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The Effects of Undervoltage on the Performance of Compact Fluorescent Systems

by M.J. Ouellette and R. Arseneau

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The Effects of Undervoltage on the Performance of Compact Fluorescent Systems

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Abstract-- Compact fluorescent (CF) products are not recommended for undervoltage use. Nevertheless, power demands are increasing and occasional voltage sags and brownouts may become less avoidable. This paper describes the lighting and electrical performance of eleven different types of CF systems operating at 100, 110 and 120 Vac. Performance parameters include relative luminous efficacy, active and apparent power consumption, harmonic distortion, power factor and flicker index. Economic analysis for the operation of the CF systems at 120 V is also provided.

I. INTRODUCTION

Electric utilities have generally prided themselves on their ability to deliver dependable, high quality power meeting the performance requirements of their clients [1]. In recent years, the profile of connected equipment to the system has changed. Nonlinear loads proliferate [2,3], and many of them are potentially sensitive to changes in supply voltage [3,4]. Effects of reduced voltage on some nonlinear equipment may include malfunction, inefficient operation, reduced lifetime, and failure to operate. Consequences may range from minor nuisance to great expense [5]. Electrical reserve margins are dropping in some areas [6], and brownouts are becoming more common [7,8]. There is an increasing need to understand how all major types of nonlinear loads are affected by reduced supply voltage.

Compact fluorescent (CF) systems are increasingly popular nonlinear loads. They reportedly consume much less electricity and last much longer than incandescent lamps having comparable luminous output [9]. Many electric utility companies offer rebates on these products as part of their demand side management (DSM) programs. Kalinowsky *et al.* [10] observed that different fluorescent lighting systems performed differently from each other under reduced supply voltage. Their study did not, however, include CF systems.

A research program [11] was undertaken by the National Research Council of Canada (NRC) in cooperation with the Canadian Electrical Association (CEA) and Energy, Mines and Resources Canada, Centre for Mineral Energy Technology (EMR/CANMET) to study the economic aspects and the lighting and electrical performance of a wide range of different CF systems under a range of operating conditions including reduced supply voltage. The program involves the participation of national lighting research and electrical metrology laboratories in Canada, the U.S., and abroad. This paper reports some of the results from this program.

II. COMPACT FLUORESCENT SAMPLES

Table 1 describes the CF samples studied. They represent a wide range of products currently available. Samples include both T4 and T5 sized lamps (i.e., 10 mm and 15 mm tube diameter). Twin tubes, Quad (Quad.) tubes and miscellaneous (Misc.) lamp shape configurations were included. Both bare lamps (Exposed) and units with fixed or detachable diffusers (Enclosed) were used. The lamps were controlled with either magnetic core (Magnetic) or electronic ballasts. The ballasts were either built into the lamps (Integral), separably wired (Separate), or fixed within medium based socket adapters (Adapter).

TABLE I
DESCRIPTION OF THE CF SAMPLES

SAMPLE	LAMP	RATING	BALLAST	LAMP COST	BALLAST COST
1	Twin, T4, Exposed	13W	Magnetic, Separate	4.90	15.05
2	Misc., T4, Enclosed	16 W	Magnetic, Integral	21.00	0.00
3	Quad., T4, Exposed	20 W	Electronic, Integral	26.50	0.00
4	Misc., T4, Enclosed	18 W	Electronic, Integral	26.70	0.00
5	Quad., T4, Exposed	13 W	Magnetic, Adapter	9.70	11.00
6	Quad., T4, Enclosed	13 W	Magnetic, Adapter	9.70	18.50*
7	Quad., T4, Exposed	26 W	Magnetic, Separate, HP†	21.66	34.03
8	Twin, T5, Exposed	24 W	Magnetic, Separate, HP†	18.33	26.70
9	Quad., T5, Exposed	28 W	Magnetic, Separate	18.20	8.41
10	Quad., T4, Exposed	13 W	Magnetic, Separate	12.00	23.00
11	Twin, T4, Exposed	13 W	Magnetic, Adapter	4.90	12.68
13	Incandescent, T10, Longlife	60 W		0.88	0.00

*Includes cost of detachable globe diffuser.

