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Obtaining Steady High-Voltage Direct Current from a Thermionic Rectifier, Without a Filter.

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Obtaining Steady High-Voltage Direct Current from a Thermionic Rectifier, Without a Filter.

The research problem here described was suggested by Dr. R. A. Millikan and its solution developed to a considerable extent by Mr. J. W. M. Du Mond. At the point where a special generator was to be designed, it was taken up by the writer and carried out to a degree of perfection limited practically by the available transformers and generator frame. The perfection actually obtained is given by two statements. (1) Maximum variation on each side of a mean, for best conditions and with full load output of the generator, is 2.8% of the mean. (2) The frequency of the variation is at least twelve times that of the A. C. impressed frequency, an advantage in case a filter is to be used for further smoothing of the direct current output. The possible perfection is much better with similar but more highly specialized apparatus.

Review of the Subject.--The usual polyphase high-voltage rectifier produces a potential essentially constant but having superposed on it a "ripple" or alternating component whose amplitude on each side of the mean is from five to seven per cent of the total d-c. voltage. Condensers and reactors are used to filter the ripple out. The paper describes a special type of a-c. generator which will give the proper low-voltage wave form for rectification as a more nearly smooth direct potential. A method of manually or automatically varying the low-voltage wave form according to load demands is provided so as to keep the rectified potential steady, thus avoiding the necessity for the filter which in sets for 100,000 volts or more would be quite expensive and troublesome.

INTRODUCTION

Many types of circuits* have been suggested and used for stepping up a sine wave single or polyphase low-voltage alternating current and then rectifying it by means of either a synchronous commutator or one of the forms of electric valve. The resultant unidirectional potential and current have an alternating component which must usually be considered and in many cases, eliminated to a fraction of a per cent before the high voltage direct current is suitable for the desired purpose.

The apparatus which suppresses this alternating component, the filter, consists of a condenser or set of condensers suitably connected with inductances and tuned to draw a large current at the principal frequency of the undesirable alternating component wave, i.e., the sixth harmonic of the fundamental impressed on the

* A Schmidt--G.E.Review, Feb. and May 1923, "Thermionic Rectifiers".

low-voltage side of the rectifier. For voltages up to 15,000, such a filter is a fairly easy problem, but for 100,000 volts or more, the condensers become bulky and expensive.

In order to avoid the necessity for a filter, the wave form of the alternating potential impressed on the transformer low side must be of special shape. It is proposed to outline here the features of a special generator which employs straight forward methods of altering the field distribution as the load requires and which has a distributed armature winding capable of generating the desired wave form at no-load when the field distribution is uniform under the pole face.

THE GENERATOR

A three-phase Y-connected winding has voltages across its terminals which are the instantaneous differences of the component leg voltages and it will be seen by an inspection of the ideal diagram, Fig. 1, that by generating a triangular wave in each leg of the Y, a flat-top wave, horizontally flat for 60 electrical degrees of every half cycle, results. Furthermore, the flat top wave coming from a Y-connection contains no third harmonic or its multiples. It may therefore be used equally well in a $\triangle$ or a Y-connected transformer bank. The triangular wave contains theoretically, in addition to the fundamental, 11.11 per cent third harmonic, 4 per cent fifth, 2.04 per cent seventh, 1.235 per cent ninth, 0.828 per cent eleventh, etc. The fraction representing the harmonic amplitude is $1/n^2$ of the fundamental amplitude, where n is the number of the harmonic. The even harmonics are absent. The flat top wave contains theoretically, no third harmonic, 4 per cent fifth, 2.04 per cent seventh, no ninth, 0.828 per cent eleventh, etc. The even harmonics and multiples of three are absent.

Mechanically, the generator has a 50 per cent pole arc and a coil span of 50 per cent, the individual turns being full or fractional pitch but average coil pitch is 100 per cent.

