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# Automatic Fluorescent Lamp Detection for Electronic Ballasts Based on Operating Frequency and Phase Shift Compensation

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***Abstract*—Generally, an electronic ballast drives a fluorescent lamp at fixed operating frequency or by regulating the lamp current. Such methods can be used for the designed lamp type and power rating. This paper presents an automatic fluorescent lamp detection for electronic ballasts based on operating frequency and phase shift compensation. The classification of lamp power rating is based on the possibility weight distribution of the lamp operating frequency. Moreover, the phase shift compensation is also included in the detection algorithm in order to address the variations of the resonant circuit parameters. The results from simulation and experiment verify that an electronic ballast with the proposed detection algorithm can automatically detect and drive the fluorescent lamp at the correct lamp power rating.**

## I. INTRODUCTION

The fluorescent lamps are accepted as one of the highest power efficiency lamp. These lamps are widely used in many organizations. The problem is that there are many types and power ratings. With a large number of fluorescent types used, the more stocked lamps and ballasts are required, since ballasts for 18W, 32W and 36W T8 lamps are not interchangeable. Any mismatch of ballast and lamp power ratings will usually lead to damage of lamp and/or ballast by either over current or hard switching. To solve this problem, automatic lamp detecting methods were presented [1], [2].

There are some literature techniques on lamp detecting methods. One of them using lamp operating voltage[1]. This method can differentiate the lamp power ratings by using the lamp voltage. After ignition, the lamp voltage is collected and used to identify the lamp wattage. However, the striking frequency of the fluorescent lamp can be varied, depending on the lamp temperature, age and manufacturer. Therefore, the lamp voltage after striking(ignition) is also varied. Generally, different lamp types may have overlapping voltage range for example, 32WT8 and 58WT8 lamps operate on the same voltage ranging from 117V to 127V as shown in Fig. 1. The Voltage detection method proposed in [1] may result in misdetection between both lamp. In addition, the voltage can easily be interfered by noise which is always occurred in switching systems. Our previous method[2] fixed the detecting condition by regulating output power at proper rated. By doing this, the power of the lamp is fixed and easier to classify the lamp. Instead of using voltage, this paper uses the operating frequency to classify the lamp. This outcome more accuracy results because the frequency is generated by controller itself (Fig. 5). However, frequency considering is highly depended on the variation of resonant parameters. By changing the value of inductor or capacitor, the controller will changes the operating frequency to regulate the output power. This may results the misclassifying.

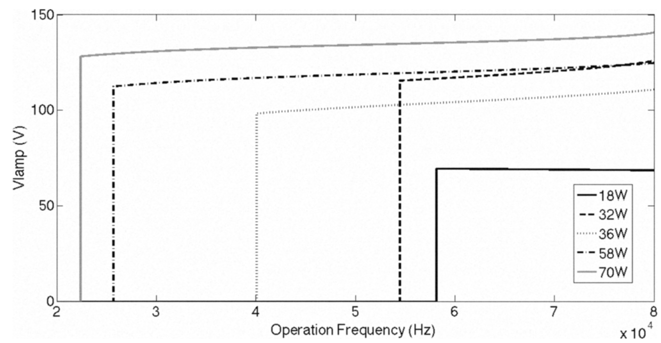


Fig. 1. Operating frequency VS Lamp voltage

This paper proposes an automatic fluorescent lamp detection for electronic ballasts based on the operating frequency and phase shift compensation. A slight deviation of resonant parameters are recognized by considering the phase shift between the inverter output voltage and current. The frequency detection region is then shifted to the appropriate range. Although the system parameter is dependent on the resonant circuit, the error from small variation of resonant parameters is decreased. The proposed algorithm can easily implemented on a 8-bits micro-controller based electronic ballast.

## II. BALLAST DESIGN CONSIDERATION

In this work, a typical 2-stages electronic ballast is considered. It consists of a DC-DC converter and a half bridge inverter with resonant circuit. The micro-controller controls the inverter by generating a signal to the MOSFET driver. In Fig. 2, by varying the square wave frequency, the ballast can operate in pre-heat, strike and running stages. The lamp current can also be controlled through frequency variation as shown in Fig. 3 [3]. Fig. 2 shows the block diagram of the electronic ballast and its driving circuit used in this paper.