†High power factor

$$V_{rms} = \sqrt{\sum_{h=1}^{100} V_h^2} \quad (1)$$

$$I_{rms} = \sqrt{\sum_{h=1}^{100} I_h^2} \quad (2)$$

$$P = \sum_{h=1}^{100} V_h I_h \cos \phi_h \quad (3)$$

$$THD_v = \left[\frac{\sqrt{\sum_{h=2}^{100} V_h^2}}{V_{rms}} \right] \times 100\% \quad (4)$$

$$THD_i = \left[\frac{\sqrt{\sum_{h=2}^{100} I_h^2}}{I_{rms}} \right] \times 100\% \quad (5)$$

where V_h , I_h , and ϕ_h are magnitudes and phase shift of the voltage and current h order harmonics. Apparent power S and power factor PF were calculated as shown in (6) and (7).

$$S = V_{rms} \times I_{rms} \quad (6)$$

$$PF = P / S \quad (7)$$

It is estimated that the accuracy of the values obtained from (1) through (7) are better than 0.25%.

During the tests, a true RMS multifunction meter with bandwidth of 20 kHz was used to independently monitor the values of voltage, current and consumed active power of the lamps under tests. Readings from this multimeter are not specifically reported in this paper but agreed with the computed values from (1) through (7) for all test conditions.

Illuminance measurements from the three lamps under tests were collected horizontally with an illuminance photometer at a location equidistant from each lamp in a plane of 1 m below the lowest point of the lamps. The illuminance photometer was calibrated against the responses of a portable spectroradiometer for each of the different CF samples [14]. The procedure corrected for inexact matches between photometer relative spectral responsivity and human spectral luminous efficiency [15].

Luminous flicker of the CF samples was measured with a silicon pin diode of rise time < 80 ns. The diode was sampled at 20 kHz by a 12 bit A/D board under computer control. For one lamp of each sample, the computer stored 1000 values of instantaneous relative luminous intensity throughout 3 complete cycles of supply voltage. A program later calculated flicker index, FI, as follows:

$$FI = (L_A / L_T) \quad (8)$$

where L_A is the area above the mean of the relative luminous intensity waveform and L_T is the total area under the same waveform [16,17]. FI ranges from 0 to unity with 0 for steady light output.

IV. RESULTS AND DISCUSSION

The results of the tests are summarized in Table II and Fig 2. The measurements of current, active power, apparent power, and illuminance in Table II are one third of the measured quantities. This represents values for one lamp in each 3-lamp sample tested. The samples are grouped in the Table into five sets (Set I to Set V) in accordance with observed similarities in their electrical performance, determined mainly by the ballast characteristics.

All CF lamps consumed less power than the reference incandescent sample, although not necessarily as low as the rated lamp wattages. Discrepancies between observed system wattages and rated lamp wattages were due, in part, to ballast power consumption - an important parameter in the economics of compact fluorescent lighting.

The CF systems all consumed more apparent power S than active power P . The differences were much greater for the samples with ballasts lacking power factor correction circuits. The distinction between S and P is important. Residential energy meters measure only P , a value directly related to the costs of producing the energy consumed. Large utility customers, however, are billed not only to cover the costs of the energy production but also to recover the high capital costs associated with the delivery of the highest energy demand. In Canada, it has become common practice to use S rather than P for demand billing purposes. Consequently, two indices of relative luminous efficacy are presented in this paper. The first, η_1 , is given in units of lux per watt. The second, η_2 , is in lux per VA.

