second and third days. The charging cycle shown by the curves of the second day in Fig. 9 is probably characteristic of the Ingalls substation. The charge curve of the third day in Fig. 13, it is believed, represents the ordinary charge cycle of the Anderson battery; but for the depression which occurred on the second day during the 8 to 12 A. M. period the charging cycle would have repeated itself during the two last days of the test. The charging cycle of the Daleville substation is not specially characteristic in outline. The first and second days, however, show in general what is to be expected. In the case of Muncie the first and third days are probably more representative of the charging cycle in this station than is the second day.

It very frequently happens that for a while in the early morning the generators in the central station at Anderson are shut down. During these periods such trains as may be operating are supplied with energy from the substation storage batteries. For instance, none of the generators was in service between 1.30 A. M. and 4.15 A. M. on April 18th and none of them was in service between 1.30 A. M. and 4.15 A. M. on April 19th. Here then we have two periods of 2.75 hours during which such trains as were operated were supplied with power from the storage batteries. This condition of rest in the central station is reflected in the curves of Figs. 5, 9, 13, 17 and 21 by the discharge peaks which are shown between 12 midnight and 4 A. M. of April 19th. All of the batteries were then required to discharge quite heavily. The demand which was made upon the Lawrence, Ingalls and Anderson substations being particularly heavy. Between 12 midnight and 4 A. M. on April 18th, owing to some local cause a demand was made upon the battery in the Anderson substation. On the morning of the 18th, however, none of the other substations is carrying any special load except the Muncie substation. The Muncie battery discharge curve as shown in Fig. 21 differs very markedly from the discharge curves of the other substations owing to the fact that during the whole of the three days the average of four hours never falls below 44 k.w.h. nor rises above 85 k.w.h. In other words, this battery maintains a discharge rate averaging closely 58 k.w.h. for each 4-hour period during the three days. There is evidently "something doing" in Muncie all the time.

Tables VII., VIII. and IX. contain data which show the degree to which the storage-batteries in the substations were worked over 4-hour periods. The Ingalls substation developed

the highest discharge performance, as during the four hours between 12 midnight and 4 A. M. on April 19th, it developed 39 per cent. of its discharge capacity. The Marion, Anderson and Muncie batteries never developed more than 28 per cent. of their discharge capacity over a 4-hour period, and at Daleville the discharge performance during a 4-hour period did not exceed 14 per cent. These figures all go to show that as gauged by the average demand on the substations, the batteries are amply large enough to take care of variations in the demands made on the substations by the trains. It is confidently believed, however, as has already been pointed out in the discussion of the

special test on the storage-battery at the Ingalls substation (see Figs. 2 and 3), the motors driving the booster armatures were not heavy enough to hold up to the momentary demands which rapid changes in the load bring upon the substations, assuming the booster field windings are correctly designed. Proper adjustment would undoubtedly cause the batteries to show a very much higher charge and discharge k.w. performance during the 4-hour intervals, and they would better serve to reduce the fluctuations reflected through the substations from the trains to the central station. A diminution in the fluctuations of the load on the central station at Anderson will in turn increase the economy of the generating machinery. This is a point to which

attention should be given in laying out substations for work of this character, and it is one to which it is believed sufficient attention has not heretofore been directed.

The average commercial performance shown by the batteries during the three days of the test turns out to be 74 per cent. for the Marion battery, 88 per cent. for the Ingalls, 96 per cent. for the Anderson battery, 76 for the Daleville and 112 per cent. for the Muncie battery. Taking the ratio of the total discharge of all of the batteries to the total charge of all the batteries in these five substations, we obtain an aggregate efficiency of 95 per cent. for the batteries in the substation; or, if we average the efficiency values as obtained for the five substations, we get 89 per cent. as the average efficiency of the batteries during this time. These values are high, and yet they continue so for relatively long periods without any special indications of deterioration in the batteries. The batteries were left entirely in charge of the station attendants, and no effort was made at any time to in any way modify the usual performances. The tests indicate that these high efficiencies have been maintained, owing to the fact that only a slight tax has been made upon the capacity of the batteries by the service to which they are commonly subjected. Of course, the continuation of this kind of service indefinitely would in time make itself felt and cause deterioration in the batteries, a condition indicated by marked changes in the density of the electrolyte and rectified by a special charge being given to the battery at relatively long intervals to bring it back to normal condition. Over the system tested it is the practice to give the batteries a special charge on Sunday morning, thus bringing them back to good normal condition once every seven days. At this time the voltage and density of the electrolyte of each cell is taken and made of permanent record.

SPECIAL INSTANTANEOUS DEMAND TEST.

It was possible during the test to make an exact instantaneous record of the current fluctuations occurring at the Anderson substation on March 19th by the following method: A strip of paper was fastened on a tin holder placed in front of the needle of a millivoltmeter and bent to conform to the path traced by the tip of the millivoltmeter needle. The tin holder was then lowered at a uniform rate in front of the voltmeter needle by a clock-work mechanism. The actual record was made on the paper by a continuous induction coil spark from the end of the needle to the

tin back of the paper. Deflections of the millivoltmeter were brought about by placing the instrument in shunt with a sufficient length of the bus-bar to give a considerable deflection. With the apparatus it was possible to obtain records of only twenty minutes duration; and, of course, curves could not be taken at the same time of both the rotary load and line load, as was the case in the Ingalls substation test, the results of which are shown in Figs. 2 and 3; but the instantaneous curves *were* taken under similar conditions of loading.