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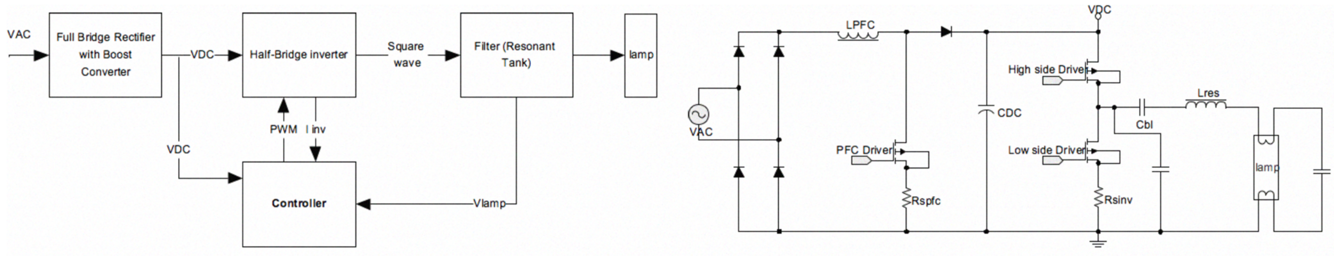


(a) Block Diagram (b) Schematic of power parts

Fig. 2. Block diagram and schematic of electronic ballast using in this paper

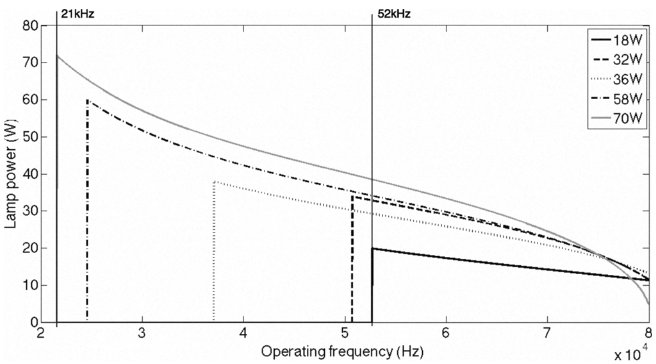


Fig. 3. Operating frequency VS Lamp power

### A. Resonant circuit design

First of all, both inductor and capacitor of resonant circuit should be selected. Note that, this paper focuses on driving all of the lamp power ratings in T8 series, which are widely used and easily to purchase. The resonant inductor is calculated using the method from [5]. This method assumes that the resonant circuit with the lamp in configuration will appear to the source as positive resistance. Thus the lamp resistance, negative differential resistance [6], is disappeared from the following equation.

$$L = \frac{V_{DC}^2 \eta}{4 f_{run} \sqrt{2} \pi^2 P_{lamp}} \tag{1}$$

where $V_{DC}$ is the DC supply voltage(V); $\eta$ is the efficiency of inverter; $f_{run}$ is the running or operating frequency and $P_{lamp}$ is the power using by the lamp.

An operation at a frequency lower than 25kHz would significantly reduce the light efficacy. If the operating frequency is chosen too high, more current will be drawn to the lamp terminals due to the lower capacitor reactance (Xc). The increased current however, turns into power loss at the lamp terminals and the light efficacy would further decrease. In this work, the frequency range of 25kHz to 65 kHz is empirically chosen and substituted in (1) with $\eta$ = 0.95 and VDC = 400V. The inductances of each lamp wattage are shown in TABLE I. Notice that for the lamp wattage of 32W to 70W, the overlapped inductance is in the range of 1.309mH to 1.556mH while the lamp wattage of 18W to 36W gives the inductance of 2.327mH to 3.025mH. The midpoint inductance between the two ranges is chosen at 1.9mH and used in the design procedure in [5] to determine the operating frequency. The resonant capacitance is calculated by