$$\eta_1 = E / P \quad (9)$$

$$\eta_2 = E / S \quad (10)$$

The flicker index of all magnetically ballasted CF samples was 0.11 to 0.14 at 120 V and increased by no more than 0.03 under reduced voltage. In comparison, warm white, white, cool white, and daylight fluorescent lamps have, respectively, flicker index values of 0.05, 0.06, 0.08, and 0.12, corresponding to 20%, 25%, 34% and 50% peak-to-peak modulation [17]. Flicker from these sources, when operated on 60 Hz supply, is generally not perceptible to the majority of people under static visual conditions [17]. However, rapidly moving stimuli may appear slightly blurred or stroboscopic when flicker index approaches the higher magnitudes observed in this study [18]. Wilkins and colleagues [19] suggest that a very small portion of people may respond unfavourably to the 40% peak-to-peak modulation of a mixture of cool white and white fluorescent lamps operated on 50 Hz British supply. In a double-blind cross-over experiment involving approximately 150 workers in a government office building, twice as many headache and eyestrain complaints were tallied [19] when the light flickered within the magnitude observed in the present study. The researchers cautioned that only a small number of their subjects reported adverse effects while experiencing the pulsating illumination over a period of 19 weeks.

All the CF samples were designed to operate at 120 Vac and had power ratings of 13 to 28 W. The retail cost of each lamp and ballast combination ranged from 17 to 55 Canadian dollars. Sample 13, a tube shaped white frosted incandescent lamp, served as a reference sample. It was approximately the same physical size as the Quad-shaped CF samples. The ballasts of samples 7 and 8 included high power factor correction (HP) circuits. In addition, the latter included a constant-illumination circuit. Sample 12, a DC unit, was not considered for this paper.

Each sample consisted of a group of seven new lamps and ballasts aged and stabilized for approximately 100 h. During the aging period, the seven lamps were mounted base-up and powered together at room temperature at 120 V. Their relative luminous intensity, voltage, current, wattage, and power factor were monitored until stable. After aging, a final selection of three lamps from each sample were chosen for evaluation under different sinusoid supply voltages and distorted waveforms [12].

III. PROCEDURES

A diagram of the test system is shown in Fig. 1. Procedures and equipment were identical to those described elsewhere [12] except that the present study employed only sinusoid waveforms of 120, 110, and 100 V rather than waveforms of varying harmonic content. Test voltages were provided by a system consisting of a personal computer, a digital arbitrary waveform generator (ARG) and a voltage amplifier [13]. The required voltage conditions were entered from the computer keyboard. A program loaded the sinusoid waveform into the ARG. The output of the ARG was then amplified and supplied to the three lamps under tests for each sample. Technical characteristics of this low impedance

system are conservatively estimated as follows: harmonic distortion < 0.5%, stability better than 0.002% over 15 min, amplitude resolution 0.1%.

For the tests, all lamps were mounted base-up in a uniform circular arrangement of radius 60 cm. They were enclosed within a dark room to eliminate stray light. The dark room was ventilated from above by natural convection. Ambient temperature in the room was monitored during the tests. Following stabilization, the lamps were tested at room temperature for a pure sinusoid waveform of 120 V then again under the series of reduced voltages. The lamps were then re-tested at 120 V to ensure reproducibility. Repeated measures typically agreed to within 1%.

A calibrated 12 bit dual channel digital oscilloscope (DSO) was used to record the voltage and current waveforms of the lamps under tests. The recorded waveforms were later transferred via IEEE Bus to a computer for harmonic analysis and calculation of the electrical quantities shown in Table II. The sampling clock of the DSO was synchronized with the test voltage waveform. The harmonic content of the recorded waveforms was limited to 100 harmonics. The sampling frequency was therefore set at 1024 times the fundamental frequency - an order of magnitude greater than the maximum harmonic frequency.