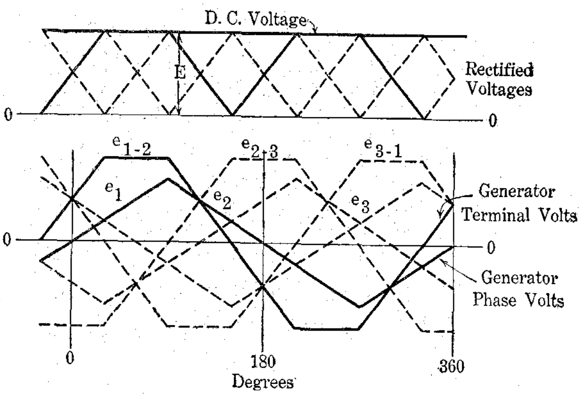

FIG. 1—THEORETICAL DIAGRAM OF VOLTAGES IN THE VARIOUS CIRCUITS OF GENERATOR AND RECTIFIER

E = D-c. voltage

$e_1 = 0.607\,E\,[\sin \omega t - 1/9 \sin 3\,\omega t + 1/25 \sin 5\,\omega t - 1/49 \sin 7\,\omega t + 1/81 \sin 9\,\omega t - \ldots]$

$e_{1-2} = 1.051\,E\,[\sin(\omega t + \pi/6) + 0 - 1/25 \sin 5(\omega t + \pi/6) + 1/49 \sin 7(\omega t + \pi/6) + 0 - 1/121 \sin 11(\omega t + \pi/6) + \ldots]$

Thus the generated voltage in one leg of the Y is zero only when the armature turns of one phase are all in the interpolar space and maximum only when they are all under the poles. Intermediate voltages are proportional to the number of inductors under the pole, and hence proportional to angular displacement from a reference point. This forms a triangular wave. The other necessary conditions are: no flux fringing at the pole tips and uniform distribution under the poles. How closely these conditions can be met experimentally is shown by the oscillogram, Fig. 2. The top curve shows generator terminal voltage, the middle curve transformer exciting current on the flat-top wave, and the lower curve, voltage on one leg of the generator.

The experimental generator was a rebuilt Crocker-Wheeler bipolar 10-kw. d-c. machine having a smooth core, 8-inch diameter, armature, and 3/8-inch air gap. The armature was specially wound as described above. The field poles were cut away to suit, and a pole face "compensating" * winding inserted to control the flux distribution under load conditions.

COMPENSATING WINDING

The pole face winding is d-c. excited, corresponding

* Langsdorf, Principles of D.C. Machines, p. 348.

to one of the methods of controlling field distribution on a d-c. generator for purposes of improving commutation. On account of the small pole arc, armature reaction is not as bad in this type of generator as in standard D.C. generators. Also the nearly unity power factor characteristic of the load makes armature reaction largely cross magnetizing. The compensating winding ought therefore to have its field axis at right angles to the main field axis. A modification of the above theory results from the intermittent manner in which the load is suddenly applied to and then removed from the transformers by the rectifier. Distributed secondary capacitance likewise influences the current wave drawn by the transformer. It was found necessary to shift the axis of the compensating winding about 22½ deg. beyond the ideal 90-deg. position, moving it against rotation. (See Fig. 3). The effect of the compensating m.m.f. is to tilt the top of the voltage wave away from the horizontal, causing it to rise on the leading end from 5 to 30 deg. The necessary tilt is greater when a Y--Y transformer bank is used than with a Δ-Δ bank. Thus it will be expected that more ampere turns of compensating field are needed for the same generator load when the former connection is used.