TABLE I
RESONANCE INDUCTOR CALCULATED USING EQUATION 1

| Power rate(W) | L(mH) at f=25kHz | L(mH) at f=65kHz |
|---|---|---|
| 18 | 6.050 | 2.327 |
| 32 | 3.403 | 1.309 |
| 36 | 3.025 | 1.163 |
| 58 | 1.878 | 0.722 |
| 70 | 1.556 | 0.598 |

$$C = \frac{I_{ph}^2 L}{(V_{ph} + V_{DC}/\pi)^2 - (V_{DC}/\pi)^2} \tag{2}$$

Where Iph is the preheat current (A); Vph is the peak preheat voltage (V) and L is the resonant inductance obtained from (1). A quick substitution in (2) gives the resonant capacitance of 4.11nF. Due to availability, a typical capacitance of 4.7 nF is chosen. Once the inductance and capacitance are obtained, they are used in computer simulation to validate the operating frequency as shown in Fig. 3. The operating frequency is located in the range of 21kHz to 52kHz where the lowest frequency is slightly lower than the originally selected frequency of 25kHz with no noticeable difference in light efficacy [6].

### B. Lamp power regulation

The operating frequency plays an important role since the lamp power is increased as the frequency is reduced. The inverter must operate under appropriate frequency to avoid lamp damages. The current regulation method is used to control the lamp power with in its rating[4]. The average voltage of the $R_{sinv}$ on the low side driver MOSFET in Fig. 2(b) represents the current through the half-bridge driver. This current is provided by the DC-BUS voltage which is regulated by the boost converter. The input power($P_{inv}$) is given as,

$$P_{inv} = V_{DC} . I_{inv} \tag{3}$$

With constant DC voltage:

$$P_{inv} \ \alpha \ I_{inv} \tag{4}$$

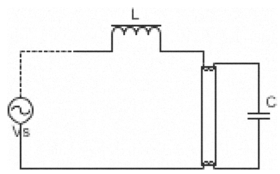


Fig. 4. Simplify version of inverter

Thus,

$$P_{inv} = P_{lamp} + P_{loss} \quad (5)$$

where $P_{loss}$ is the system loss and constant related to $P_{lamp}$. The power relationship is found as,

$$P_{inv} \; \alpha \; P_{lamp} \; \alpha \; I_{inv} \quad (6)$$

where $I_{inv}$ is the current through the inverter; $P_{inv}$ is the power supplied by $V_{DC}$ through the inverter and $P_{loss}$is the ower loss by lamp filaments and electrical components From (6), controls $V_{R_{sinv}}$ indirectly control $P_{lamp}$.

The simplify version of inverter [9] as shown in Fig. 4 is used to simulate the results. Lamp power can be calculated as;

$$I_{lamp} = \frac{\sqrt{2}V_S}{Z_0\sqrt{Q_L^2\left[1-\left(\frac{\omega}{\omega_0}\right)^2\right]^2+\left(\frac{\omega}{\omega_0}\right)^2}} \quad (7)$$

$$P_{lamp} = \frac{V_S^2 R_{lamp}}{Z_0^2\left[Q_L^2\left(1-\left(\frac{\omega}{\omega_0}\right)^2\right)^2+\left(\frac{\omega}{\omega_0}\right)^2\right]} \quad (8)$$

where $V_S = \frac{\sqrt{2}}{\pi}V_{DC}$, $\omega_0 = \frac{1}{\sqrt{LC}}$, $Z_0 = \sqrt{\frac{L}{C}}$ and $Q_L = \frac{R_{lamp}}{Z_0}$. From [7] the negative differential resistance of fluorescent is simplified as;

$$R_{lamp} = \frac{V_0 R_S}{V_0 - V_H} \quad (9)$$

where $V_0$ is the voltage at present condition and $R_S$ and $V_H$ are defined as;

$$R_S = \frac{V_{Max} - V_{min}}{I_{Max} - I_{min}} \quad (10)$$

$$V_H = V_{min} - I_{min}R_S \quad (11)$$

where $V_{Max}$ is lamp voltage at the highest power; $V_{min}$ is the lamp voltage at the lowest power; $I_{Max}$ is the lamp current at the highest power and $I_{min}$ is the lamp current at the lowest power. These parameters were acquired from [8]. To simulate the results, assume the initial $R_{lamp}$ is 1000. Use (7) to calculate the current. Then the new $V_0$ is calculated using $V = IR$. Using this $V_0$ to calculate the new $R_{lamp}$. Recalculate the current and $R_lamp$ until the current is stable. Then the lamp power from this current is calculated. If the lamp power is less than the power command then reduce the frequency and recalculate the lamp power. Repeat these procedures until lamp power is equal to the power command. After that, this frequency and power command is plotted in Fig. 5. Since the high frequency ballast result 10% higher efficacy than magnetic ballast, the fluorescent lamp usually set the output power 2W below its rating as using in this paper.