The rms values of supply voltage V_{rms} and current I_{rms} , active power P , voltage total harmonic distortion THD_V and current total harmonic distortion THD_I were calculated directly from the harmonic components obtained with a Fast Fourier Transform of the recorded waveforms. These quantities are calculated as follows:

Fig. 1. Diagram of the test system

TABLE II
PERFORMANCE* OF THE TESTED SAMPLES

SAMPLE - RATING	V_{rms} (V)	I_{rms} (A)	P (W)	S (VA)	PF	THD _v (%)	THD _i (%)	E (lux)	FI	η_1	η_2
SET I, MAGNETIC:											
1 - 13 W	120	0.281	16.5	33.6	0.49	0.14	12.9	22.5	0.14	1.36	0.67
	110	0.227	13.4	24.9	0.54	0.17	15.1	20.4	0.15	1.53	0.82
	100	0.156	9.4	15.7	0.60	0.27	20.9	15.5	0.18	1.66	0.99
2 - 16 W	120	0.251	16.0	30.2	0.53	0.24	11.3	52.7	0.12	3.30	1.75
	110	0.208	13.2	22.9	0.58	0.20	12.8	46.0	0.13	3.49	2.01
	100	0.154	9.9	15.5	0.64	0.21	16.9	35.6	0.15	3.61	2.31
5 - 13 W	120	0.233	14.7	28.0	0.52	0.17	10.2	29.5	0.12	2.01	1.06
	110	0.196	12.2	21.6	0.57	0.18	11.7	25.8	0.13	2.12	1.20
	100	0.145	9.1	14.5	0.63	0.19	15.5	19.9	0.15	2.18	1.37
6 - 13 W	120	0.239	14.9	28.7	0.52	0.14	9.4	22.3	0.12	1.50	0.78
	110	0.205	12.4	22.6	0.55	0.18	10.6	20.0	0.13	1.62	0.89
	100	0.160	9.7	16.0	0.60	0.18	13.7	17.1	0.14	1.76	1.07
9 - 28 W	120	0.615	33.8	73.7	0.46	0.15	8.9	62.9	0.11	1.86	0.85
	110	0.523	28.6	57.5	0.50	0.18	10.3	57.2	0.11	2.00	1.00
	100	0.410	22.8	41.0	0.56	0.20	13.7	49.3	0.13	2.17	1.20
10 - 13 W	120	0.278	18.2	33.3	0.55	0.18	12.0	32.0	0.12	1.76	0.96
	110	0.230	14.8	25.3	0.58	0.19	13.3	28.2	0.13	1.91	1.11
	100	0.162	10.4	16.2	0.64	0.25	18.5	22.4	0.16	2.16	1.39
11 - 13 W	120	0.238	14.5	28.5	0.51	0.18	10.1	26.7	0.12	1.84	0.94
	110	0.202	12.2	22.2	0.62	0.26	11.4	23.9	0.13	1.96	1.08
	100	0.150	9.3	15.0	0.51	0.18	15.6	19.6	0.15	2.11	1.31
SET II, ELECTRONIC:											
3 - 20 W	120	0.280	18.5	33.6	0.55	0.27	82.9	52.1	0.02	2.83	1.55
	110	0.276	17.0	30.4	0.56	0.25	82.3	47.9	0.02	2.82	1.58
	100	0.276	15.7	27.6	0.57	0.38	81.5	43.8	0.02	2.80	1.59
4 - 18 W	120	0.222	15.4	26.7	0.58	0.22	78.6	32.1	0.03	2.09	1.20
	110	0.215	13.8	23.7	0.58	0.20	77.9	29.6	0.03	2.15	1.25
	100	0.209	12.3	21.0	0.59	0.22	76.9	27.6	0.02	2.24	1.32
SET III, MAGNETIC, HP1:											
7 - 26 W	120	0.252	29.5	30.2	0.98	0.14	21.2	55.0	0.12	1.87	1.82
	110	0.232	24.3	25.5	0.95	0.17	23.0	48.7	0.13	2.00	1.91
	100	0.223	17.5	22.3	0.79	0.22	7.0	34.2	0.15	1.95	1.53
SET IV, MAGNETIC, HP2:											
8 - 24 W	120	0.288	34.2	34.5	0.99	0.17	12.4	45.1	0.14	1.32	1.31
	110	0.304	33.0	33.4	0.99	0.15	11.2	44.9	0.14	1.36	1.35
	100	0.333	32.1	33.3	0.97	0.20	10.9	44.6	0.15	1.39	1.34
	95	0.349	31.6	33.1	0.95	0.15	10.5	44.2	0.15	1.40	1.34
	90	0.366	31.1	32.9	0.95	0.16	10.3	43.8	0.15	1.41	1.33
SET V, INCANDESCENT:											
13 - 60 W	120	0.446	53.5	53.5	1.00	0.12	0.7	16.8	0.02	0.31	0.31
	110	0.426	46.8	46.8	1.00	0.14	0.7	11.8	0.02	0.25	0.25
	100	0.406	40.6	40.6	1.00	0.14	0.6	8.0	0.02	0.20	0.20

