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A.C. Harmonics in M.A.N.W.E.B. supply due to Laboratory Rectifier Loads

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17th July, 1963.

1.0 Summary

This report describes a proposed arrangement of the Laboratory rectifier loads and supply network, that will meet the harmonic restrictions imposed by the supply authority and at the same time give a reasonable freedom of choice for the selection of economic individual rectifier units.

2.0 General

The Electron Laboratory at Daresbury will require a number of direct-current power supplies, for magnet excitation and other purposes, ranging from 100 Kw up to 1000 Kw with a total load of approximately 6½ MW.

At some later stage in the Laboratory development (1968 onwards) additional beam experimental devices or storage facilities may add a further 2-3 MW to the total DC power requirement.

It is proposed to provide these DC power sources by rectification of the AC supply, and since rectifier operation produces harmonic distortions of the voltage and current waveforms in both the AC supply and DC output circuits the choice of rectifier circuit arrangements will be governed by:-

a) the limit imposed by the supply authority on the harmonic content produced in the AC supply.

b) the limit imposed by the load on the DC output voltage ripple.

Limit (a) will determine the minimum effective pulse number of the total Laboratory rectifier load, and limit (b) will determine the minimum pulse number of the individual rectifier units based on the economics of pulse number versus filter costs.

3.0 Harmonics in DC output

The DC output voltage has harmonic components of order $n = kmp$ whose magnitudes are functions of the load current, circuit constants, amount of grid control and rectifier pulse number.

It can be shown that, for the principle rectifier loads at the laboratory, the degree of ripple attenuation required can be achieved most economically by six-phase rectification in conjunction with filter networks. Hence there is no technical justification, based on DC harmonic considerations, for individual pulse numbers above mp = 6.

4.0 Harmonics in AC supply

The currents produced in the AC supply by a rectifier load may be resolved into a fundamental and harmonic components, with the harmonics having orders $n = kmp \pm 1$ whose magnitudes, as in the DC case, are also functions of load current, circuit constants, amount of grid control and rectifier pulse number.

The percentage harmonic/fundamental current amplitude $(\frac{I_n}{I_1})$ decreases with increase in pulse number (mp), and increases for increase in grid control angle (α), also the harmonic phase angle (ϕ) changes with change in α.

Values of $\frac{I_n}{I_1}$ and $\frac{\phi}{n}$ are shown in Fig.1. and table 1. respectively for a range of α values based on circuit constants giving $\mu_o = 25^\circ$.

5.0 Limit on AC Harmonics by Supply Authority

The flow of AC harmonic currents, due to rectifier commutation, through the supply system impedance generates harmonic voltages which can cause interference with other consumers apparatus. Consequently the amplitude of these harmonic currents is restricted by the supply authority; based on the values given in table 2; to the CEGB recommendation shown in Fig.2. which relates the permissable free-firing rectifier load to the system short-circuit MVA at the point-of-common-coupling.

Reference to the schematic diagram of the supply authorities main feeders to the Electron Laboratory at Daresbury (fig.3) shows that the present arrangement would exclude rectifier loads in excess of

300 kw - 6 pulse or 1.2 MW - 12 pulse since the fault level is some 60 MVA at the 11 kV bus which is also coupled into the local MANWEB 11 kV network.

Some modification to the supply network is therefore necessary in combination with an increase in the effective pulse number of the laboratory rectifier loads.

6.0 Rectifier Loads at the Laboratory.

The principle loads comprise:-

a) Pulse Power Supply (1000 kw). - 6 phase rectifier set drawing a current that fluctuates smoothly between 0.87 and 1.1 of its average value at the accelerator frequency of 50 c.p.s. (nominal). Output voltage range 0-100% by combination of stepless variable transformer and 5% voltage control on rectifier grids (18°). Inversion duty for fault protection of 15 KJ.

b) D.C.Bias Power Supply (650 KW) - 6 phase rectifier set - constant load. Output voltage range 0-100% by either, combination of stepless variable transformer and 18° grid control or, off-load taps and 30° grid control.

c) Radio Frequency Power Supply (650KW) - 6 phase rectifier set drawing a current that fluctuates between 1.31 and 0.61 of its average value at the accelerator frequency of 50 c.p.s. (nominal). Output voltage range 0-100% by combination of stepless variable transformer and 18° grid control.

d) Experimental Magnet Power Supplies (4000 KW total). The experimental magnet power supplies will comprise a number (approx 40) of 3 phase bridge rectifier sets ($mp = 6$) ranging from 100 KW to 350 KW. Output voltage range 0-100% by either i) off-load tap changing and 30° grid control ii) stepless variable transformers and 18° grid control iii) no separate transformers and 80° grid control on S.C.R!^{s}.

e) Future beam experimental and storage devices (2000-3000 KW)

Details unknown except that it will be almost certainly a constant load.

