Investigation of using a 1-phase to 3-phase static phase converter for fluorescent lighting loads
by Kung-Wei Hsiao

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University

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The purpose of this investigation is to determine how the l-phase to 3-phase static phase converter can be used on fluorescent lighting loads.

Two types of lamps have been tested, namely, the 96-T12-73 slim lamp and the 15-watt cold-white lamp.

The lamps are connected into delta to the phase converter. The balances of the system have been investigated for various supply voltages. Lamps starting under this circuit connection is tested.

The stroboscopic effect of the fluorescent lamp is reduced to 5% to 8% by this circuit connection.

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Approved:

E.W. Schilling
Head, Major Department

G. Dale Shickels
Chairman, Examining Committee

Leon H. Johnson
Dean, Graduate Division

Bozeman, Montana
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ABSTRACT

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CHAPTER I

INTRODUCTION

Every lamp when burned in the usual manner on alternating current has a non-uniform light output caused by the cyclic variations in current. A fluorescent lamp is an electric discharge device. Instead of generating light from direct heating of the tungsten wire, as in an incandescent lamp, the fluorescent lamp is not to produce light, but rather to generate a short-wave ultraviolet and then employ fluorescent chemicals or phosphors which can effectively convert this ultraviolet energy into visible light. As soon as the current which passes through the lamp is zero, there will be no more short-wave ultraviolet wave to excite the fluorescent chemicals, the lamp will practically generate no light at this event. Therefore, the light drops to zero along with the current between each half cycle.

This flicker or stroboscopic effect causes certain strain on human eyes. Hence various means have been developed in order to reduce this effect. One of the effective means to reduce this flicker is by using several lamps together, each supplied by a different phase voltage, so that the flicker of each lamp occurs at a different time. The net result will greatly reduce this stroboscopic effect. The two-lamp ballast is practically based on this fact.

It is easy to see that by supplying a balanced three-phase voltage to a three-lamp set, the flicker of this whole set will be far more reduced than the flicker of a two-lamp circuit.

Recently certain means have been developed which serve as a very convenient way to split a single phase, almost under all load conditions, into a balanced three-phase system. Therefore, by suitable application of this circuit, it is possible to reduce the stroboscopic effect in fluorescent lights.

This investigation is mainly concerned with the application of this static phase converter to the fluorescent lamp and to see how the circuit will be balanced and how the stroboscopic effect is reduced.

In this investigation, two types of fluorescent lamps have been tested, namely the 96-T12-73 slim lamp and the 15-watt cold-white lamp.

CHAPTER II

THE STATIC PHASE CONVERTER

In a recent article,[1] J. C. Hogan suggested a static phase converter which consists of a condenser and an autotransformer. By adjusting the value of the condenser and the ratio of the autotransformer, it can convert a single phase into a well balanced three-phase system for any load possessing a lagging power factor. The general form of the circuit is shown in Figure 1.

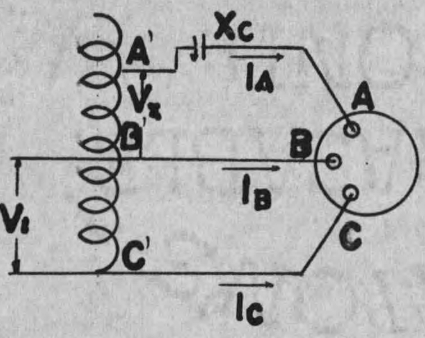

Figure 1. Circuit of the static phase converter.

Where: A, B and C are the terminals of the three balanced phases.

To secure a balanced three-phase system the value of Xc and the N of the transformer can be calculated from the following formulas. (See Appendix)

$$X_C = \frac{3}{2}\,\frac{Z_{m1}}{\sin\theta_{m1}}$$

$$N = \frac{\cos(\theta_{m1} + 30^\circ)}{\sin\theta_{m1}}$$

---

[1] Hogan, J. C., AIEE Transaction, "Analyzing Single-Phase to 3-Phase Static Phase Converter," January 1956, p. 403.

Where: Zm_1 is the positive sequence impedance per phase of the load which is in Y connection.

θm_1 is the positive sequence power factor.

In order to make this static phase converter apply to the fluorescent lamp, certain changes are necessary.

Since most lighting systems are 110 volts, to secure enough voltage for the fluorescent lamps, the lamps should be connected in delta. Since these lamps are similar, they may be treated as a balanced three-phase load which can be easily transferred into an equivalent Y connected load by letting:

$$Zm_1 = \frac{1}{3}Za$$

Where: Za is the impedance of each lamp in delta connection.

Zm_1 is the equivalent impedance per phase in Y connection.

Furthermore, since the lamps form a balanced delta circuit, it can be assumed that their negative and zero sequence impedance is zero. Knowing the Za and power factor of each lamp, the values of N and Xc may be readily determined.

CHAPTER III

TESTING ON INDIVIDUAL LAMPS TO FIND THEIR ELECTRICAL CHARACTERISTICS

The aim of this test is to find out the impedance and power factor of each lamp so as to apply to the foregoing equations to secure a balanced three-phase system.

However, as the lamp circuit is connected in delta to the static phase converter, the third harmonic of the lamp current will circulate around the delta and will not appear in the line current. Hence the impedance and power factor of each lamp which is calculated, based on testing of individual lamps, will be different from those in delta connection owing to the absence of the third harmonic. To make less error, it is assumed that there is no third harmonic in the lamp current. A wave analyzer is used to determine the fundamental, third harmonic and fifth harmonic of the lamp current. The fifth harmonic is negligible compared to the fundamental; hence only the fundamental along with the power consumed and applied voltage is used to find the power factor of each lamp which has been shown in Table 1 and Table 2.[1/]

There is a condenser in the ballast of the fluorescent lamp circuit which merely serves as a power-factor correction device, therefore in our test we disconnect it from the circuit.

The impedance and power factor of the fluorescent lamp is not a constant. It changes with different supply voltages. The supply voltage

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[1/] The lamp impedance is calculated based on the total lamp current (including the third harmonic) since it is closer to the value of the actual balance by this way.

was varied from 80 volts to 140 volts with an increase of 5 volts in each step. Then all readings were taken and the impedances and power factors were calculated. The complete data is shown in Table I and Table II. The power consumed as listed in the tables is the actual power consumed in the lamp. The meter loss has been subtracted.

Three different lamps of each kind have been tested.

TABLE Ia. FIRST LAMP (15-WATT COLD-WHITE).

V	I	P	I_1	I_3	I_5	$\text{Cos}\ \Theta m_1$	Z
140	0.55	29.4	0.50	.108		0.420	254
135	0.48	26.1	0.436	.089		0.444	281
130	0.422	22.7	0.38	.070		0.460	308
125	0.372	20.6	0.336	.0538		0.491	336
120	0.330	18.0	0.296	.041		0.508	364
115	0.285	16.4	0.260	.0324		0.550	404
110	0.254	14.8	0.234	.0268		0.576	433
105	0.227	13.3	0.212	.0230		0.598	462
110	0.200	11.8	0.186	.0200		0.634	500
95	0.178	10.2	0.160	.0190		0.672	534
90	0.151	8.6	0.138	.0176		0.692	596
85	0.126	7.0	0.114	.0160		0.724	674
80	0.100	5.6	0.090	.0150		0.779	800

Remark:
V Supply voltage in volt
I Lamp current in ampere
P Power consumed in watt
I_1 Fundamental current in ampere
I_3 Third harmonic in ampere
I_5 Fifth harmonic in ampere
$\text{Cos}\ \Theta m_1$ Power factor of fundamental
Z Lamp impedance in ohm

TABLE Ib. SECOND LAMP (15-WATT COLD-WHITE).

V	I	P	I_1	I_3	I_5	Cos Θm_1	Z
140	0.534	28.2	0.49	0.094		0.411	262
135	0.470	25.6	0.432	0.078		0.439	287
130	0.416	22.5	0.390	0.058		0.445	312
125	0.368	20.5	0.350	0.0450		0.470	350
120	0.332	18.0	0.316	0.0356		0.486	361
115	0.302	16.4	0.284	0.0296		0.503	380
110	0.272	14.9	0.252	0.0256		0.539	404
105	0.239	13.2	0.228	0.0230		0.552	440
100	0.211	12.1	0.200	0.0210		0.605	473
95	0.185	10.4	0.178	0.0200		0.616	513
90	0.159	8.4	0.150	0.0184		0.621	566
85	0.130	7.3	0.120	0.0176		0.715	654
80	0.102	5.8	0.090	0.0160		0.805	784

TABLE Ic. THIRD LAMP (15-WATT COLD-WHITE).

V	I	P	I_1	I_3	I_5	Cos θm_1	Z
140	0.518	27.7	0.476	0.104	0.0334	0.417	270
135	0.458	24.7	0.418	0.080	0.0222	0.439	295
130	0.403	22.7	0.376	0.0624	0.0152	0.464	323
125	0.358	20.1	0.334	0.0488	0.0092	0.481	349
120	0.317	17.5	0.296	0.0398	0.0044	0.493	379
115	0.274	15.6	0.264	0.0336	0.0020	0.515	420
110	0.244	14.7	0.232	0.0296	0.0011	0.575	450
105	0.220	13.2	0.208	0.0268	0.0012	0.605	476
100	0.192	11.5	0.180	0.0240	0.0012	0.640	520
95	0.167	9.9	0.154	0.0224	0.0022	0.679	570
90	0.140	8.1	0.128	0.0210	0.0028	0.704	643
85	0.114	6.5	0.100	0.0192	0.0033	0.764	745
80	0.090	4.9	0.076	0.0170	0.0037	0.805	890

TABLE IIa. FIRST LAMP (SLIM LINE LAMP 96-T12-73)

V	I	P	I_1	I_3	I_5	Cos Θm_1	Z
135	3.72	141.5	3.40	0.454	0.130	0.307	36.3
130	3.35	128.6	3.16	0.358	0.086	0.312	38.8
125	3.08	118.2	2.88	0.272	0.058	0.328	40.6
120	2.83	109.2	2.60	0.198	0.0304	0.350	42.4
115	2.64	101.8	2.40	0.156	0.0182	0.369	43.5
110	2.44	94.3	2.20	0.130	0.0160	0.390	45.1
105	2.26	87.5	2.00	0.112	0.0158	0.416	46.5
100	2.10	81.2	1.88	0.100	0.016	0.431	47.6
95	1.95	74.9	1.72	0.092	0.0158	0.458	48.7
90	1.80	69.9	1.58	0.076	0.0156	0.491	50.0
85	1.64	63.0	1.40	0.062	0.0156	0.530	51.9
80	1.49	56.7	1.24	0.056	0.0156	0.571	53.7

TABLE IIb. SECOND LAMP (SLIM LINE LAMP)

V	I	P	I_1	I_3	I_5	Cos θm_1	Z
135	3.51	135.1	3.44	.424	.116	0.291	38.4
130	3.23	123.8	3.12	.310	.072	0.305	40.2
125	2.97	114.2	2.88	.240	.040	0.318	42.1
120	2.75	105.6	2.64	.186	.030	0.333	43.6
115	2.56	99.00	2.48	.146	.020	0.347	44.9
110	2.40	92.30	2.28	.134	.018	0.368	45.8
105	2.23	85.90	2.08	.120	.018	0.393	47.1
100	2.06	79.00	1.92	.116	.017	0.411	48.5
95	1.91	73.4	1.76	.110	.017	0.439	49.7
90	1.77	67.9	1.62	.104	.017	0.466	50.9
85	1.61	61.4	1.46	.100	.016	0.495	52.7
80	1.46	55.3	1.30	.098	.016	0.531	54.8

TABLE IIc. THIRD LAMP (SLIM LINE LAMP).