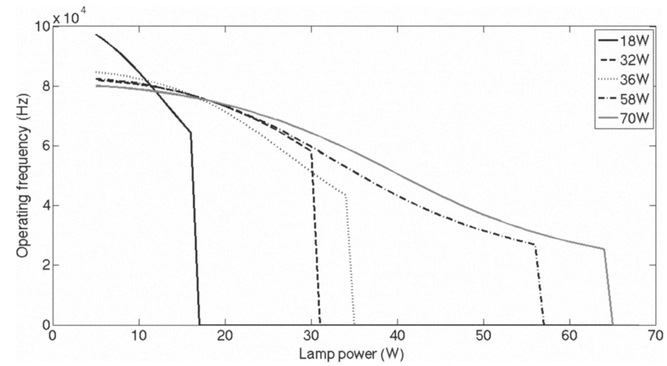


Fig. 5. Simulation output using power regulation command and frequency results

## III. Lamp detection algorithm

At preheating process, the inverter is driven at high frequency. Then the micro-controller quickly decreases the driving frequency until the lamp is striked. The striking process is detected via the negative of $\frac{dv}{dt}$. The power command is applied. This applied command is the lowest power rating of lamps to be detected. For example, the 16W power command is used for the group of T8. At the steady state ($P_{out} = P_{command}$), operating frequency is collected. The operating frequency is controlled by power regulating loop; thus, the external frequency measurement is not necessary. , it already knows the frequency itself. None of external frequency measurement is need. This frequency is used to classify the 18W(lowest) power rating lamp from the group due to 10% higher efficacy.

### A. The lamp detection by considering the operating frequency

The classification algorithm is as follows;

1) Regulate at the lowest power rating. Ex: 16W for T8 series.
2) Calculate the possibility weights ($W_P$). From the samples of lamps regulated power at each rate include 16, 30, 34, 56 and 68 W, trapezoidal-shaped possibility weight function ($W_P$) is setting as shown in (12).
   - If the highest $W_P$ is on the lamp rating related to this power regulated command then STOP. Ex:$W_P$ is the highest on 18W lamp when it is regulated at 16W ($W_{P(18at16)}$ is the highest)
   - If not, then increase to the next power command. Ex: $W_P$ is the highest on 36W lamp when it is regulated at 16W ($W_{P(36at16)}$ is the highest)
3) Step up to the next power command (30, 34, 56 and 68 in sequence) and do step 1) again until the power command reaches the highest value or STOP at step 2).
4) Sum the $W_P$ of each lamp power rating. Ex: $W_{P(36)} = W_{P(36at16)} + W_{P(36at30)} + W_{P(36at34)}$

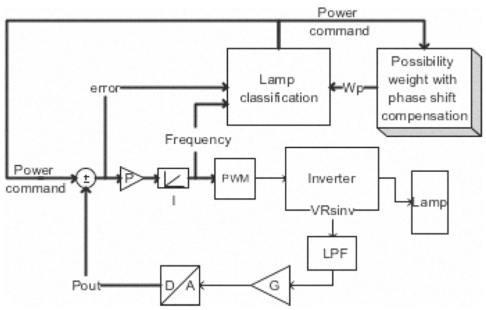


Fig. 6. Lamp detection based on operating frequency and phase shift compensation

5) Run at the maximum of sum $W_P$ in step 4).

$$W_P = \begin{cases} 1, & \overline{x}_f - 0.5sd_f < f < \overline{x}_f + 0.5sd_f; \\ \frac{1}{sd_f} f - \frac{\overline{x}_f - 1.5sd_f}{sd_f}, & \overline{x}_f - 1.5sd_f < f < \overline{x}_f - 0.5sd_f; \\ \frac{-1}{sd_f} f + \frac{\overline{x}_f + 1.5sd_f}{sd_f}, & \overline{x}_f + 0.5sd_f < f < \overline{x}_f + 1.5sd_f; \\ 0, & \text{elsewhere.} \end{cases} \quad (12)$$