7.0 Proposed arrangement of load and MANWEB feeders

Two objectives are desired:-

a) increase in effective phase number.

b) sub-division of 11 and 33 kv bus bars to provide a harmonic free supply to certain laboratory equipment and local 11 kv interconnections.

Increase in effective phase number. Since the pulse and DC bias power supplies invariably operate together they will be provided with phase shifting transformers $\angle 0^\circ$ and $\angle 30^\circ$ to produce effective 12 pulse operation. The R.F. power supply will also be given phase shift of $\angle 30^\circ$ as shown in fig.4.

The experimental magnets will normally be excited only when all the above loads are in operation consequently the two main transformers supplying the forty individual rectifier sets are phased $\angle -15^\circ$ and $\angle +15^\circ$ to produce an effective 24 pulse operation.

Due to the load mis-matching, differing grid control angles and other assymetries, complete concellation of 5th, 7th, 11th and 13th harmonic components will not occur. However the maximum distortions would not exceed the values due to the operation of the loads individually i.e.

1 MW - 6 Pulse
or 4 MW - 12 Pulse.

and would reduce during full operation to approximately:-

350 KW - 6 Pulse
2 MW - 12 pulse
4 MW - 24 pulse

The future addition of the load mentioned in para 6 (e) would be phased to balance and increase the effective 24 pulse load.

Sub-division of 11 kv and 33 kv bus. The loadings detailed above are within the acceptable limits for a supply point having a short circuit capacity of 300 MVA at the point of common coupling. Since this short-circuit level is attained by using only one 33 kv feeder we would recommend that the supply system is normally run with the 33 kv and 11 kv bus couplers open and all rectifier loads at the laboratory allocated to the L.H. section fed from P.L.P.S. (fig.4). The R.H. section will then be harmonic free and suitable for other MANWEB 11 kv network interconnections and laboratory loads requiring a respectable sinusoid.

This sub-division will require a suitably rated transformer (5 MW ?) for non-rectifier loads and other 11 kv interconnections to be provided, and an increase from 7.5 MVA to 10 MVA in the proposed transformer for the rectifier bus.

J.A.F.

17th July, 1963.

Appendix

Harmonic currents in AC supply

Symbols -

m = number of phase groups

p = number of transformer phases per group

mp = pulse number

n = harmonic number

k = any integer

I_D = direct current per phase group

I_{DC} = DC Load current

X_c = commutating reactance, anode to anode, in ohms.

E_{so} = secondary phase to neutral volts (RMS)

α = angle of grid delay

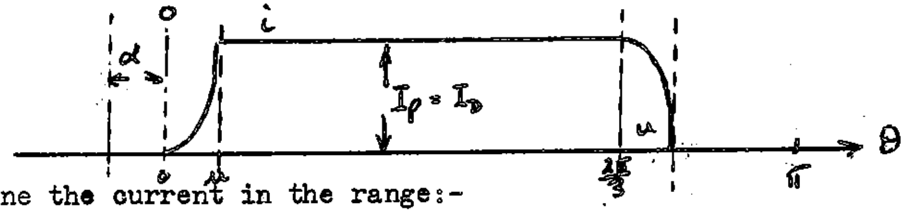
μ = overlap angle

ϕ = harmonic phase angle (in harmonic degrees)

ϕ/n = harmonic phase angle (in fundamental degrees)

The currents produced in the AC supply by a rectifier load may be resolved into a fundamental and harmonic components, with the Harmonic components having order $n = kmp \pm 1$.