V	I	P	I_1	I_3	I_5	Cos θm_1	Z
135	3.58	137.5	3.42	.372	.090	0.298	37.7
130	3.30	126.8	3.10	.288	.054	0.314	39.4
125	3.06	117.8	2.88	.210	.032	0.328	40.8
120	2.84	110.2	2.68	.162	.021	0.343	42.2
115	2.55	103.1	2.48	.150	.019	0.362	45.1
110	2.46	96.1	2.30	.132	.019	0.380	44.7
105	2.30	89.5	2.10	.124	.019	0.406	45.6
100	2.14	82.4	1.92	.116	.019	0.429	46.7
95	1.96	76.0	1.76	.108	.0186	0.455	48.5
90	1.81	70.1	1.60	.102	.0180	0.497	49.7
85	1.65	63.1	1.44	.096	.0180	0.518	51.5
80	1.50	57.0	1.28	.092	.0178	0.558	53.5

CHAPTER IV

BALANCING OF THE SYSTEM

It has been shown in Chapter III that neither the impedance nor the power factor of the lamp is a constant; they change as the supply voltage changes. But the static phase converter can furnish a balanced three-phase voltage only at a constant impedance and power factor of the load. As soon as the impedance and power factor of the lamps are changed due to the change of supply voltage, the system will no longer be balanced.

In these tests we wish to find out how the supply voltage will affect the balancing of this static phase converter.

125, 120, 115, 110 and 105 volts are chosen as the particular balancing voltages for the system. From Table I and Table II we find out the corresponding impedance and power factor of the lamps at these particular voltages. Then X_c and N values are calculated from equations 1 and 2. However, the impedances and power factors of the three lamps are not identical, so their mean values are taken. The results of these calculations are shown in Table III and Table IV.

However, the values of X_c and N for actual balance are little different from what we have calculated, which also has been shown in the same tables.

The general circuit connection is shown in Figure 2.

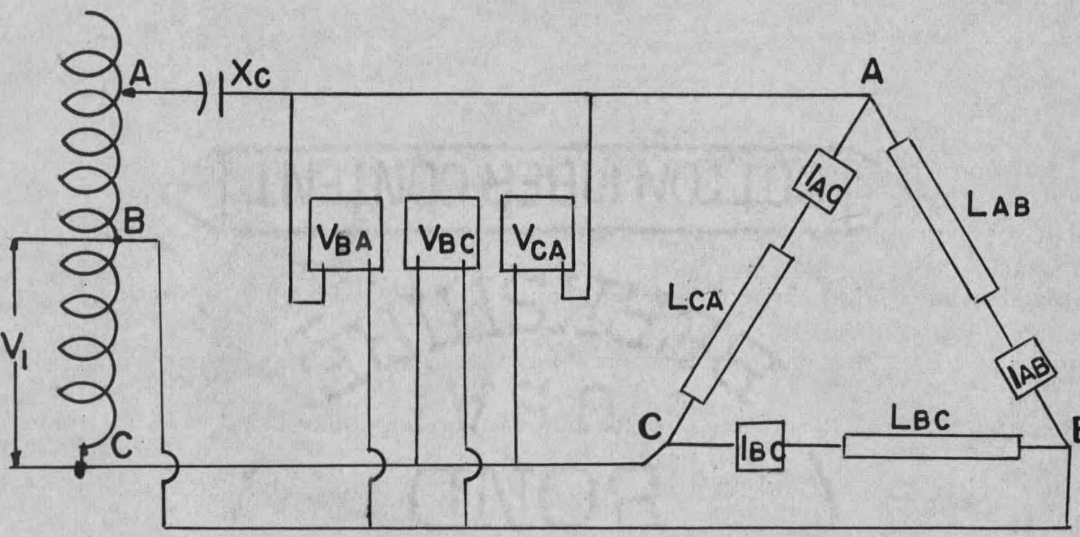

Figure 2. Lamp circuit.

After the system was balanced, the supply voltage V_1 was changed through a variac at the source. Phase current and voltage of the three lamps were recorded in order to see how the supply voltage affects the balance of the system.

Characteristic curves which show how the voltages and currents of these three lamps vary with various supply voltages are plotted in Figure 3 and Figure 4. However, as V_{bc} was the same as the supply voltage, it was not plotted on the curve sheets.

From Figures 3, and 4, it can be seen that V_{ca} and I_{ca} are almost constant during the variation of V_1, while the V_{ab} and V_{bc}, I_{ab} and I_{bc} changed proportionally to each other.

The voltage, current and power consumed of the whole system is shown in Table V and Table VI. The characteristic curve of the power factor of the whole system is shown in Figure 5 and Figure 6.

TABLE III. BALANCING CALCULATION FOR 15-WATT COLD-WHITE LAMP

Balancing Calculation					Actual Balancing	
V_1	Z	Cos θ_m	c	N	c	N
125	345	0.481	13.5 u.f.	-0.0249	13.8 u.f.	-0.024
120	368	0.496	12.5 u.f.	-0.005	12.8 u.f.	-0.0033
115	401	0.528	11.0 u.f.	0.0285	11.6 u.f.	0.0191
110	429	0.563	10.2 u.f.	0.090	10.9 u.f.	0.064

TABLE IV. BALANCING CALCULATION FOR SLIM LINE LAMP

Balancing Calculation					Actual Balancing	
V_1	Z	Cos θ	c	N	c	N
125	41.2	.326	122 u.f.	-.201	119.5 u.f.	- .205
120	42.7	.342	117 u.f.	-.185	114.65u.f.	-0.183
115	44.5	.359	111 u.f.	-.166	106.5u.f.	-0.167
110	45.2	.379	107 u.f.	-.145	107 u.f.	-0.150
105	46.1	.405	105 u.f.	-.116	104 u.f.	-0.132

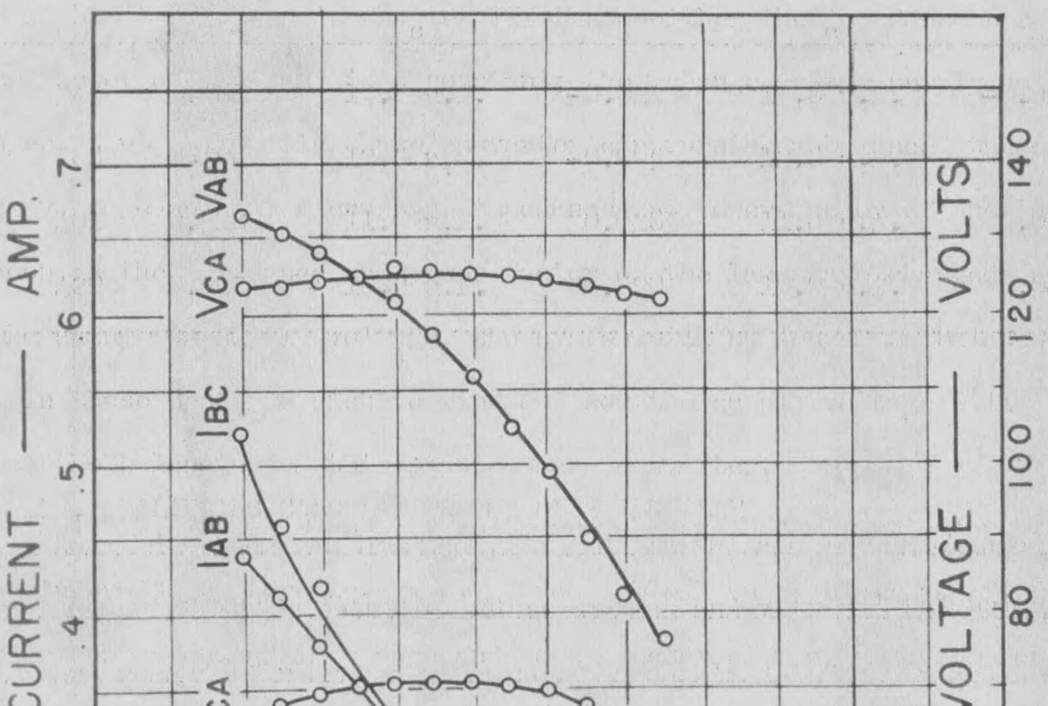

Figure 3a. 15-Watt Cold-White Lamp, Phase Current and Voltage Characteristics — Balanced at V_1 = 125 v.