* V_{rms} , I_{rms} , P, S, PF, THD_v, THD_i are electrical parameters given by (1) through (7), E is illuminance in lux, FI is flicker index given by (8), and η_1 and η_2 are relative luminous efficacies in lux per watt and lux per VA, respectively. HP1 and HP2 are high power factor ballasts, the latter of a type providing nearly constant illuminance.

Nevertheless, where the needs of this minority group is a concern, CF lamps should only be operated with high frequency ballasts. The electronic ballasts of Set II were of this kind. They gave flicker index values between 0.02 and 0.03 - approximately the same given by incandescent lamps (Set V).

A. Set I (magnetic ballasts with no power factor correction)

These samples delivered decreasing illuminance and consumed decreasing power (P and S) as voltage was reduced below the rated value of 120 V. For example, a 17% voltage drop gave a 29% drop in illuminance and a 38% drop in active power consumption. Most notably, relative efficacy (η_1 , in lux per watt) increased nearly proportionately with voltage reductions. Lines of 1:1 and -1:1 proportionality are shown dashed in Fig. 2. When defined in terms of η_2 in lux per VA, relative efficacy increased at yet a greater rate. This may appear significant from the point of view of utility DMS programs, however the gains in relative efficacy occurred at the expense of increased power factor and harmonic

distortion (Fig. 3). On average, power factor increased from approximately 0.5 to 0.6 and THD_i increased from approximately 11% to 17% when supply voltage dropped from 120 to 100 V. In addition, one lamp manufacturer cautions that their products are optimized in terms of the opposing parameters of lamp life and efficacy. Where this is the case, expected lifetime may decrease under reduced supply voltage.

B. Set II (electronic ballasts with no power factor correction)

At 120 V, relative efficacies were generally, but not universally, higher than those of Set I. Contrary to the samples in Set I, illuminance and power consumption of the Set II samples decreased at approximately the same rate in response to reduced supply voltage. This gave nearly constant efficacy as a function of voltage. Current harmonic distortion remained at approximately 80% of rms and decreased by only 1 or 2 percentage points under the reduced voltage conditions. Power factor was approximately 0.57, and, like THD_i , remained approximately independent of supply

Fig. 2. Effect of change in supply voltage on the performance of CF systems

Fig. 3. Current waveforms for a typical sample from each set

voltage. The high relative efficacies of these samples offer a high potential for energy conservation, whether measured in terms of active or apparent power. They are "utility friendly" in regards to consuming power in direct proportion to supply voltage. On the other hand, the samples tested gave generally low power factor and high harmonic distortion - parameters of concern to utility companies.

C. Set III (magnetic ballasts with power factor correction)

Active power consumption of the sample in this set followed similar trends as those of Set I in response to reduced voltage. Between 120 V and 110V, illuminance dropped at the same rate as the samples of Set I and gave approximately proportional increases in relative efficacies η_1 and η_2 . Power factor remained high (95 - 97%) at these supply voltages. Below 110 V, however, the sample performed differently. Illuminance dropped at a greater rate, and gains in relative efficacy were lost. Throughout the range of supply voltages, current harmonic distortion THD_i varied irregularly between 7% and 23%. The shape of the current waveform changed significantly when the supply voltage was reduced from 120 V to 100 V as shown in Fig. 3. This same sample malfunctioned electrically when powered by supply voltages of relatively low ($THD_v = 4.6\%$) harmonic content [12].