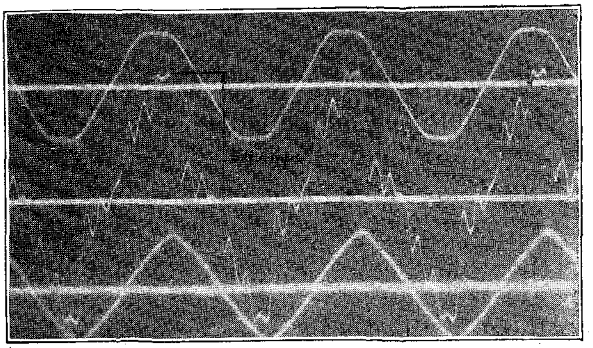

FIG. 2—VOLTAGE WAVE FORMS ON THE SPECIAL FLAT-TOP WAVE GENERATOR

Upper curve—Terminal voltage (load consists of exciting current on △ – △ transformer bank only)
Middle curve—Exciting current, Transformer No. 1
Lower curve—Voltage of one leg of generator

The necessary compensating current varies approximately directly with the load and can be manually adjusted or automatically controlled by means of a regulator.

TRANSFORMERS AND RECTIFIER

It is evident that the generator must be Y-connected because of the large third harmonic in its phase voltage wave. Generator terminal voltage will then contain no third or its multiple harmonics, and may supply either a △ - △ or a Y--Y transformer bank. Fig. 3 is a diagram of connections using the △ - △ arrangement. A Y--Y bank may be substituted without other change. Special six-phase connections may also be used if desired, so long as the flat-top wave form is preserved. The rectifier consists of six standard 100,000-volt, 200-milliampere