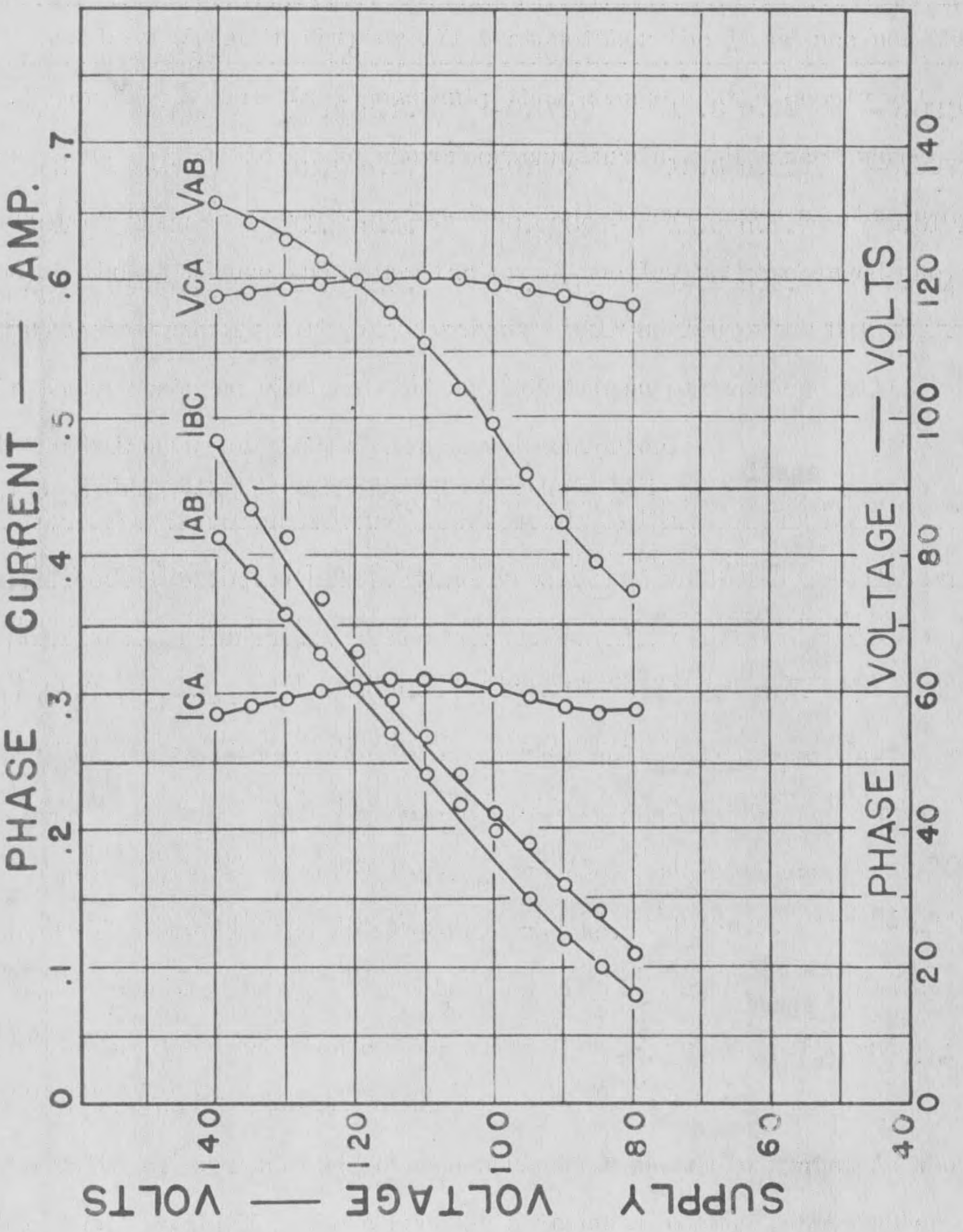

Figure 3b. **15-Watt Cold-White Lamp, Phase Current and Voltage Characteristics -- Balanced at V_1 = 120 v.**

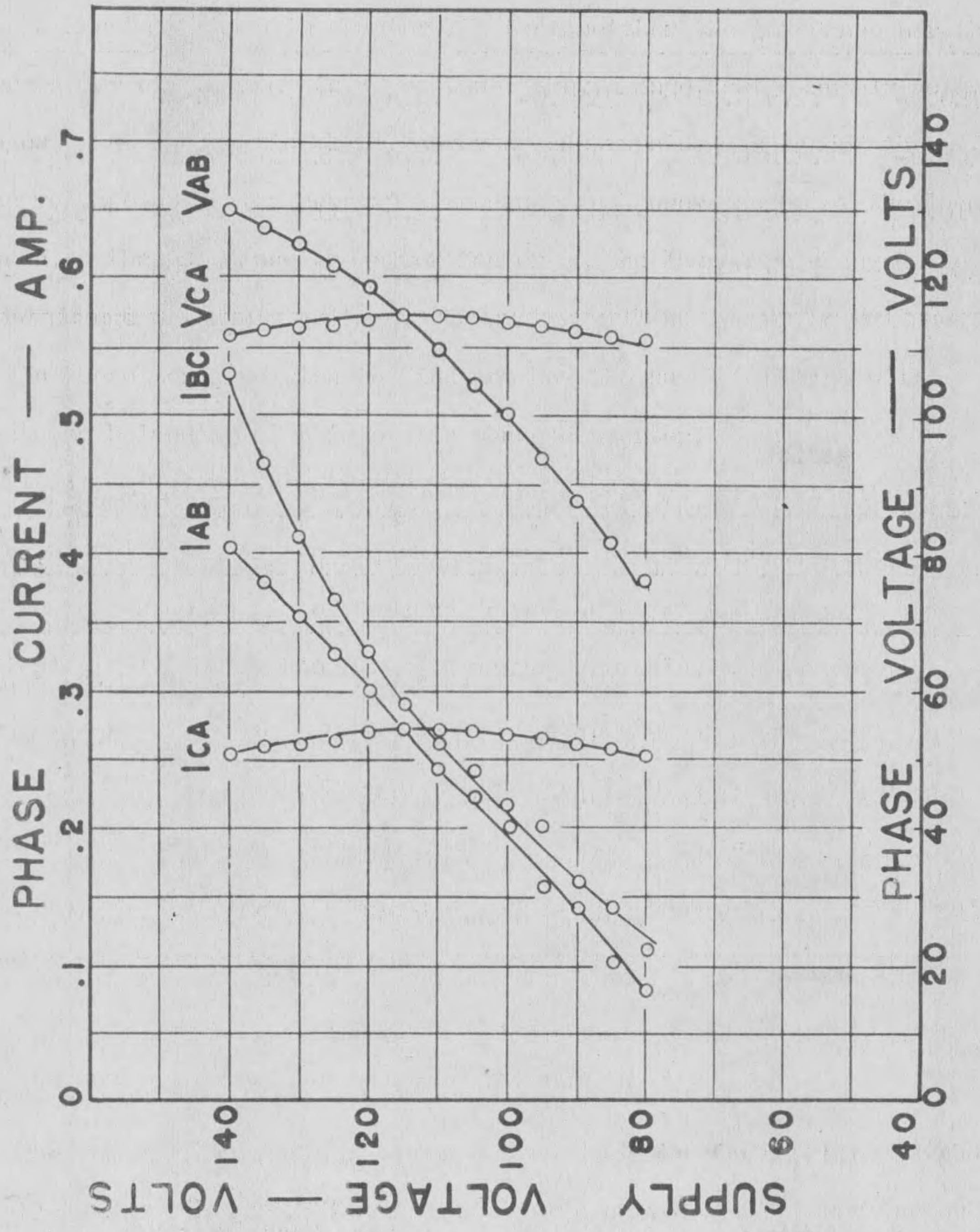

Figure 3 c. 15-Watt Cold-White Lamp, Phase Current and Voltage Characteristics — Balanced at V_1 = 115 v.

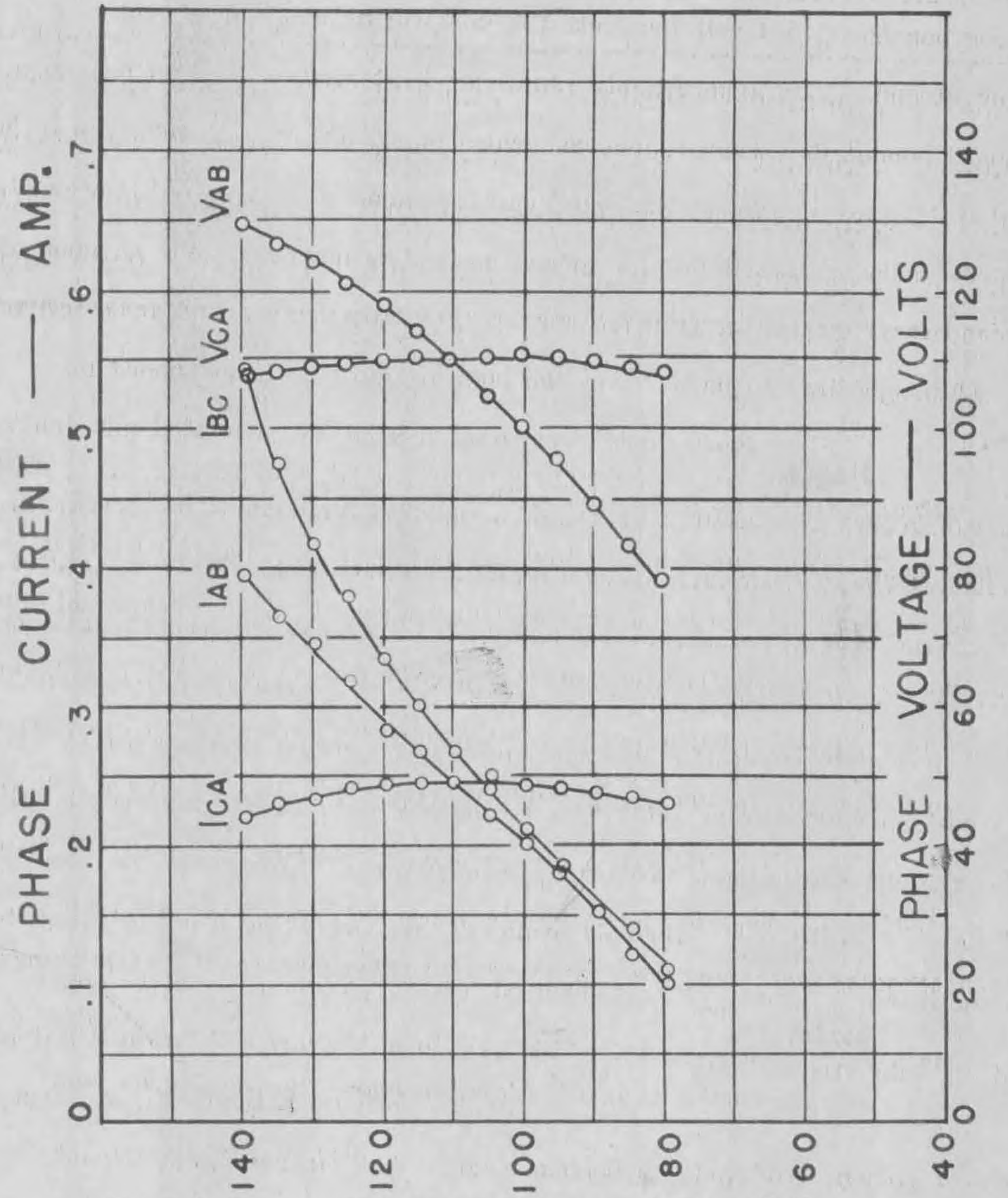

Figure 3d. 15-Watt Cold-White Lamp, Phase Current and Voltage Characteristics — Balanced at V_1 = 110 v.