D. Set IV (magnetic ballasts with power factor correction and luminous constancy feature):

The sample in this set maintained approximately constant illuminance, active power, apparent power, and relative efficacies η_1 and η_2 throughout the range of 90 to 120 V supply. These may be perceived as desirable features for lighting design, however the stability is achieved by increasing current in almost direct proportion to decreased supply voltage. Reducing voltage to circuits heavily loaded with such CF systems may, in effect, cause the circuits to overload. Thus, CF systems of this type should only be used on circuits with sufficient reserve capacity to prevent overloading during voltage sags. In short, this sample opposes load management practices of reducing power by voltage reduction [20,21]. Its benefits includes high power factor (95 - 99%) and reasonably low harmonic distortion ($THD_i \approx 11\%$) throughout all supply voltages.

V. ECONOMICS OF CF LAMPS

Pricing policies and rate structures for electricity vary greatly across North America. Cost equations used in this analysis are based upon common rate structures in Canada for residential and large utility customers. They do not include labour costs for installation and maintenance, nor do they consider effects of reduced lamp life due to switching [22]. In calculating demand charges, it was assumed that the CF systems were on at the time of peak demand.

Table III summarizes the results of an economic analysis for the operation of 11 CF samples at room temperature under sinusoid, 120 V supply. The analysis introduced cost per 100 lux of illumination. The normalization was necessary since not all retrofit options provided the same quantity of illumination. Representing costs in this manner gave a more accurate indication of the relative economic merits of the different systems.

Cost equations (11) and (12) used for Table III follow.

$$T_{Res.} = \frac{100 \text{ lux}}{E} [R.C. + (P \times 10^{-3} \times B_{rp} \times D)] \quad (11)$$

$$T_{Com.} = \frac{100 \text{ lux}}{E} [R.C. + (P \times 10^{-3} \times B_{cp} \times D) + (S \times 10^{-3} \times B_d \times D/d)] \quad (12)$$

where

- $T_{Res.}$ total cost to residential customer for D hours of 100 lux illumination;
 $T_{Com.}$ total cost to large customer for D hours of 100 lux illumination;
D duration of illumination under analysis, in h;
P active power, in watts;
S apparent power, in VA;
E illuminance, in lux;
 B_{rp} billing rate for active power, residential, in \$/kWh;
 B_{cp} billing rate for active power, large clients, in \$/kWh;
 B_d demand billing rate, in \$/peak kVA;
d demand billing cycle, in h;
R.C. retail cost of lamps and ballasts per socket during the period of interest, D; where $R.C. = (C_l \times n_l) + (C_b \times n_b)$;
 C_l retail cost of a lamp, in \$;
 C_b retail cost of a ballast, in \$;
 n_l number of lamps needed per socket during the period, D; where n_l is the greater of unity or (D/L_l) ;
 n_b number of ballasts needed per socket during the period, D; where n_b is the greater of unity or (D/L_b) ;
 L_l life of lamp, in h;
 L_b life of ballast, in h;
 10^{-3} converts watts and VA to kW and kVA.

For Table III, $B_{rp} = \$0.07/\text{kWh}$; $B_{cp} = \$0.06/\text{kWh}$; $B_d = \$6$ per peak kVA every $d = 720$ h (i.e., 30 days); C_l and C_b were taken from Table I; P, S, and E were taken from Table II. For comparison purposes, costs of operation for a conventional A19, 60 W, 120 V, 2500 h incandescent lamp were derived from the results observed for sample 13. Illuminance, E, for the A19 lamp were taken as twice that for Sample 13 based upon luminous intensity measurements of both samples, sequentially, in a 1 m diameter integrating sphere.