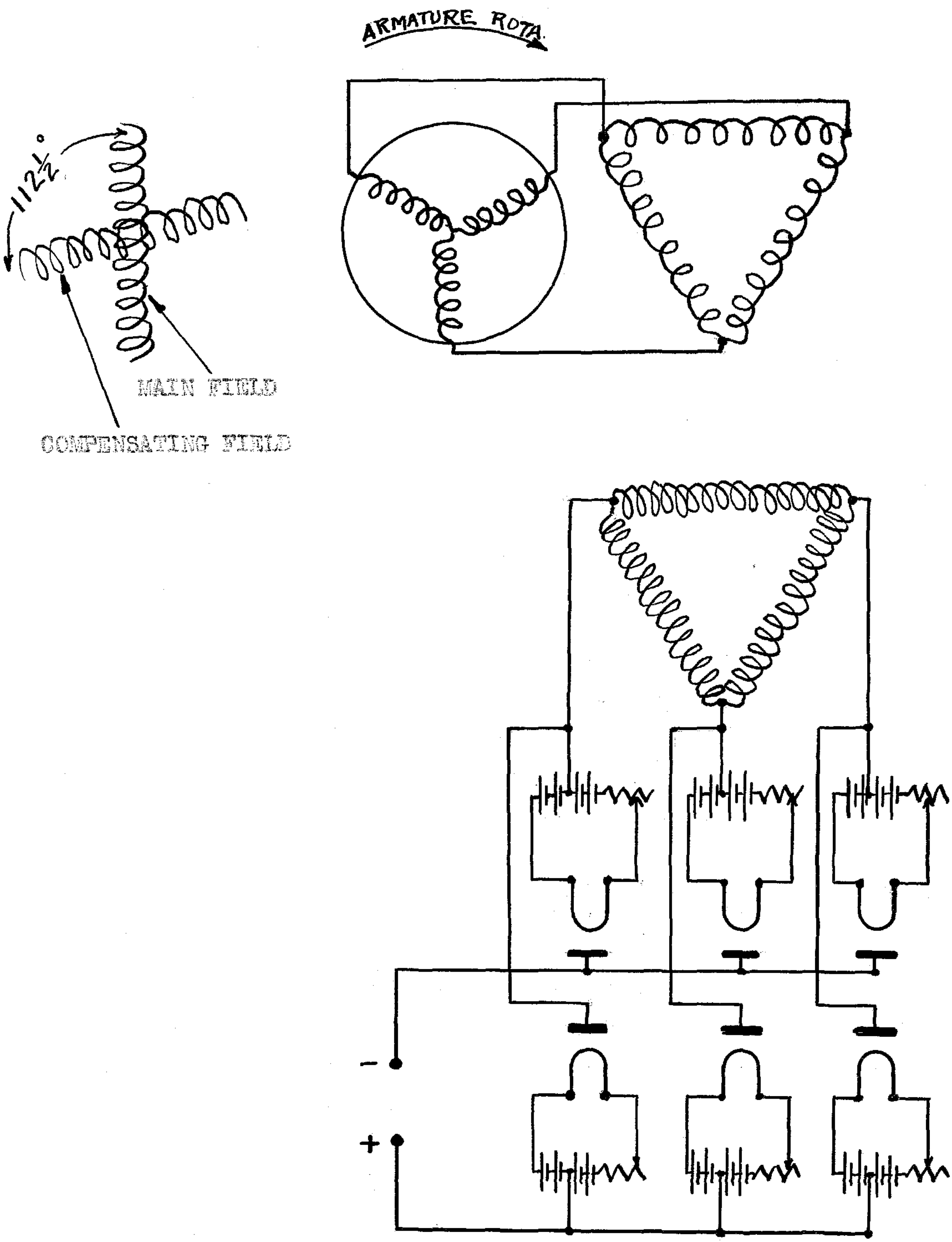

FIG.3 - Diagram of Generator, Transformer Bank, and Rectifier, Showing the Six Kenotrons with Storage Battery Excitation for the Filaments

Kenotron tubes with storage battery excitation for the filaments. (Regular high-voltage filament transformers are to be preferred for continuous operation). A 51-cycle flat-top voltage was impressed on the transformers.

EXPERIMENTAL RESULTS

Rectification of 100,000 volts and 50 milliamperes, 5 kw., was accomplished, limited by the 7½ h.p. driving motor on the generator, and the transformer bank, although the Kenotrons were capable of 20 kw. output. Fig. 4A, showing impressed voltage and current on No. 1 transformer and d-c. current in a water resistance, has a maximum variation of 4.4

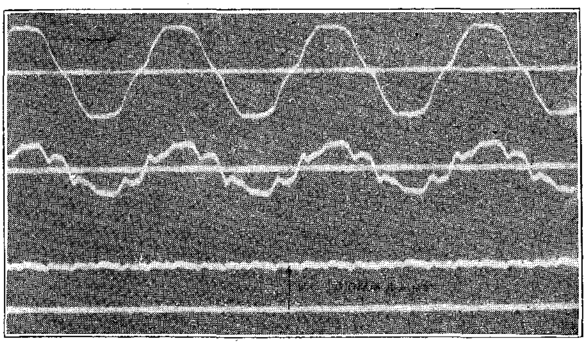

FIG. 4A—DIRECT-CURRENT CHARACTERISTICS OF THE RECTIFIER
Upper curve—Transformer impressed voltage (△ – △ bank)
Middle curve—Current in transformer low side
Lower curve—D-c. in a water tube resistance having neither inductance nor capacitance

per cent on each side of the mean. This was for a △ - △ connected transformer bank. The efficiency from the transformer input to the d-c. output, neglecting 810 watts filament excitation, which is independent of load, was 75.5 per cent. Fig. 4B is a similar set of curves for a Y--Y connected bank and shows a maximum variation of 2.8 per cent on each side of the mean. The efficiency in this case was

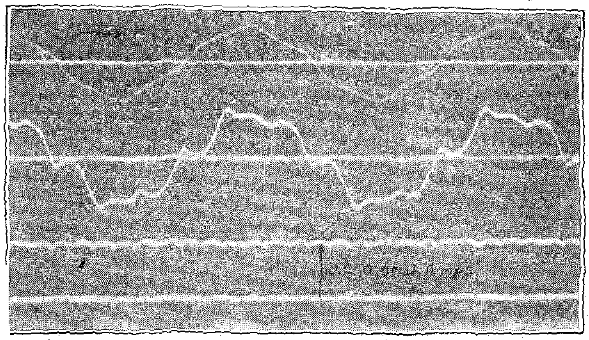

Fig. 4B—Generator Neutral Connected to Transformer Neutral

Upper curve—Transformer Impressed Voltage (Y – Y Bank)
Middle curve—Current in transformer low side
Lower curve—D-c. in a water tube resistance

80 per cent. In both oscillograms, prominent third and fifth harmonics appear in the current wave drawn by the transformer. The even harmonics are absent.