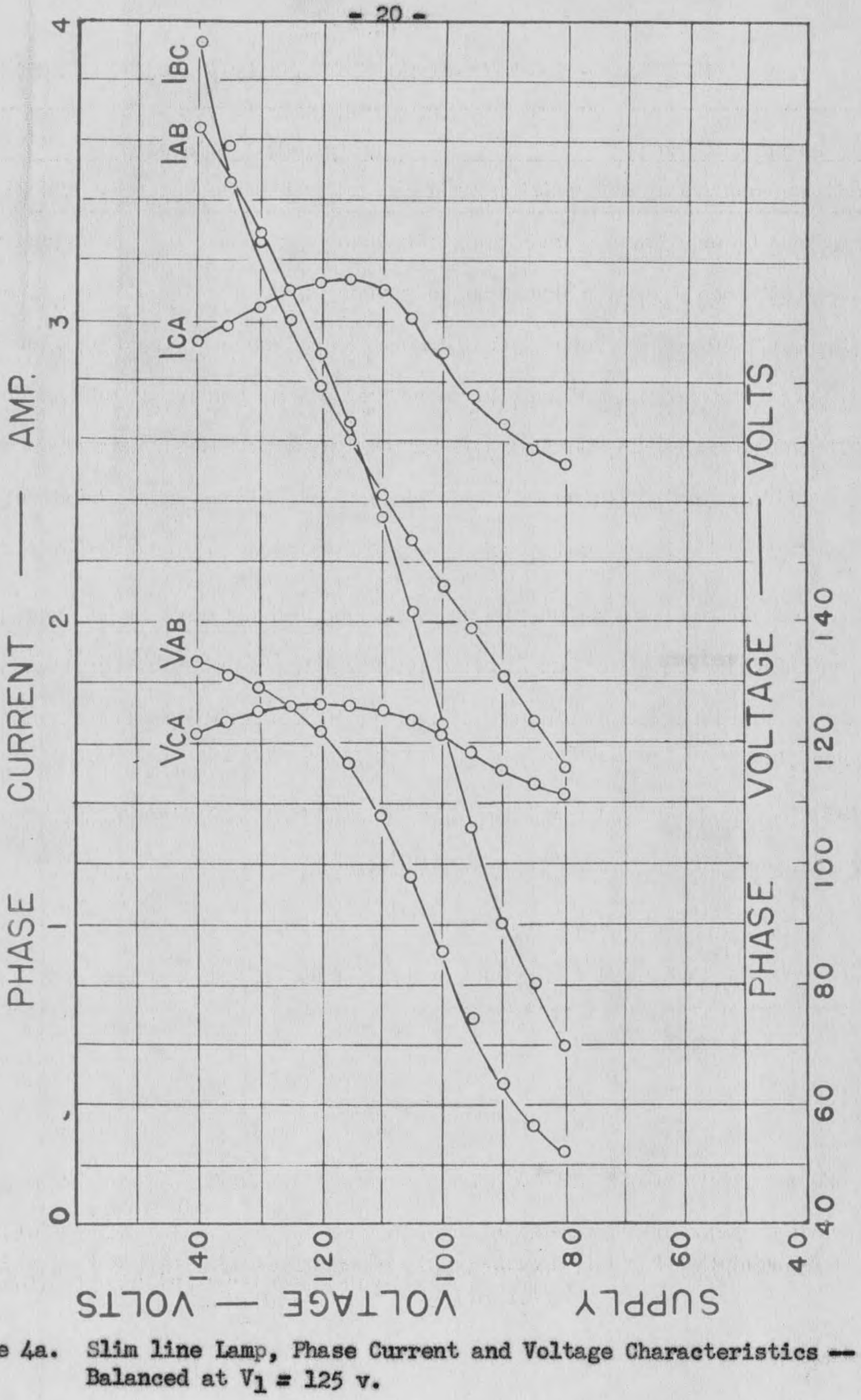

Figure 4a. Slim line Lamp, Phase Current and Voltage Characteristics — Balanced at $V_1 = 125$ v.

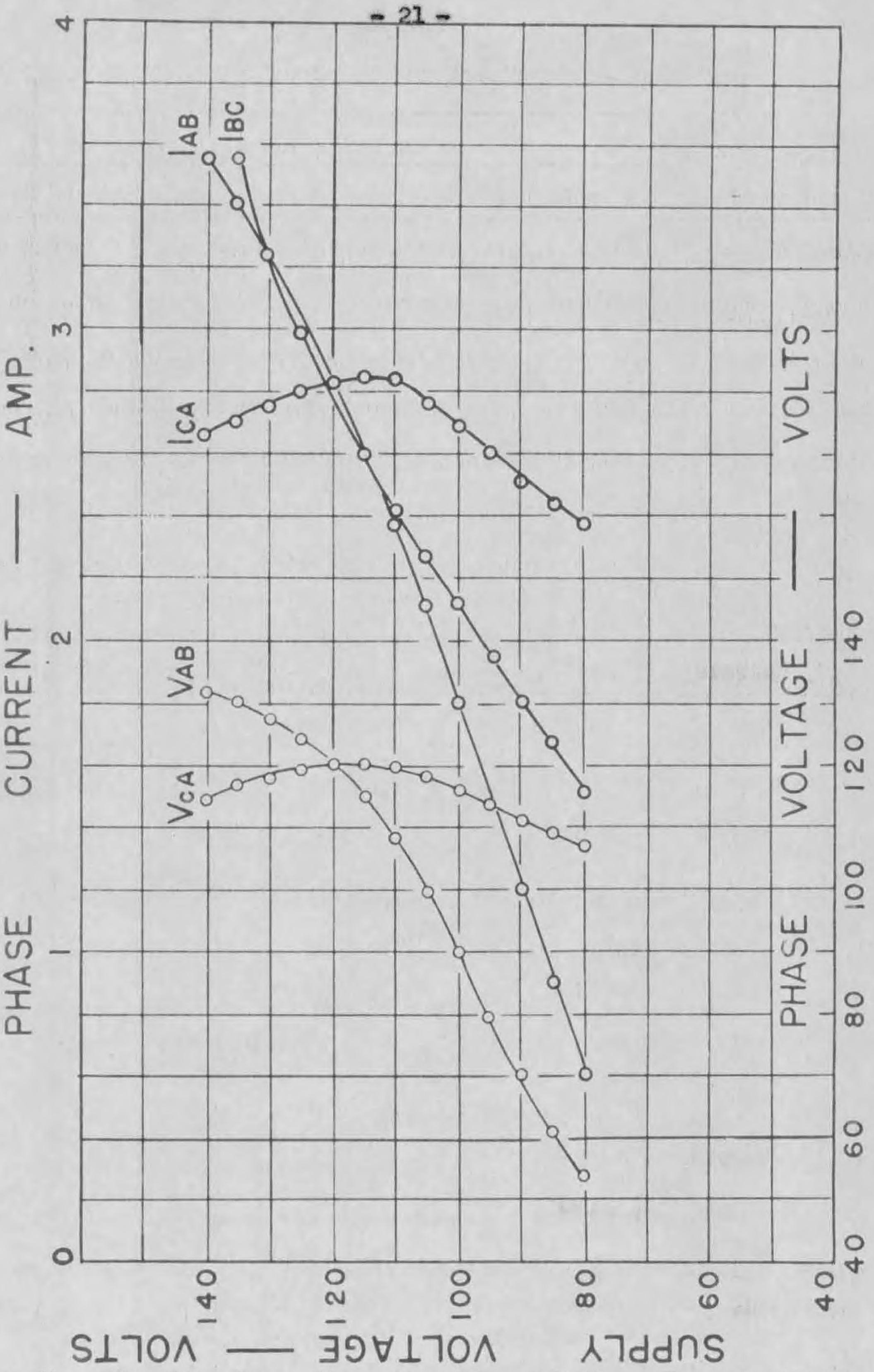

Figure 4b. Slim line Lamp, Phase Current and Voltage Characteristics -- Balanced at V_1 = 120 v.