The operating costs in Table III for residential and large utility customers do not differ greatly from each other. Under the residential rate structure considered, CF Sample 1 would not quite pay for itself in its first 10,000 h of operation when compared to the cost of an A19 lamp. Sample 2, under the same conditions, would reach its breakeven within the first 10,000 h thus resulting in a net savings to the customer. In total, six of ten CF samples (Samples 2,3,4,5, 9 and 11) would reach their break even point during the first 10,000 h of operation. Four of them (Samples 1,7,8, and 10) would achieve it during the second 10,000 h of operation. Sample 6 would only achieve it within its third 10,000 h of operation.

Comparable economic analyses for undervoltage situations are less relevant since such power disturbances are usually temporary in nature [23-24]. In addition, insufficient information is available on the potentially costly effects of reduced supply voltage on lamp and ballast life.

TABLE III
OPERATING COST FOR D = 10,000 AND 20,000 HOURS

SAMPLE	D = 10,000 h				D = 20,000 h			
	n_l	n_b	$T_{Res.}$	$T_{Com.}$	n_l	n_b	$T_{Res.}$	$T_{Com.}$
1	1	1	134	139	2	1	204	214
2	1	0	61	63	2	0	123	127
3	1	0	75	77	2	0	150	153
4	1	0	119	121	2	0	238	242
5	1	1	106	110	2	1	175	181
6	1	1	173	177	2	1	263	272
7	1	1	139	138	2	1	216	214
8	1	1	153	152	2	1	246	244
9	1	1	80	85	2	1	147	157
10	1	1	159	162	2	1	241	248
11	1	1	109	113	2	1	168	176
13	1	0	228	223	2	0	456	446
A19	4	0	131	128	8	0	262	256

Table III applies specifically to the lighting conditions studied; e.g., workplane located near the floor of a black room, 1 m below the lamps, mounted base up. Equations (11) and (12) do not apply absolutely to other lighting conditions since illumination quantity depends upon such factors as the size and reflectances of walls and other surfaces within the room. They may be generalized for other applications as follows.

Substituting $E = \Phi_1 \times CU / A$ into (11) and (12) where

- Φ_1 total luminous flux emitted by the CF system, in lumens;
CU Coefficient of Utilization, the ratio of luminous flux received on workplane to the total luminous flux emitted by the given lamps [17];
A area of workplane, in m^2

and substituting $R.C. = [(C_l D / L_l) + (C_b D / L_b)]$, then rearranging gives

$$T_{Res.} = \frac{100 D}{\Phi_1 CU/A} [C_l/L_l + C_b/L_b + (P \times 10^{-3} \times B_{rp})] \quad (13)$$

$$T_{Com.} = \frac{100 D}{\Phi_1 CU/A} [C_l/L_l + C_b/L_b + (P \times 10^{-3} \times B_{cp}) + (S \times 10^{-3} \times B_d / d)] \quad (14)$$

VI. CONCLUSIONS

In recent years, the occurrence of voltage sags and brownouts in power systems has increased. As a consequence, CF lamps are increasingly likely to be installed in locations served by occasional low supply voltage. It is therefore important to understand the performance characteristics of operating CF systems under these less-than-ideal situations.

Four general sets of luminous and electric performance characteristics were identified, based upon the test results of the CF systems studied. The behaviour patterns were determined mainly by the choice of ballast; whether magnetic or electronic, and whether power factor correction circuits were employed. The provision of a constant illumination circuit affected performance in a manner counter to load shedding practices of reducing power by means of voltage reduction. This phenomenon may be directly relevant to electric utility companies when modelling loads.

Economic analysis showed that six of the eleven CF samples would reach their break even point during the first 10,000 h of operation, i.e., their rated lamp life. Four would achieve it within 20,000 h of operation. The remaining CF system would achieve it in the third 10,000 h cycle.

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