The Block diagram of this control scheme is shown in Fig. 6. Operating frequency are acquired from sample lamps to calculate the average ($\overline{x}_f$) and deviation ($sd_f$) of operating frequency of lamps operating at 16, 30, 34, 56 and 68 W power regulated as shown in (13).

$$\overline{x}_f = \frac{1}{n}\sum_{i=1}^{n} f_i, \; sd_f = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (f_i - \overline{x}_f)^2} \quad (13)$$

For example with a Philips 36W T8 TLD lamp, if the average operating frequency of 36W lamp running at 16W regulated is 54.2 kHz and its standard deviation is 1.084 kHz. The $W_P$ can be calculated as;

$$W_{P(36at16)} = \begin{cases} 1, & 53.66 < f < 54.74 \text{ kHz;} \\ 0.92f - 48.5k, & 48.5 < f < 53.66 \text{ kHz;} \\ -0.92f + 51.5k, & 54.74 < f < 55.83 \text{ kHz;} \\ 0, & \text{elsewhere.} \end{cases} \quad (14)$$

Where the 36W T8 lamp is operated at 16W (Ex:$f$ = 55.8kHz), $W_{P36at16}$ equals 0.32. Using this frequency to calculate another $W_P$, results $W_{P18at16} = 0$, $W_{P32at16} = 0.32$, $W_{P58at16} = 1$ and $W_{P70at16} = 0.45$. The highest $W_P$ is not on $W_{P18at16}$. Thus, the next power command is 30W regulated and $W_P$ is recalculated again at this level. The calculated results is shown in TABLE II. The algorithm stops at 36W lamp due to the maximum on $W_{P(36at34)}$. The summation of $W_P$ as 2.32 is the highest at 36W so the lamp is detected as 36W which is correct.

### B. Phase shift compensation

Change in parameters of resonant circuit affects this algorithm which results misclassification. These variation might occur from the production, temperature and life of each L or C. Fig. 7 and 8 show the change in operating frequency due to the variation of capacitance and reductance in this circuit.

TABLE II
CALCULATED RESULT OF $W_P$ OF UNKNOWN CONNECTED LAMP

| Power command / Lamp rating | 16W | 30W | 34W | 56W | 68W | Sum |
|---|---|---|---|---|---|---|
| 18W | 0 | | | | | 0 |
| 32W | 0.32 | 0 | | | | 0.32 |
| 36W | 0.32 | 1 | 1 | | | 2.32 |
| 58W | 1 | 0 | 0 | | | 1 |
| 70W | 0.45 | 0 | 0 | | | 0.45 |

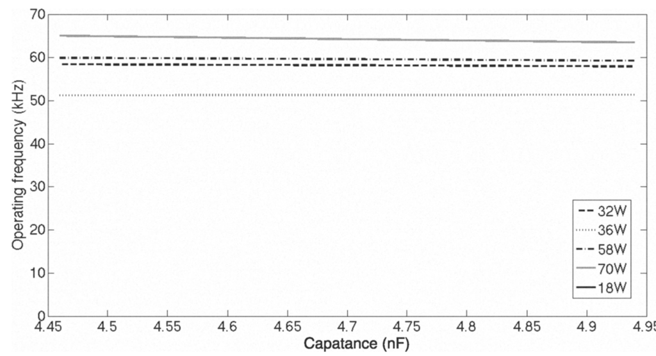


Fig. 7. Relation between capacitance and operating frequency

From Fig. 7, there is a small change in operating frequency because the capacitance is very high compare to a lamp resistance. The variation of inductance affects the operating frequency and consequently the output power as shown in (8).The relations between L and f, L and phase angle ($\phi$) and phase angle and f are plotted in Fig. 8, 9 and 10. The relationship between frequency and phase angle due to the variation of L within 10% is almost straight line. Thus, this can be approximate as linear equations (15).

$$\overline{x}'_f = a\phi + b : \phi_{min} < \phi < \phi_{max} \quad (15)$$

$$a = \frac{f_2 - f_1}{\phi_2 - \phi_1}, \; b = f_1 - a\phi_1 \quad (16)$$

By using (15), the $\overline{x}_f$ in (12) is changed to $\overline{x}'_f$ in order to compensate with small change in resonant circuit parameters.