On the basis of the primary current waveform of a 6 phase double star rectifier as shown below:-



we define the current in the range:-

θ		i
$0 \longrightarrow \mu$	AS	$\dfrac{\cos\alpha - \cos(\theta+\alpha)}{\cos\alpha - \cos(\mu+\alpha)} I_p$
$\mu \longrightarrow \frac{2\pi}{3}$	"	I_p
$\frac{2\pi}{3} \longrightarrow \left(\frac{2\pi}{3}+\mu\right)$	"	$\dfrac{\cos(\theta+\alpha-\frac{2\pi}{3}) - \cos(\mu+\alpha)}{\cos\alpha - \cos(\mu+\alpha)} I_p$
$\left(\frac{2\pi}{3}+\mu\right) \longrightarrow \pi$	"	0

The fourier analysis of this current waveform (i) can be expressed in the series:-

$$i = a_1 \sin\theta + a_5 \sin 5\theta + a_7 \sin 7\theta + a_{11} \sin 11\theta + \cdots$$
$$+ b_1 \cos\theta + b_5 \cos 5\theta + b_7 \cos 7\theta + b_{11} \cos 11\theta + \cdots$$

and we require to calculate the values a_n and b_n

$$b_n = \frac{1}{\pi}\int f(\theta) \cos n\theta \, d\theta$$
$$a_n = \frac{1}{\pi}\int f(\theta) \sin n\theta \, d\theta$$

These coefficients are given in terms of the harmonic number (n), overlap angle (μ) and delay angle (α) by:-

$$a_n = \frac{4I_f}{\pi}\left[\frac{P_n \sin\frac{\pi n}{3} + Q_n \cos\frac{\pi n}{3}}{n(n^2-1)\left[\cos\alpha - \cos(\mu+\alpha)\right]}\right] \sin\frac{\pi n}{3}$$

and $$b_n = \frac{4I_f}{\pi}\left[\frac{Q_n \sin\frac{\pi n}{3} - P_n \cos\frac{\pi n}{3}}{n(n^2-1)\left[\cos\alpha - \cos(u+\alpha)\right]}\right] \sin\frac{\pi n}{3}$$

where
$$P_n = n\sin(u+\alpha)\cos nu - \cos(u+\alpha)\sin nu - n\sin\alpha$$
$$Q_n = n\sin(u+\alpha)\sin nu + \cos(u+\alpha)\cos nu - \cos\alpha$$

and
$$\cos(u+\alpha) = \cos\alpha - \frac{I_D X_c}{\sqrt{2}\sqrt{3}E_{s0}}$$

The RMS of the n^{th} harmonic current is therefore given by:-

$$I_n = \frac{\sqrt{a_n^2+b_n^2}}{\sqrt{2}} = \frac{2\sqrt{2}I_f}{\pi}\left[\frac{\sqrt{P_n^2+Q_n^2}\sin\frac{\pi n}{3}}{n(n^2-1)\left[\cos\alpha - \cos(u+\alpha)\right]}\right]$$

Since the expressions for a_n and b_n above, become indeterminate when n = 1 the fundamental current component must be derived seperately as follows:-

$$a_1 = \frac{\sqrt{3}\,I_p}{2\pi}\left[\frac{1}{\cos\alpha - \cos(u+\alpha)}\right]\Big\{\cos\alpha\left[\sin^2 u - \sqrt{3}(u - \sin u\cos u)\right] + \sin\alpha$$
$$\times\left[-\sqrt{3}\sin^2 u + u + \sin u\cos u\right]\Big\}$$

$$b_1 = \frac{\sqrt{3}\,I_p}{2\pi}\left[\frac{1}{\cos\alpha - \cos(u+\alpha)}\right]\Big\{\cos\alpha\left[\sqrt{3}\sin^2 u + (u - \sin u\cos u)\right] + \sin\alpha$$
$$\times\left[\sin^2 u + \sqrt{3}(u + \sin u\cos u)\right]$$

The RMS of the fundamental current is therefore given by:-

$$I_1 = \frac{\sqrt{3}\,I_p}{\sqrt{2}\,\pi}\left[\frac{1}{\cos\alpha - \cos(u+\alpha)}\right]\sqrt{u^2 - 2u\sin u\cos u\cos 2\alpha + \sin^2 u + 4u\sin^2 u\cos\alpha\sin\alpha}$$

These expressions for I_n and I_1, are used in the calculation of the curves of $\frac{I_n}{I_1}$ versus α in Fig.1, based on rectifier circuit constants giving $\mu = 25^\circ$ when $\alpha = 0$.