The upper half of Fig. 24 shows the variation in the demand made upon the Alexandria substation by the interurban cars; this record extends from 4.10 to 4.30 on the afternoon of March 19th. The maximum fluctuation in the load at any given time occurred just after 4.21 P. M., when there was an almost instantaneous demand of 500 amps., the load going from 200 to 700 amps. *instantly*, as nearly as it is possible to read the record.

The instrument was connected to the rotary bus-bar from 4.50 to 5.00 P. M. on the same day. There is no reason to believe that the demand upon the station during this time was very different from the demand upon the station during the time that the instrument was connected to register the line fluctuations. Accordingly, it would seem that on the afternoon in question the substation at Alexandria was working much more efficiently as an equalizer than was the battery at the Ingalls substation at the time the records were made which are recorded in Fig. 3. Owing to an unfortunate accident to the millivoltmeter it was impossible to obtain other instantaneous records than those presented, and, therefore, no estimate can be made of the exact efficiency of equalization of the Alexandria battery. Presumably, however, it is higher than that developed at the Ingalls substation, since the average load shown in the curves of Fig. 24 in both cases runs not far from 350 amps.; and while the upper curve is extremely irregular, the lower curve is comparatively uniform.

The maximum one-hour discharge rate of the Alexandria battery is 320 amps. The curves of Fig. 4 show that the demand on the batteries and rotaries together exceeded this discharge rate about once in every thirty seconds, with periods of very light load between. How much of these peaks the battery actually took is not possible to say, presumably, however, its maximum discharge rate for one hour of 320 amps. was frequently exceeded.

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TABLE I.
SUBSTATION ROTARY OUTPUT.
K.W.H.

Station.	April 17	April 18.	April 1	Total.
Lawrence	1791	1780	1780	5351
Ingalls	1825	1742	1881	5448
Anderson	4400	4340	4827	13567
Daleville	1670	1690	1706	5066
Muncie	3406	3210	3658	10274
Alexandria	3235	2550	2945	8730
Fairmount	1440	1508	2050	4998
Marion	5330	5865	8040	19235
Elwood	1860	1825	1970	5655
Total.....	24957	24510	28857	78324

TABLE II.
EFFICIENCY OF HIGH-TENSION LINES, TRANSFORMERS AND ROTARIES.

Date.	A.C.Output* K.W.H.	D.C.Output* K.W.H.	Efficiency.
April 17	28,000	20,557	73.3
April 18	27,270	20,170	73.9
April 19	32,750	24,030	73.3
Total	88,020	64,757	73.5

*This column is the total output of the Anderson generators as given by the recording wattmeter on the load panel, less the Anderson rotary input, obtained by dividing the Anderson rotary output by the efficiency of the rotaries—88%.

°This column is the sum of all the readings of the rotary wattmeters, less the output of the Anderson rotaries, as these were fed directly from the bus bars, through auto-transformers and not through the high-tension lines.

TABLE III.
RESULTS OF EFFICIENCY TEST, ROTARY NO. 19.

12-Hour Test.			6-Hour Test.		
Average Load K.W.	Per Cent. Load.	Efficiency.	Average Load K.W.	Per Cent. Load.	Efficiency.
84	33.6	88	88	35.2	88
88	35.2	88	91	36.5	92
98	39.3	88	87	34.9	88
98	39.3	90	88	35.2	88
73	29.2	85	91	36.5	89
78	31.2	88	103	41.2	92
Average ...		87.8	77	30.8	83
			85	34.0	89
			59	23.6	74
			Average		87

TABLE III. (Continued.)

1-Hour Test.

Average Load K.W.	Per Cent. Load.	Efficiency.
60.0	24.0	81.0
74.4	29.8	80.0
74.4	29.8	82.0
76.4	30.5	79.0
78.0	31.2	94.0
86.4	34.6	95.0
89.0	35.5	89.0
91.2	36.0	82.0
99.6	39.8	92.0
100.8	40.5	89.0
102.0	40.8	97.0
104.4	41.7	87.0
105.6	42.1	84.0
105.6	42.1	90.0
106.8	42.9	85.0
118.8	47.5	84.0
133.4	53.3	94.0
135.4	54.0	97.0
Average 96.8	38.7	88.3

TABLE IV.
EFFICIENCY OF HIGH-TENSION LINES, TRANSFORMERS AND ROTARIES.