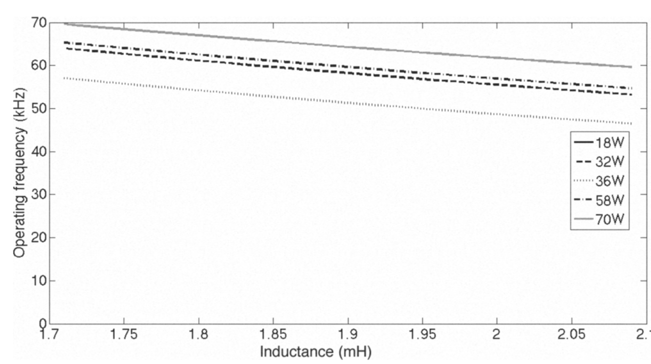


Fig. 8. Relation between inductance and operating frequency

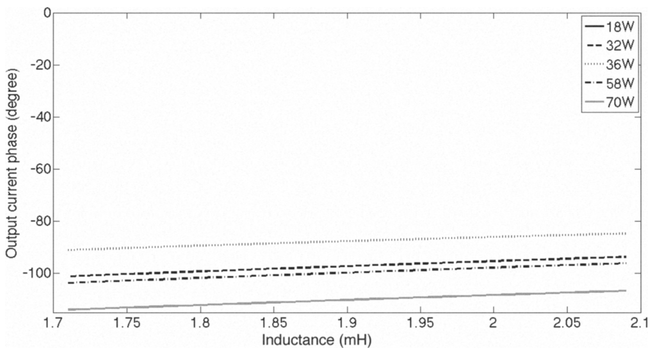


Fig. 9. Relation between inductance and current phase angle

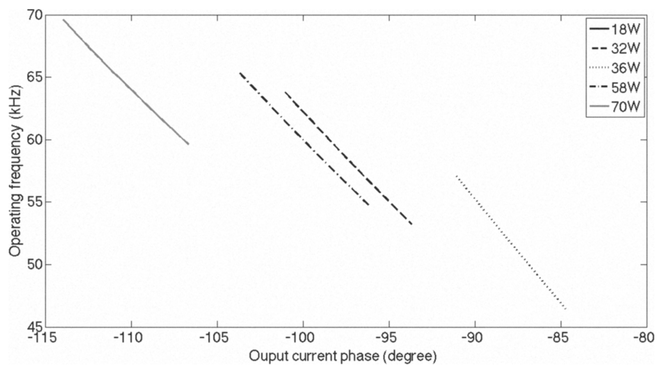


Fig. 10. Relation between operating frequency and current phase angle

This will make the better classification results.

## IV. Experimental results

This experiment is divided into 4 groups. The first group uses the plain frequency detection with designed L and C. The second group decreases L by 5%. The third group heat up the lamp to change the resistance. The last group decreases C by 5%.

Using designed resonant inductor and capacitor, the results of the tested lamps with frequency detection is outcome the correct results since the variation of lamp resistance has not much effect on frequency. TABLE III shows the highest $W_P$ at 32W. This is the worst case because the impedance of 32W is very close to that of 58W lamp. The small variation of L makes the big change in operating frequency with results in the misclassification.

By changing L from 1.9 to 1.8 mH causes the operating frequency move from 58.2 to 61.1 kHz when ballast regulates at 30W. This frequency will be considered as 58W lamp which has average operating frequency around 59.62kHz using L 1.9mH. Driving 32W at 56W is danger and will damage lamp and ballast. With the phase shift compensation (15) the new $\overline{x'}_f$ is 61.12kHz ($\phi$=-99.25). This process makes the recognition result to the right 32W lamp (TABLE V). The "or" in TABLE IV means $\phi$ is over $\phi_{Max}$ or under $\phi_{min}$. It blocks the algorithm not to detect.

With the rising of lamp temperature it has an effect on lamp resistance and will change the current phase angle too. With the phase angle change, this algorithm will move the $\overline{x}_f$ to $\overline{x'}_f$ as shown in (15). Fig. 11 shows the relation between $\phi$ and f when lamp resistance is varied. This graph shows the same slope direction as the change of L but with difference slope values. From the result the change in phase angle, it does not much affect the frequency calculated by phase shift compensation.