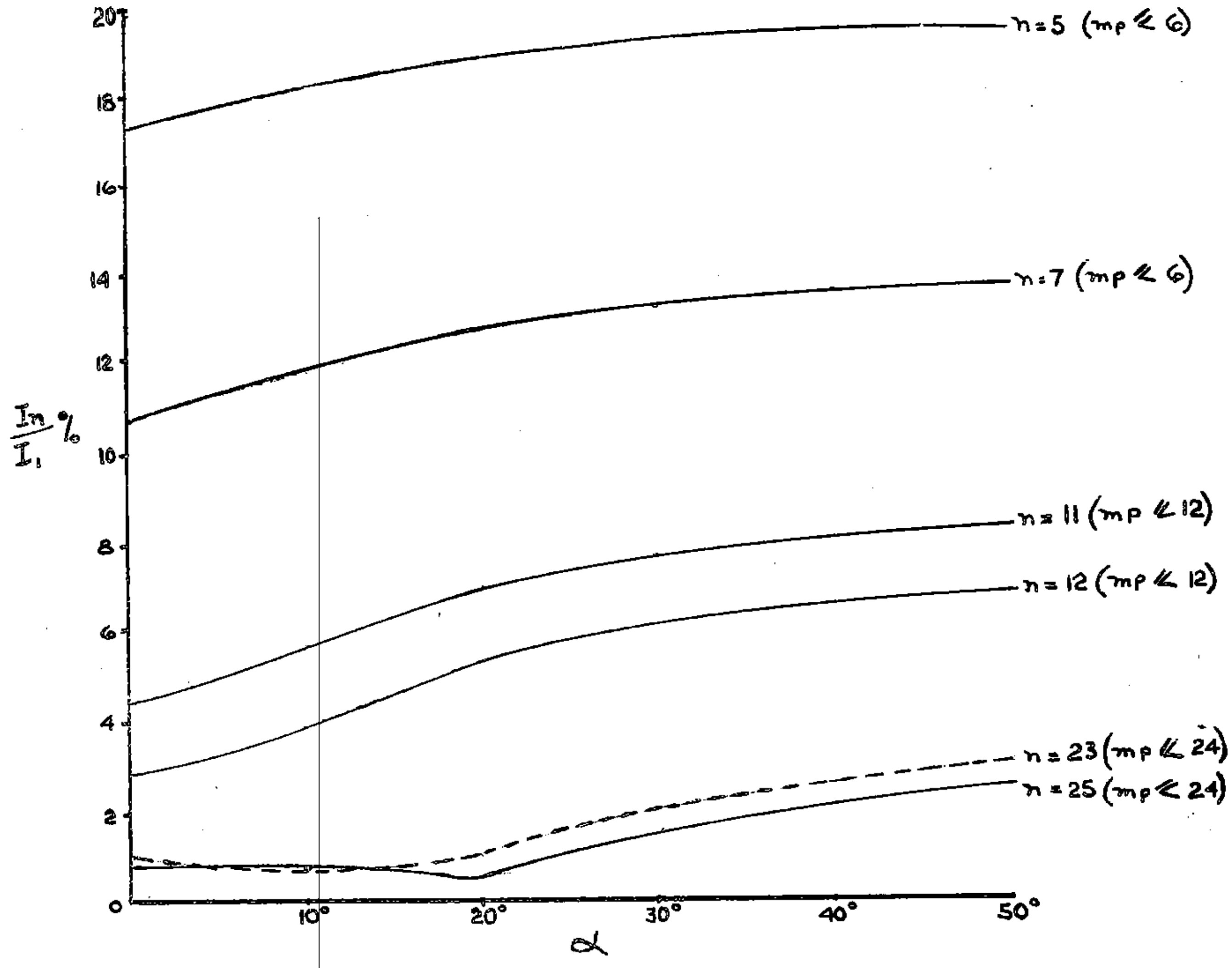
The phase angle of the harmonic is given by

$$\phi = -\frac{\pi n}{3} - \tan^{-1}\frac{a_n}{b_n} \qquad \text{in harmonic degrees}$$

for $\frac{di_n}{dt}$ is positive with respect to $\theta = 0$

Or in terms of table 1 zero point

$$\phi = -\frac{\pi n}{3} - \tan^{-1}\frac{a_n}{b_n} - \alpha n \qquad \text{in harmonic degrees.}$$