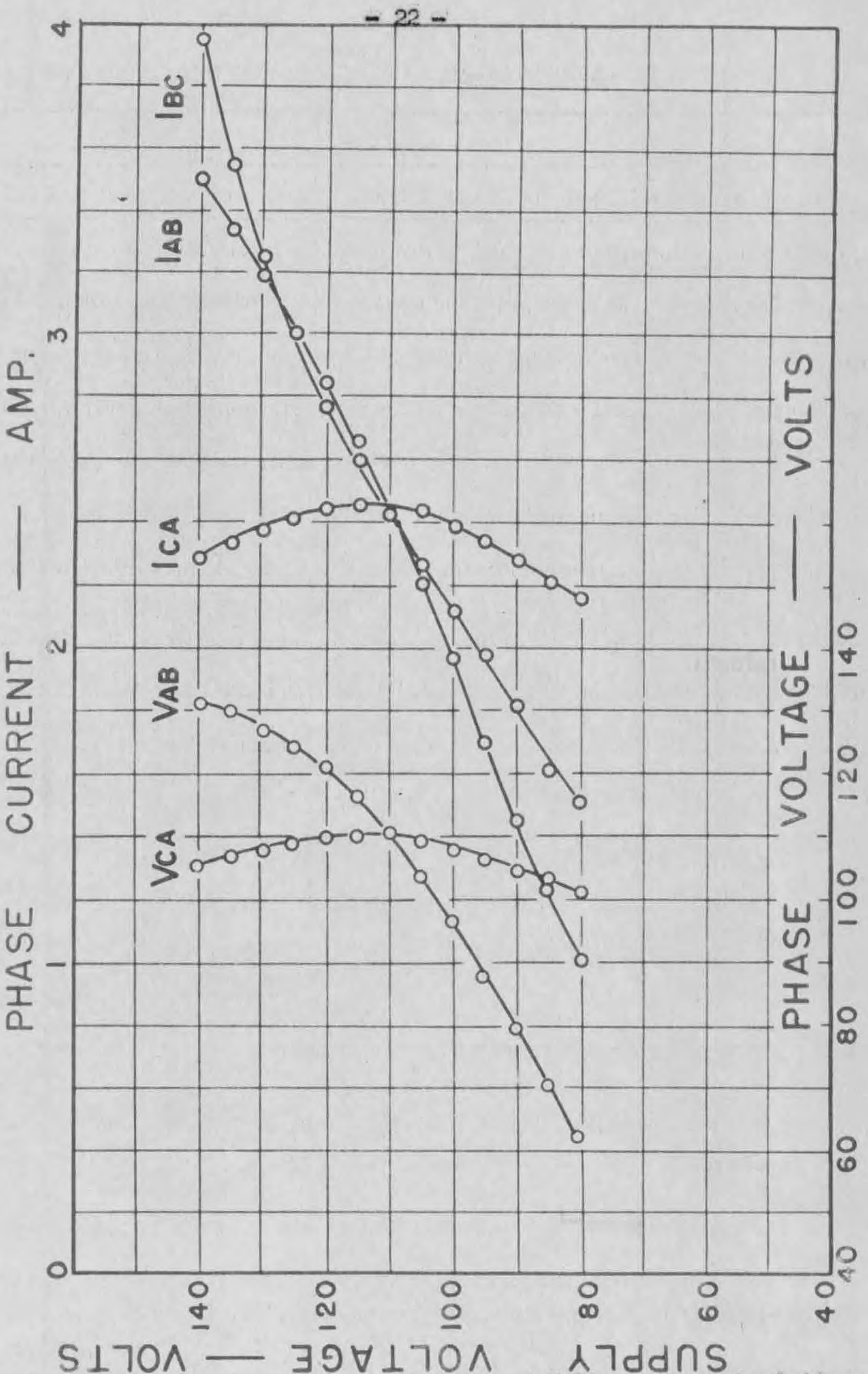

Figure 4c. Slim line Lamp, Phase Current and Voltage Characteristics — Balanced at $V_1 = 115$ v.

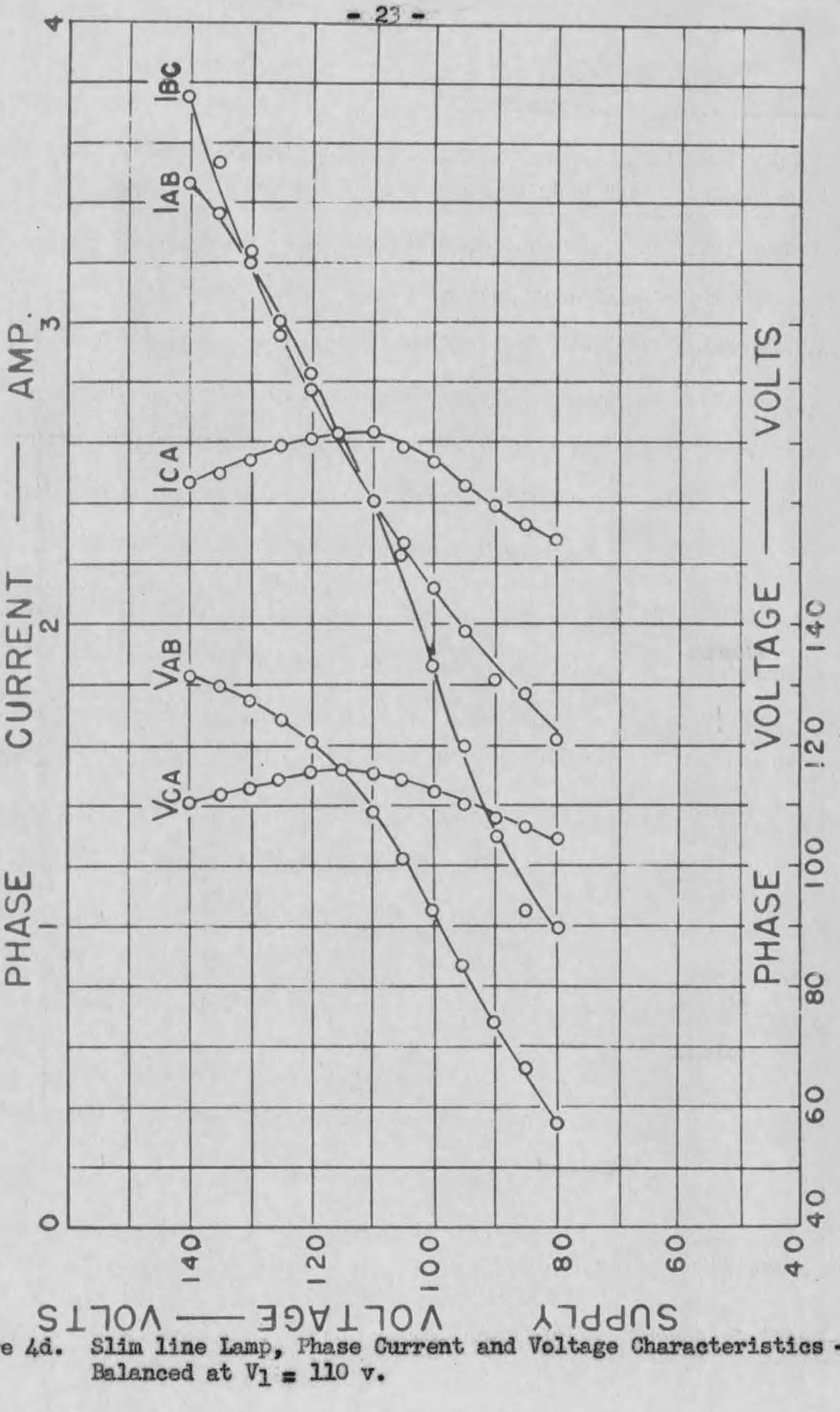

Figure 4d. Slim line Lamp, Phase Current and Voltage Characteristics -- Balanced at V_1 = 110 v.

TABLE Va. (15-WATT LAMP BALANCED AT $V_l =$ 125 VOLTS)

V_L	I_L	P_a	Cos Θ
140	0.800	83.0	0.741
135	0.770	79.0	0.760
130	0.728	75.1	0.794
125	0.692	71.2	0.823
120	0.667	67.4	0.842
115	0.645	64.5	0.870
110	0.632	61.2	0.880
105	0.621	57.8	0.886
100	0.609	54.3	0.892
95	0.593	50.4	0.895
90	0.579	46.5	0.892
85	0.552	40.9	0.871
80	0.518	35.3	0.851

P_a Power consumed in the system - watts
Cos Θ Power factor of the whole system

TABLE Vb. (15-WATT LAMP BALANCED AT V_L = 120 VOLTS)

V_L	I_L	P_a	Cos θ
140	.809	82.0	0.724
135	.735	77.2	0.777
130	.700	73.3	0.805
125	.668	68.8	0.824
120	.644	65.4	0.845
115	.622	61.4	0.859
110	.602	59.0	0.891
105	.593	55.8	0.896
100	.580	52.4	0.903
95	.565	48.7	0.908
90	.543	44.7	0.915
85	.520	39.7	0.898
80	.490	34.3	0.875

TABLE Vc. (15-WATT LAMP BALANCED AT V_1 = 115 VOLTS)

V_L	I_L	P_a	Cos θ
140	.757	79.9	0.753
135	.708	74.7	0.781
130	.670	70.7	0.812
125	.640	67.4	0.842
120	.615	64.1	0.869
115	.595	60.7	0.889
110	.578	57.2	0.900
105	.564	53.8	0.909
100	.550	50.8	0.923
95	.536	47.1	0.925
90	.519	43.5	0.930
85	.490	38.7	0.929
80	.461	34.3	0.929

TABLE Vd. (15-WATT LAMP BALANCED AT V_1 = 110 VOLTS)

V_L	I_L	P_a	Cos θ
140	.765	76.8	0.726
135	.695	71.8	0.764
130	.648	68.3	0.810
125	.629	65.1	0.829
120	.598	61.8	0.860
115	.577	58.5	0.881
110	.560	55.4	0.900
105	.548	52.6	0.915
100	.531	49.3	0.927
95	.518	45.8	0.930
90	.500	42.5	0.945
85	.476	37.9	0.961
80	.450	33.6	0.933

TABLE VIa. (SLIM LINE LAMP BALANCED AT V_1 = 125 VOLTS)

V_L	I_L	P_a	Cos θ
135	5.49	421	0.568
130	5.20	404	0.597
125	4.98	386	0.620
120	4.81	371	0.644
115	4.70	354	0.655
110	4.59	332	0.658
105	4.48	307	0.654
100	4.30	276	0.641
95	4.11	246	0.630
90	3.98	218	0.609
85	3.80	190	0.589
80*	3.90	187	0.600

*One lamp blacked out.

TABLE VIb. (SLIM LINE LAMP BALANCED AT V_1 = 120 VOLTS)

V_L	I_L	P_a	Cos θ
135	5.30	405	0.566
130	5.00	385	0.592
125	4.80	369	0.615
120	4.64	355	0.637
115	4.51	336	0.649
110	4.39	318	0.659
105	4.25	297	0.665
100	4.10	270	0.659
95	3.96	246	0.654
90	3.80	218	0.638
85	3.65	198	0.637
80	3.50	173	0.617

TABLE VIc. (SLIM LINE LAMP BALANCED AT V_1 = 115 VOLTS)

V_L	I_L	P_s	Cos θ
135	5.18	388	0.555
130	4.89	370	0.582
125	4.68	355	0.607
120	4.50	341	0.631
115	4.35	325	0.650
110	4.21	306	0.661
105	4.09	287	0.669
100	3.95	266	0.674
95	3.82	243	0.670
90	3.70	219	0.657
85	3.55	198	0.655
80	3.40	176	0.646

TABLE VId. (SLIM LINE LAMP BALANCED AT V_1 = 110 VOLTS)

V_L	I_L	P_a	$\cos\theta$
135	5.00	376	0.557
130	4.73	361	0.587
125	4.52	345	0.610
120	4.31	330	0.639
115	4.18	316	0.658
110	4.05	300	0.674
105	3.92	285	0.693
100	3.80	263	0.692
95	3.70	242	0.689
90	3.59	220	0.680
85	3.44	198	0.676
80	3.30	178	0.674

TABLE VIe. (SLIM LINE LAMP BALANCED AT V_1 = 105 VOLTS) LINE CURRENT VOLTAGE AND POWER FACTOR.