Excitation of the compensating field amounted to 2800 ampere turns in the case of the △ - △ transformer connection and 4000 ampere turns for the Y--Y connection. Armature reaction in each case was 600 ampere turns. This apparently excessive compensating m.m.f. was necessary on account of the large air gap.

For comparison, Fig.5 is presented to show the action of the rectifier with a sine wave voltage impressed. A △ - △ connection was used on the transformer bank. The maximum variation of the direct current from its mean was 10.5 per cent. It will be noted also that the rectified currents produced by the flat-top wave have sharp dips occupying only about 10 per cent of the time duration of the steady portion so that even though the amplitude of the dip is four or five per cent of the total current, its net result is quite small. Sine wave impressed voltage, however, produces ripples occuping the whole time duration of the direct current.

CONCLUSIONS

There are several advantages in producing a steady high-voltage direct current without the use of a filter.

1. The expense and weakness of a high-voltage condenser are avoided.
2. Space requirements are reduced.
3. Power losses in the filter are avoided. (This will show up to a greater degree as the rating of the plant increases both in voltage and kilowatts).
4. Steadiness of direct current changes very little with load, whereas the filter may change its tuning under load variations.
5. The practical upper voltage limit of the rectifier is raised.

6. Undesirable even harmonics which sometimes result from polyphase rectifier loads on a power system are completely avoided, because a separate generator is interposed.

7. The recent exhibition in England of a high-voltage d-c. generator, designed by Messrs. Highfield and Calverley,* has awakened new interest in the possibilities of d-c. power transmission. The feasibility of getting a better and more easily controlled wave form for thermionic tube rectification may be another step in the solution of the d-c. transmission problem.

Results as shown leave something still to be desired in the direction of greater smoothness of d-c. voltage. Part of the unsteadiness is due to one of the transformers which was of different design, being about three per cent lower ratio and somewhat lower impedance. The ratio and impedance partly counterbalanced under load. Referring to the theoretical wave forms, Fig. 1, it will be seen that the flat-top wave has all its harmonic components, above the seventh, less than one per cent of the fundamental amplitude. If all harmonics above the

* The English--Electric Transverter. May 9, 1924
Calverley and Highfield, Electrician (London)

seventh are missing, the total dip in the d-c. voltage wave will be only 3.5 per cent. Adding the eleventh and thirteenth harmonics reduces the dip to 2.03 per cent at the same time shortening its time duration. Further improvement, then, is to be obtained by using lower impedance transformers and a smaller air gap in the generator.

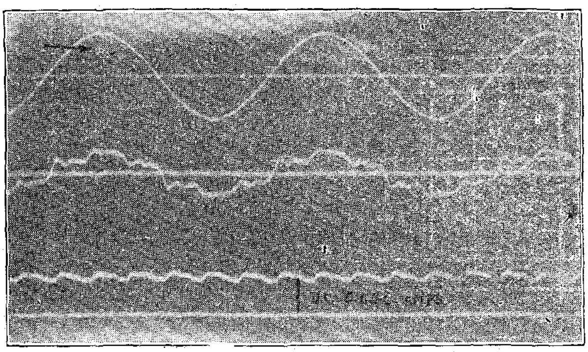

FIG. 5—CHARACTERISTICS OF THE RECTIFIER ON SINE WAVE VOLTAGE

Upper curve—Transformer impressed voltage (△ – △ bank)
Middle curve—Transformer current in low side
Lower curve—D-c. in water tube resistance