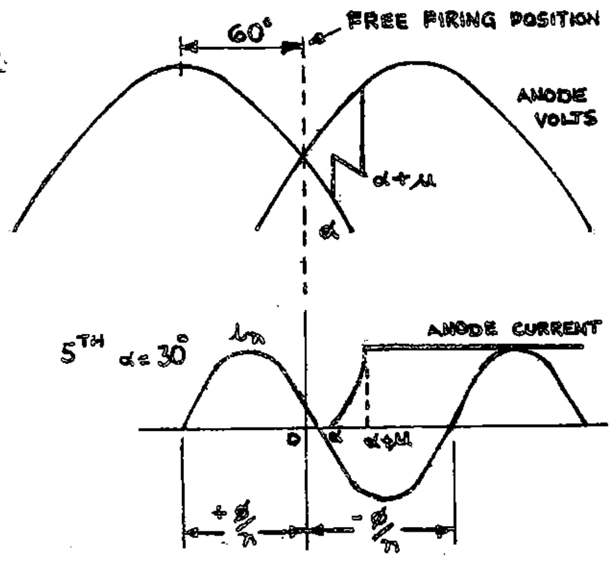
HARMONIC CURRENT AS A PERCENTAGE OF THE FUNDAMENTAL. (FOR CIRCUIT HAVING $\mu_0 = 25°$)

FIG. 1.

TABLE 1.

HARMONIC PHASE ANGLE (ϕ/n) VERSUS GRID DELAY ANGLE (α).

α	HARMONIC ORDER $n = kmp \pm 1$						
	5TH	7TH	11TH	13TH	23RD	25TH	
0°	-23.4°	-13°	-20.7°	-16.6°	-7.85°	-6.4°	
10°	-26.4°	-16.3°	-23.2°	-18.5°	-10.5°	-9.6°	
20°	-33°	-22.4°	-29.8°	-25°	-13.3°	-12.4°	
30°	-41.4°	-30.9°	-5.5°	-5.2°	-5.2°	-5.6°	
40°	-50.4°	-40°	-14.3°	-13.8°	-14.3°	0°	
50°	-59.4°	-49.5°	-23.8°	-15.8°	-7.8°	-9.2°	



ORDER OF HARMONIC	EFFECTIVE NUMBER OF PHASES		
	6	12	24
5	18.5	4.5 ✱	2.25 ✱
7	12	3 ✱	1.5 ✱
11	6	6	3 ✱
13	4.5	4.5	2.25 ✱
17	2	0.5 ✱	0.25 ✱
19	1.5	0.4 ✱	0.2 ✱
23	1	1	1
25	1	1	1

TABLE 2.

MAXIMUM HARMONIC CURRENTS AS A PERCENTAGE OF RATED LOAD CURRENT (FOR $\alpha = 0$)

✱ THEORETICALLY ZERO FOR (IDEAL) SYMMETRICAL CONDITIONS.