V_L	I_L	P_a	Cos θ
135	4.84	364	0.557
130	4.58	346	0.581
125	4.35	331	0.609
120	4.18	318	0.635
115	4.02	306	0.662
110	3.91	289	0.672
105	3.80	277	0.694
100	3.70	258	0.697
95	3.61	238	0.695
90	3.51	220	0.696
85	3.35	200	0.701
80	3.20	181	0.705

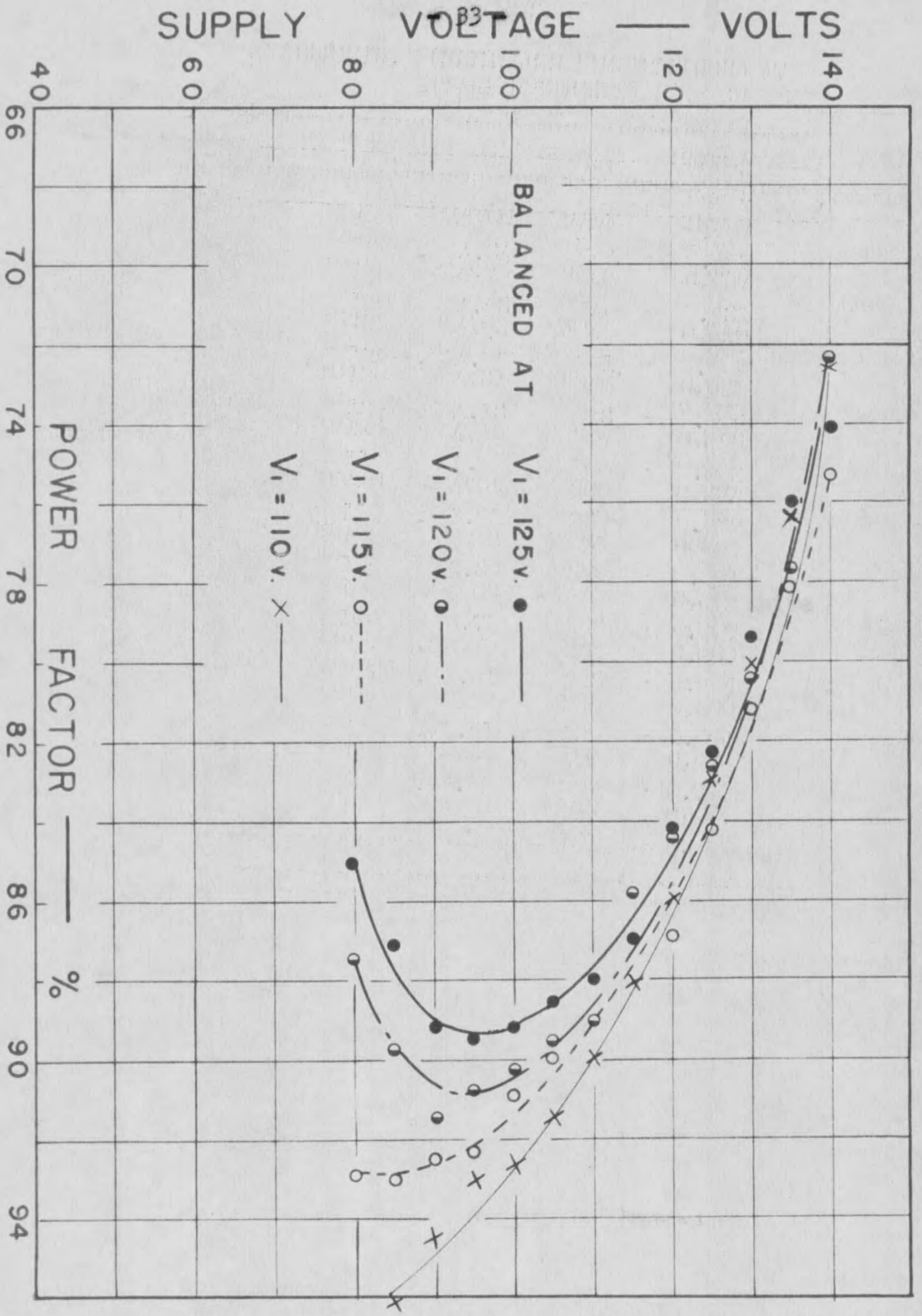

Figure 5. Power Factor Characteristics — 15-Watt Cold-White Lamp.

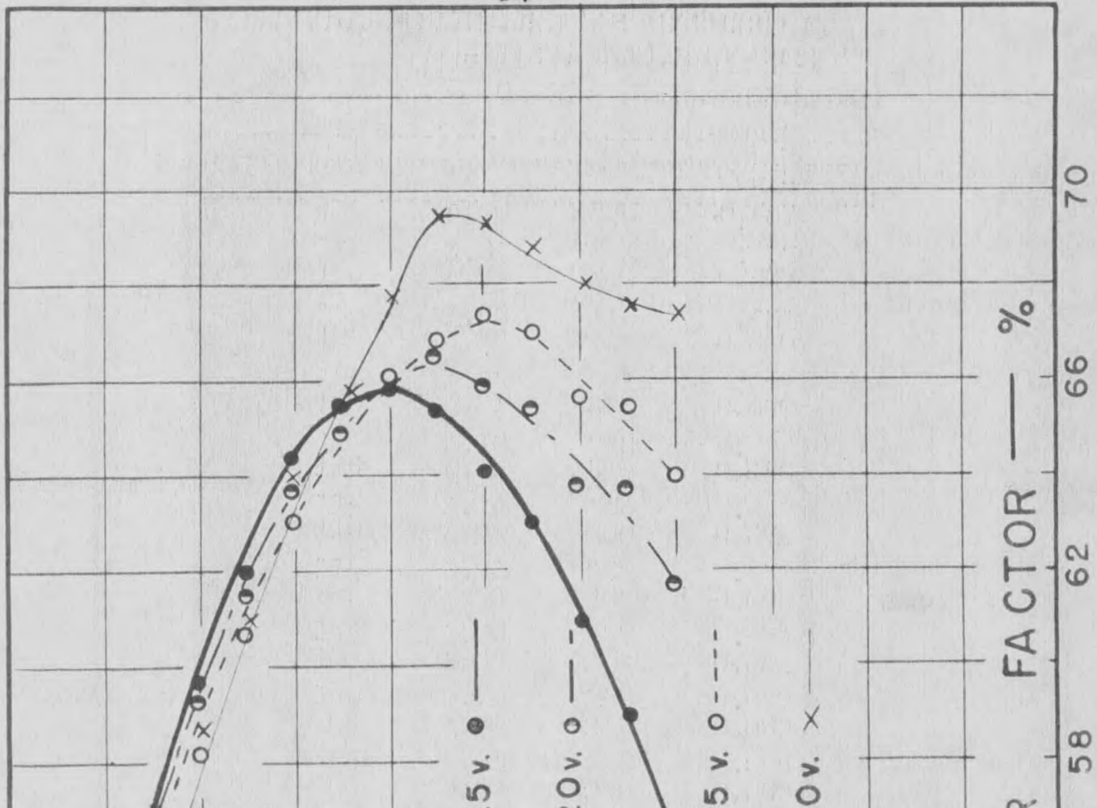

Figure 6. Power Factor Characteristics -- Slim Line Lamp.

CHAPTER V

STARTING TEST

In this test, we are trying to see how the lamps will start under this circuit connection. The three lamps are connected the same as in Figure 2. The source voltage V_L is varied through a variac. The starting time of the lamps at each balanced voltage is shown in Table VII and Table VIII. The starting time of a single lamps of each type is also shown in the same tables for comparison.

In each step of this test, the lamps are given enough time to cool down so as to assure that the starting time will not be affected by the temperature of the lamps.

From the tables, it shows that except for the 15-watt lamps balanced at 110 volts, all lamps start very well, almost the same as the single lamps.

TABLE VII. (15-WATT COLD-WHITE LAMP)

Balanced at 125 Volts

V_1	Starting time
80	No
90	Lab not started, others started after 12 seconds.
95	After 11.5 seconds all started.
100	" 7.5 " " " .
105	" 6.0 " " " .
110	" 5.5 " " " .
115	" 5.0 " " " .
120	" 4.0 " " " .
125	" 2.0 " " " .

Balanced at 120 Volts

V_1	Starting time
80	No
90	After 12 seconds, all started.
95	" 11 " " " .
100	" 10 " " " .
105	" 9 " " " .
110	" 7 " " " .
115	" 5 " " " .
120	" 5 " " " .
125	" 4 " " " .

Balanced at 115 Volts

V_1	Starting time
80	No
90	After 13.5 seconds, all started.
95	" 11.0 " " " .
100	" 10.0 " " " .
105	" 9.0 " " " .
110	" 8.5 " " " .
115	" 8.0 " " " .
120	" 7.0 " " " .
125	" 6.0 " " " .

Balanced at 110 Volts

V_1	Starting time
80	No
90	L_{ca} not started
95	" " "
100	" " "
105	" " "
110	" " "
115	" " "
120	" " "
125	" " "

SINGLE LAMP

V_1	Starting time
90	21.0 seconds
95	20.0 "
100	6.5 "
105	6.0 "
110	5.0 "
115	4.0 "
120	3.0 "
125	2.0 "

TABLE VIII. (SLIM LINE LAMP)

Balanced at 125 Volts

V_1	L_{ab}	L_{bc}	L_{ca}
80	No	Blinked but not started	No
85	No	2 seconds	No
90	4.5 seconds	1 "	3 seconds
95	1.5 "	0.5 "	1.5 "
100	1 "	Inst.	1 "
105	0.5 "	"	0.5 "
110	Inst.	"	Inst.
115	"	"	"

Balanced at 120 Volts

80	No	Blinked but not started	No
85	No	3 seconds	No
90	2 seconds	1 "	2 seconds
95	1 "	0.5 "	1 "
100	0.5 "	Inst.	0.5 "
105	Inst.	"	Inst.
110	"	"	"
115	"	"	"

Balanced at 115 Volts

80	No	Blinked but not started	No
85	No	3 seconds	no
90	2.5 seconds	1 "	1.5 seconds
95	1.0 "	0.5 "	1.0 "
100	0.5 "	Inst.	0.5 "
105	Inst.	"	Inst.
110	"	"	"
115	"	"	"

TABLE VIII. (Continued)

Balanced at 110 Volts

V_1	L_{ab}	L_{bc}	L_{ca}
80	No	Blinked but not started	No
85	No	4.5 seconds	No
90	2 seconds	1.0 "	2 seconds
95	1 "	.5 "	.5 "
100	0.5 "	Inst.	Inst.
105	Inst.	"	"
110	"	"	"
115	"	"	"

Balanced at 105 Volts

V_1	L_{ab}	L_{bc}	L_{ca}
80	No	Blinked but not started	No
85	No	3 seconds	No
90	1.5 seconds	1 "	1.5 seconds
95	1.0 "	0.5 "	1.0 "
100	0.5 "	Inst.	Inst.
105	Inst.	"	"
110	"	"	"
115	"	"	"

Single Lamp

V_1	Time
80	Blinked but not started
85	4 seconds
90	1.5 "
95	1.0 "
100	0.5 "
105	Inst.