Quantity.	April 17.	April 18.	April 19.	Total.
Step-up trans. input.....	28,000	27,270	32,750	88,020
Step-up trans. efficiency.....	95	95	95	95
High-tension line input.....	26,600	25,900	31,070	83,570
High-tension line efficiency.....	93.0	92.0	92.7	92.9
Step-down trans. input.....	24,700	23,800	28,750	77,450
Step-down trans. efficiency.....	95.0	95.0	95.0	95.0
Rotary input.....	23,500	22,600	27,360	73,560
Rotary efficiency.....	88.0	88.0	88.0	88.0
Rotary output.....	20,657	19,770	24,030	64,557
TOTAL EFFICIENCY.....	73.3	73.9	73.3	73.5

TABLE V.
EFFICIENCY OF D.C. DISTRIBUTION.
ANDERSON-MUNCIE DIVISION.
Input to Line

	April 17.	April 18.	April 19.	Total.
Anderson Inter. East	73.2	3.0	75.5	181.7
Daleville Rotary	1670.0	1681.3	1706.0	5057.3
Daleville Bat. Dis.	67.0	89.4	77.5	233.9
Daleville Bat. Ch.	75.8	107.1	112.0	294.9
Muncie Inter. West	268.5	268.8	355.0	892.3
Total.....	2002.9	1935.4	2102.0	6092.3

INPUT TO CARS.

	April 17.	April 18.	April 19.	Total.
Regular cars	1448.2	1435.3	1465.0	4348.5
Special cars.....	56.9	103.6	173.0	333.5
Total.....	1505.1	1538.9	1638.0	4682.0
Efficiency	78.2	79.5	77.9	77.7

ANDERSON-INDIANAPOLIS DIVISION.
INPUT TO LINE

	April 17	April 18	April 19.	Total.
Lawrence Rotary	1780.0	1784.88	2001.0	5565.88
Lawrence Bat. Dis	122.6	101.03	67.1	290.73
Lawrence Bat. Ch	115.2	131.79	147.0	393.99
Ingalls Rotary	1830.0	1703.59	1880.0	5413.59
Ingalls Bat. Dis	98.2	180.15	147.0	425.35
Ingalls Bat. Ch	156.0	140.26	182.0	478.26
Anderson Int. W.	714.0	735.60	1030.0	2479.6
Total.....	4273.6	4233.2	4796.0	13302.8

INPUT TO CARS

	April 17	April 18	April 19	Total.
Regular cars	3096.8	3060.6	3340.4	9497.8
Special cars.....	42.4	79.1	26.3	147.8
Total.....	3137.2	3139.7	3366.7	9643.6
Efficiency	73.5	74.1	70.4	71.3

TABLE VI.
AVERAGE D.C. LINE EFFICIENCY

Division.	April 17	April 18	April 19.	Total.
Anderson-Muncie	78.2	79.5	77.9	78.5
Anderson-Indianapolis.....	73.5	74.1	70.9	72.5

TABLE VI.—Continued.
AVERAGE D. C. LINE EFFICIENCY.

Date.	Total Input to Line. K.W.H.	Total Input to Cars. K.W.H.	Efficiency. In. Indianapolis. Muncie.
April 17	6197.3	4644.3	75.0%
April 18	6165.7	4678.6	76.0
April 19	6898.0	5004.7	73.0%
Total	19261.0	14227.6	74.5%

TABLE VII.
SUBSTATION BATTERY OUTPUT.

	April 17 K.W.H.	April 18 K.W.H.	April 19 K.W.H.	Total K.W.H.	Three day Effi ciency.
Lawrence Charge	115.2	131.8	147.0	394.0	74%
Lawrence Discharge	123.6	101.0	67.1	290.7	
Ingalls Charge	156.0	140.3	182.0	482.3	88%
Ingalls Discharge	98.0	180.2	147.0	425.2	
Anderson Charge	477.4	423.7	503.2	1404.3	96%
Anderson Discharge	364.5	446.7	537.9	1348.0	
Daleville Charge	100.3	107.1	112.0	319.4	76%
Daleville Discharge	75.0	89.1	77.5	241.6	
Muncie Charge	293.0	282.0	367.0	942.0	112%
Muncie Discharge	332.0	359.0	365.0	1056.0	
Total Charge				3541.0	95%
Total Discharge				3362.0	
Average					89%

TABLE VIII.
CAPACITY OF SUBSTATION BATTERIES

Battery in Sub- station at	Battery Discharge Rate in Amperes for			Battery Capacity in K.W.H. when Discharged in		
	1 Hr.	4 Hrs.	8 Hrs.	1 Hr.	4 Hrs.	8 Hrs.
Anderson	400	160	100	211	337	422
Muncie	320	128	80	169	271	338
Lawrence	160	64	40	85	135	169

Batteries at Alexandria and Marion have same capacity as battery at Muncie.
Batteries at Ingalls, Daleville, Fairmount and Elwood have same capacity as battery at Lawrence.

TABLE IX.
PER CENT. OF BATTERY CAPACITY DEVELOPED.

	4 Hour Discharge Rating.	Max. Discharge in 4 Hrs K.W.H.		Per Cent. of 4 Hour Discharge Capacity Developed.	
	K.W.H.	Total.	Dif.	Total.	Dif.
Lawrence	135.0	33.0	30.0	24.4	22.2
Ingalls	135.0	52.0	50.0	38.5	37.0
Anderson.....	337.0	111.0	89.0	32.9	26.4
Daleville.....	135.0	24.0	18.0	17.7	21.7
Muncie.....	271.0	85.0	59.0	31.3	