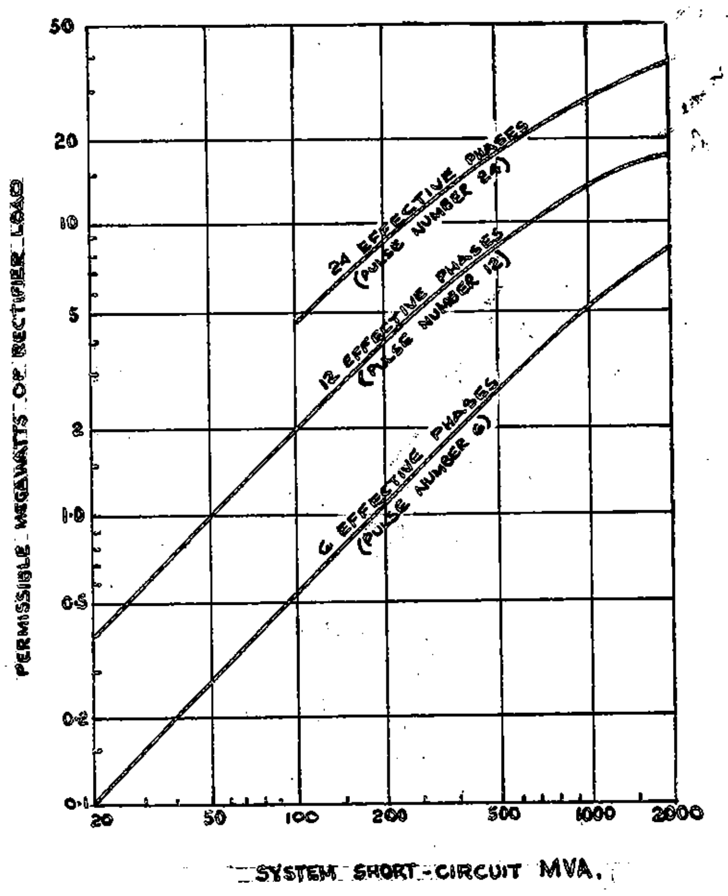
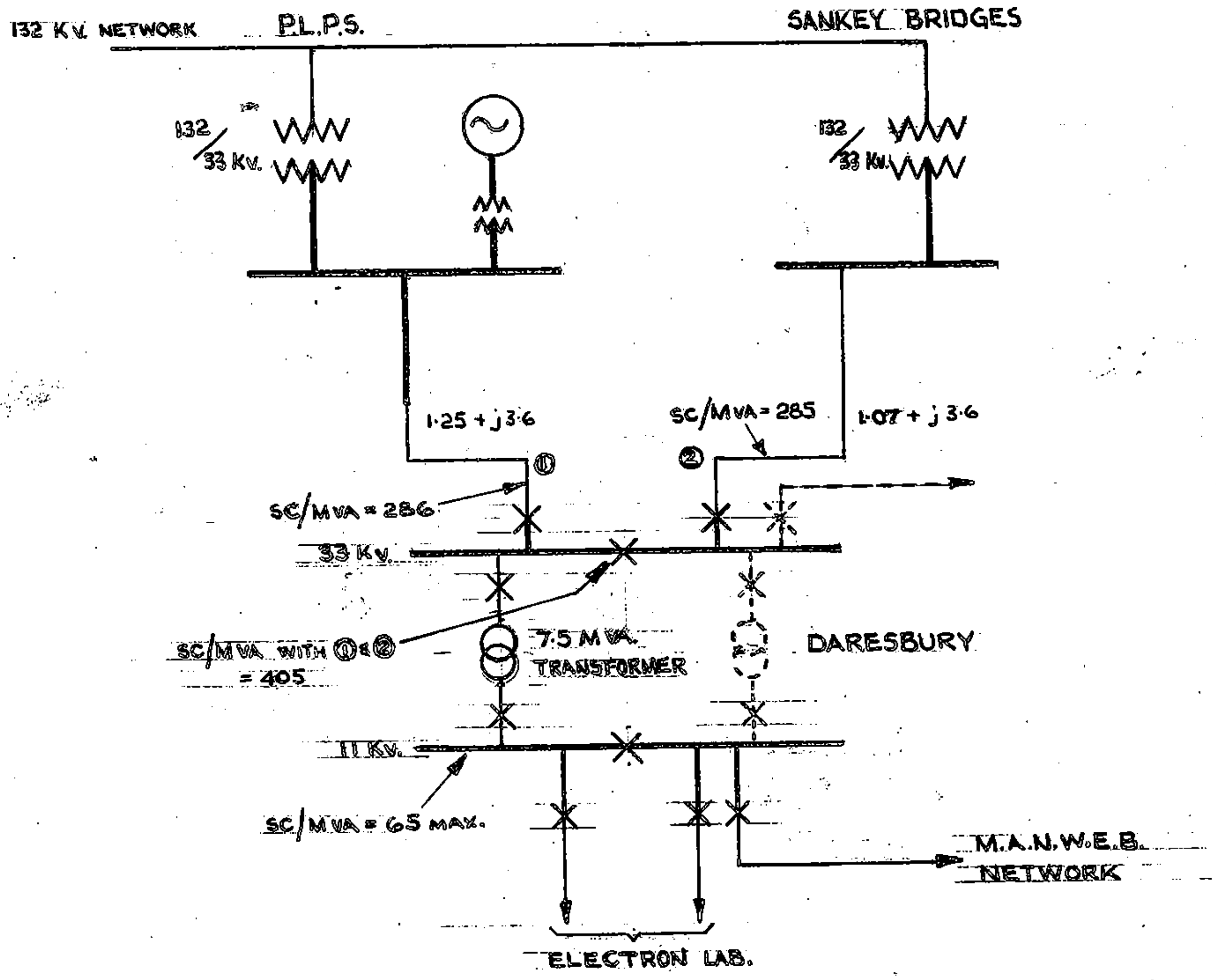


FIG. 2.