CHAPTER VI

STROBOSCOPIC EFFECT INVESTIGATION

The lamp circuit was connected as shown in Figure 2. Source voltage was varied through a variac

A PJ-23 photocell and a G-E oscilloscope were used to investigate the relative light output wave of the lamps. The photocell circuit was connected as shown in Figure 7.

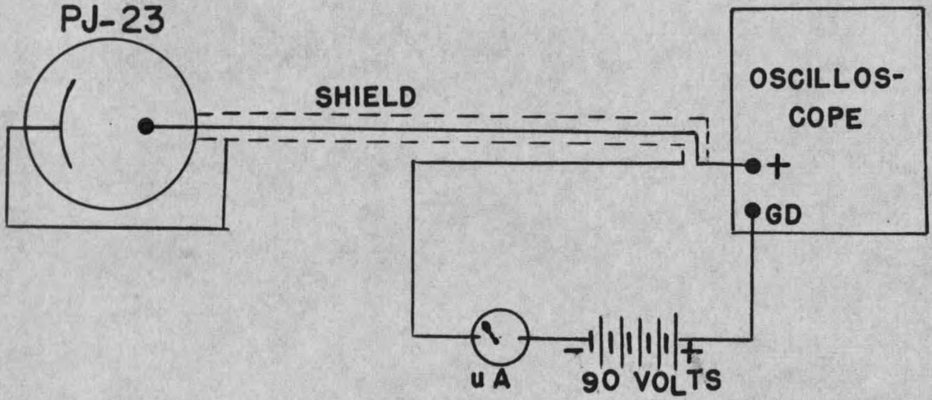

Figure 7. Photocell circuit.

The photocell was placed at a distance from the lamps more than ten times as far as the distances between each lamp in order to assure that the light from each lamp to the photocell would be even.

The test was accomplished in a completely dark room in order to assure that it would not be affected by other light sources.

Relative light output was sketched from the oscilloscope in its exact form. From these relative light putput curves the percentage deviation was calculated which is shown in Table IX and Table X for various supply voltages at different balanced voltages.

The table shows at balanced voltage that the light percentage deviation is from 5% to 8% which is nearly the value for the filament lamps.1/ However, it is very sensitive to any change of the source voltage.

The characteristic curves of the light output percentage deviation versus supply voltage is shown in Figure 8 and Figure 9.

1/ Charles L. Amick, Fluorescent Lighting Manual, 2nd Edition, McGraw-Hill Book Company, New York, 1947, p. 73.

TABLE IX. (15-WATT COLD-WHITE LAMP)

	Balanced at			
V_1	125 v	120 v	115 v	110 v
140	12.5	12.0	14.4	18.3
135	9.86	11.8	14.3	17.5
130	5.55	7.8	14.1	13.0
125	5.07	7.25	7.85	15.5
120	5.90	6.8	7.7	12.2
115	8.10	9.3	6.9	10.8
110	13.00	13.2	10.4	7.1
105	13.30	13.9	11.8	10.0
100	16.00	17.0	14.0	13.9
95	22.10	22.0	18.0	17.4
90	29.90	25.0	22.4	25.8
85	34.10	32.4	27.5	32.7
80	48.50	48.8	46.0	41.0

TABLE X. (SLIM LINE LAMP)

V_1	Balanced at 125 v	120 v	115 v	110 v	105 v
140	9.44	13.2	14.3	16.0	18.3
135	6.47	11.7	13.2	15.1	16.9
130	5.69	10.7	11.7	14.4	15.5
125	4.82	8.35	11.1	10.8	14.3
120	5.36	6.85	9.2	9.7	12.7
115	6.41	7.55	8.6	9.3	11.8
110	6.85	8.00	8.05	8.03	9.8
105	11.76	12.20	11.1	9.40	8.34
100	20.70	15.40	12.0	12.10	10.0
95	24.50	20.80	12.8	13.60	15.40
90	27.40	25.60	17.4	17.00	15.80
85	43.90	30.5	22.0	21.60	20.6

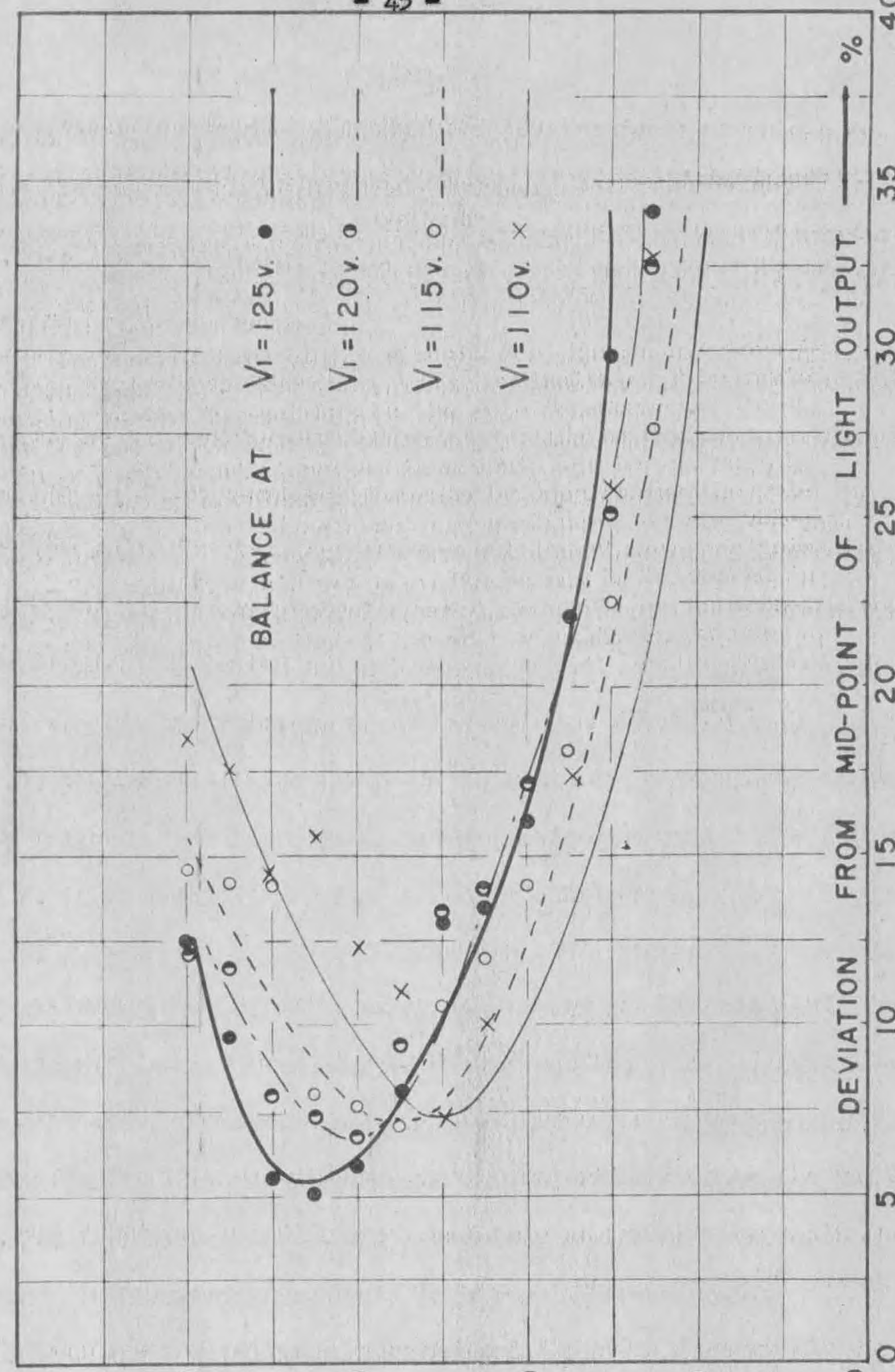

Figure 8. Light Output Deviation — 15-Watt Cold-White Lamp.

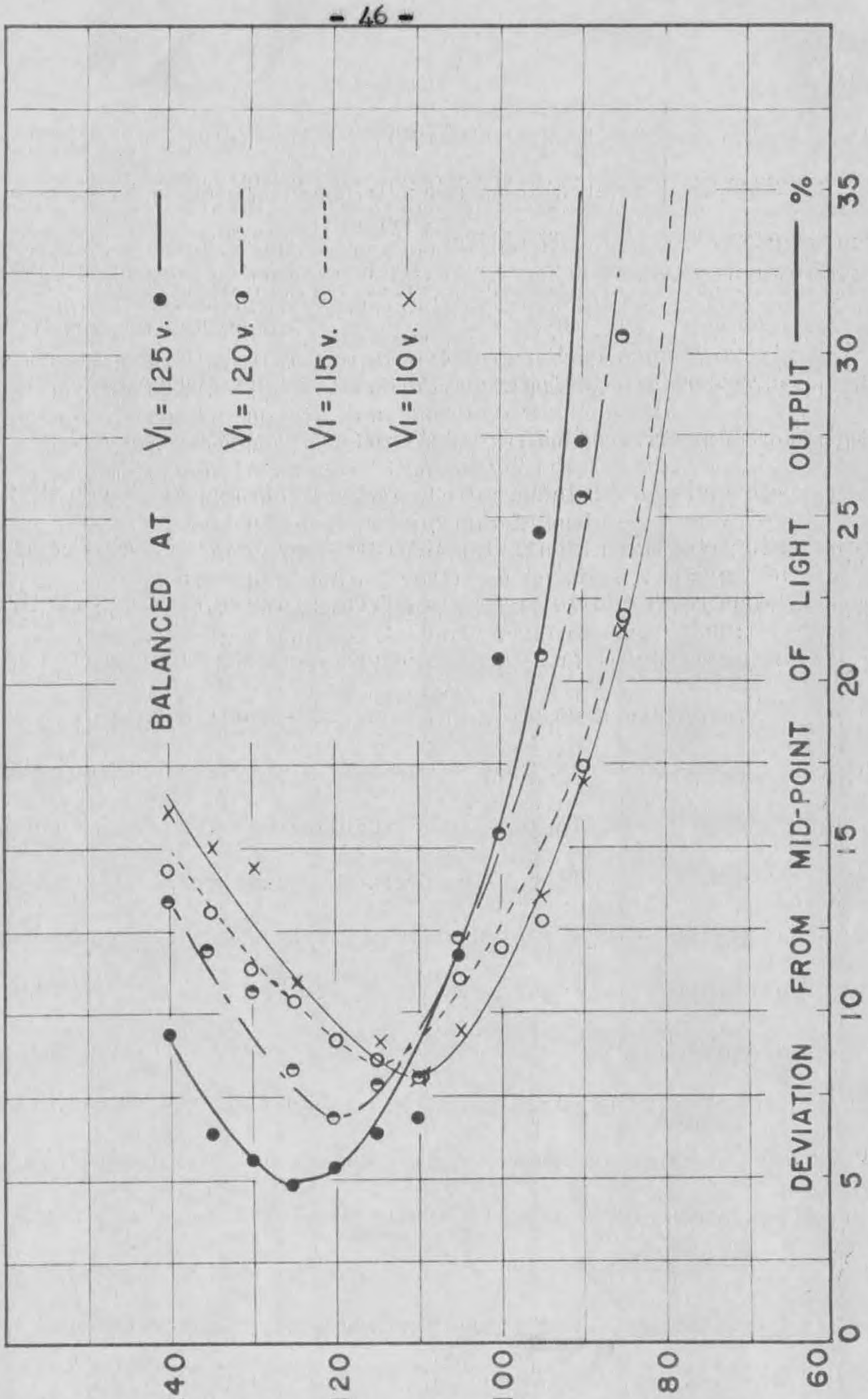

Figure 9. Light Output Deviation — Slim line Lamp.

CHAPTER VII

CONCLUSIONS

From this investigation of the static phase converter, the following conclusions can be drawn:

1. The stroboscopic effect is greatly reduced. Using two-lamp ballast the stroboscopic effect of white lamps is 16% while in this circuit it is only 5% to 8% or about the same as for filament lamps.[1]

2. The circuit is very easy to construct. Only an additional autotransformer and capacitor are needed. Omission of the power factor correction capacitor in the ballast can compensate at least a part of the extra cost of the autotransformer and capacitor combination.

3. The overall power factor of this circuit is better than individual lamps (without the power factor correction device).

4. Lamps start very well at normal supply voltage.

5. The circuit may go out of balance by a slight change of supply voltage; however, most lighting systems have very good regulation. Even when slightly out of balance, the stroboscopic effect is still very low. Since the current and voltage of one of the three phases remains nearly constant while the other two phases change proportionately to the supply voltage, the light output will be reduced only as much as for a single lamp.

6. It can operation from a conventional 115 volt light supply circuit.

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[1] Ibid, p. 73.

Appendix

The following material is copied from AIEE Transaction, January 1956, p. 403, "Analyzing Single Phase to 3-Phase Static Phase Converter," by J. C. Hogan:

> "The general form of the circuit for phase converters is given in Figure 1a. The voltage at terminal A' may be varied according to the tap setting on the autotransformer. The capacitor X_c in series with phase A may also be varied to obtain balanced conditions. This circuit may be analyzed by the method of symmetrical components by considering the voltages at A', B', and C' as a set of unbalanced 3-phase voltages applied to a circuit with unequal line impedances going to a 3-phase load. This set of voltages may be expressed in terms of the single-phase voltage applied to the phase converter and the tap setting of the autotransformer. Thus:

$$V_{A'B} = N V_1 \qquad (1)$$

$$V_{BC} = V_1 \qquad (2)$$

$$V_{CA'} = -(1 + N) V_1 \qquad (3)$$

where: $$N = \frac{|V_{A'B}|}{|V_{BC}|} \qquad (4)$$

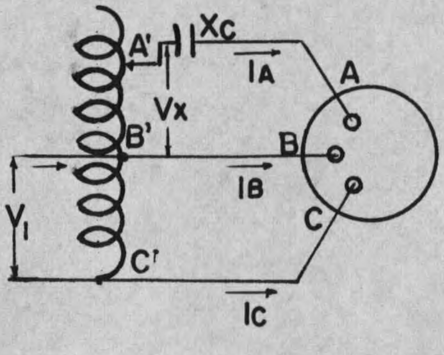

Figure 1a. Circuit of Static Phase Converter

"The positive, negative and zero-sequence component voltage are given by:

$$V_{A'B_1} = \frac{1}{3}\left(V_{ab} + aV_{bc} + a^2V_{ca}\right) \qquad (5)$$

$$V_{A'B_2} = \frac{1}{3}\left(V_{ab} + a^2V_{bc} + aV_{ca}\right) \qquad (6)$$

$$V_{A'B_0} = \frac{1}{3}\left(V_{ab} + V_{bc} + V_{ca}\right) \qquad (7)$$

Substituting equations 1 to 3 into equations 5 to 7 yields:

$$V_{A'B_1} = \frac{V_1}{\sqrt{3}}\left(1\underline{/90^\circ} + N\underline{/30^\circ}\right) \qquad (8)$$

$$V_{A'B_2} = \frac{V_1}{\sqrt{3}}\left(1\underline{/-90^\circ} + N\underline{/-30^\circ}\right) \qquad (9)$$

$$V_{A'B_0} = 0 \qquad (10)$$

"Since the sum of the three currents must also equal zero, the zero-sequence component of the current is also zero.

"The load circuit is expressed in terms of an equivalent wye circuit, with the applied voltage being a line-to-neutral voltage. Expressing the component voltages of equations 8 and 9 in terms of line-to-neutral voltages gives:

$$V_{A'n_1} = \frac{V_{A'B_1}}{\sqrt{3}}\underline{/-30^\circ} \qquad (11)$$

$$V_{A'n_1} = \frac{V_1}{3}\left(N\underline{/0^\circ} + 1\underline{/60^\circ}\right) \qquad (12)$$

$$V_{A'n_2} = \frac{V_{A'B_0}}{\sqrt{3}}\underline{/30^\circ} \qquad (13)$$

$$V_{A'n_2} = \frac{V_1}{3}\left(N\underline{/0^\circ} + 1\underline{/-60^\circ}\right) \qquad (14)$$

"Next the unsymmetrical line impedances must be resolved into a form suitable for application of the sequence rule. The sequence components of these unbalanced line impedances are:

$$Z_{A_0} = \frac{1}{3}\left(Z_A + Z_B + Z_C\right) \qquad (15)$$

$$Z_{A_1} = \frac{1}{3}\left(Z_A + aZ_B + a^2Z_C\right) \qquad (16)$$

$$Z_{A_2} = \frac{1}{3}\left(Z_A + a^2Z_B + aZ_C\right) \qquad (17)$$

"In the phase-converter circuit:

$$Z_B = Z_C = 0 \qquad (18)$$

"Thus equations 15, 16 and 17 become:

$$Z_{A0} = Z_{A1} = Z_{A2} = \frac{Z_A}{3} \qquad (19)$$

"The equations of the circuit may now be written in terms of the sequence components. Thus:

$$V_{am_1} = I_{a1}(Z_{A0} + Z_{m1}) + I_{a2} Z_{A2} \qquad (20)$$

$$V_{am_2} = I_{a1} Z_{A1} + I_{a2}(Z_{A0} + Z_{m1}) \qquad (21)$$

where:

I_{a1}, I_{a2} = the positive- andnegative-sequence component currents going to the load respectively.

Z_{m1}, Z_{m2} = the positive- and negative- sequence impedances per phase of the load respectively.

"Substituting equations 12, 14 and 19 into equation 20 and 21 yields:

$$\frac{V_1}{3}(N \angle 0^\circ + 1 \angle 60^\circ = I_{a1}\left(\frac{Z_A}{3} + Z_{m1}\right) + I_{a2}\frac{Z_A}{3} \qquad (22)$$

$$\frac{V_1}{3}(N \angle 0^\circ + 1 \angle -60^\circ = I_{a1}\frac{Z_A}{3} + I_{a2}\left(\frac{Z_A}{3} + Z_{m2}\right) \qquad (23)$$

"Solving for the sequence currents gives:

$$I_{a1} = \frac{V_1}{3}\left(\frac{Z_{m1}(N \angle 0^\circ + 1 \angle 60^\circ) + \frac{Z_A}{\sqrt{3}} \angle 90^\circ}{Z_{m1} Z_{m2} + \frac{Z_A}{3}(Z_{m1} + Z_{m2})}\right) \qquad (24)$$

and

$$I_{a2} = \frac{V_1}{3}\left(\frac{Z_{m1}(N \angle 0^\circ + 1 \angle -60^\circ - \frac{Z_A}{\sqrt{3}} \angle 90^\circ}{Z_{m1} Z_{m2} + \frac{Z_A}{3}(Z_{m1} + Z_{m2})}\right) \qquad (25)$$

"The ideal operating condition for a 3-phase load is to have balanced 3-phase voltages applied to the terminals of the load which should result in balanced line currents. Thus, the negative-sequence current must equal zero. From equation 25 it is seen that this condition is satisfied by the relationship:

$$Z_{m1} \angle \theta_{m1} (N \angle 0^\circ + 1 \angle -60^\circ = \frac{Z_A \angle 90^\circ}{\sqrt{3}} \qquad (26)$$

where θm_1 is the positive-sequence power-factor angle of the load. Z_a may be any type of impedance but to minimize losses it is usually a capacitor for inductive loads. Thus:

$$Z_A = -jX_C \qquad (27)$$

"Since both the autotransformer tap setting N and the capacitive reactance X_c may be varied, it is possible to satisfy equation 26 for any polyphase inductive load and thus insure balanced operation at that particular load. As the load requirements change, the load will no longer have exactly balanced currents. It is, therefore, important to adjust initially the values of N and X_c so as to give balanced operation for the particular load condition most usually encourtered. Solution of equation 26 gives:

$$X_C = \frac{3}{2} \quad \frac{|Z_{m1}|}{\sin \theta_{m1}} \qquad (28)$$

and

$$N = \frac{\cos(\theta_{m1} + 30^\circ)}{\sin \theta_{m1}} \qquad (29)$$

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	NAME AND ADDRESS
NOV 7 '[illegible]	
4/29/[illegible]	Tom Froelich [redacted]
[illegible] 10 '[illegible]	[redacted]