BASED ON M.A.N.W.E.B. SCHEMATIC MNW 2A-9313 W. DATED 4/7/63.

FIG. 3.

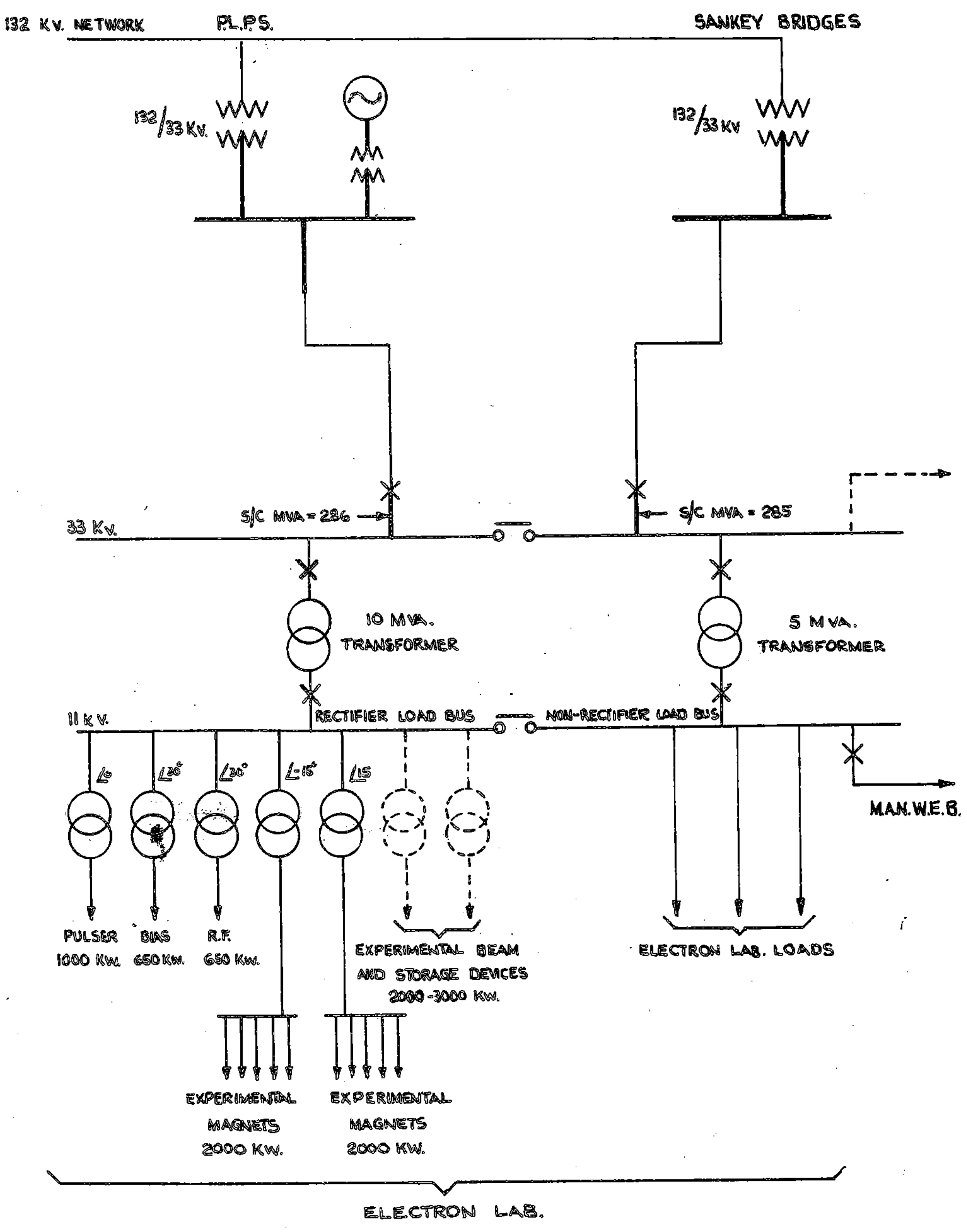


FIG. 4. PROPOSED ARRANGEMENT OF LABORATORY LOADS AT M.A.N.W.E.B. BUS.