By heating up the lamp, the operating frequency increases to 58.5kHz and $\phi$ is -97.67. This phase shift make the new $\overline{x}_f$ move to 58.84kHz. The result is shown in TABLE VI. It also results the correct 32W.

The last test deals with changing C to 4.5nF. It results

TABLE III
Calculated results of $W_P$ for an unknown lamp

| Power command / Lamp rating | 16W | 30W | 34W | 56W | 68W | Sum |
|---|---|---|---|---|---|---|
| 18W | 0 | | | | | 0 |
| 32W | 1 | 1 | | | | 2 |
| 36W | 0 | 0 | | | | 0 |
| 58W | 1 | 0.44 | | | | 1.44 |
| 70W | 0.94 | 0 | | | | 0.94 |

TABLE IV
Phase shift compensation for 30W regulated, L=1.8$mH$

| Rating | a | b | $\phi_{min}$ | $\phi_{Max}$ | $\overline{x'}_f$ |
|---|---|---|---|---|---|
| 32W | -1.4328 | -81.0834 | -99.26 | -95.33 | 61.12 |
| 36W | -1.6652 | -94.6468 | -89.38 | -86.06 | 70.62(or) |
| 58W | -1.4054 | -80.5046 | -101.76 | -97.8 | 58.98 |
| 70W | -17.4 | -1884.8 | -112.17 | -108.32 | -157.85(or) |

TABLE V
Calculated results of $W_P$ of 32W lamp with L=1.8$mH$

| Power command / Lamp rating | 16W | 30W | 34W | 56W | 68W | Sum |
|---|---|---|---|---|---|---|
| 18W | 0(or) | | | | | 0 |
| 32W | 0.22 | 1 | | | | 1.22 |
| 36W | 0(or) | 0(or) | | | | 0 |
| 58W | 0 | 0 | | | | 0 |
| 70W | 0(or) | 0(or) | | | | 0 |

TABLE VI
Phase shift compensation for 30W regulated, R=624.2Ω

| Rating | a | b | $\phi_{min}$ | $\phi_{Max}$ | $\overline{x'}_f$ |
|---|---|---|---|---|---|
| 32W | -1.4328 | -81.0834 | -99.26 | -95.33 | 58.84 |
| 36W | -1.6652 | -94.6468 | -89.38 | -86.06 | 67.98(or) |
| 58W | -1.4054 | -80.5046 | -101.76 | -97.8 | 56.75 |
| 70W | -17.4 | -1884.8 | -112.17 | -108.32 | -185.52(or) |

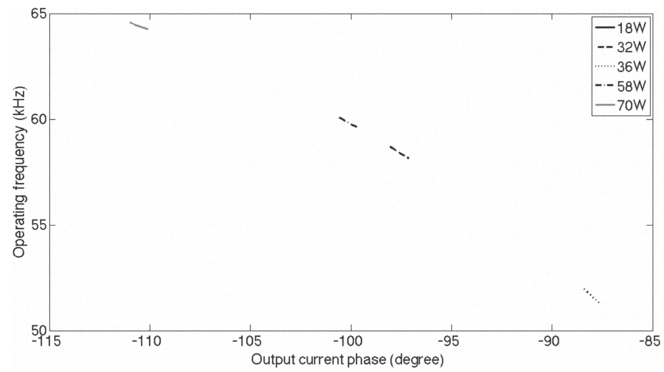


Fig. 11. Relation between operating frequency and current phase angle

TABLE VII
PHASE SHIFT COMPENSATION FOR 30W REGULATED, C=4.5$nF$

| Rating | a | b | $\phi_{min}$ | $\phi_{Max}$ | $\overline{x'}_f$ |
|---|---|---|---|---|---|
| 32W | -1.4328 | -81.0834 | -99.26 | -95.33 | 55.92 |
| 36W | -1.6652 | -94.6468 | -89.38 | -86.06 | 64.58(or) |
| 58W | -1.4054 | -80.5046 | -101.76 | -97.8 | 53.88(or) |
| 70W | -17.4 | -1884.8 | -112.17 | -108.32 | -221.01(or) |

in frequency changing to 58.4kHz and $\phi$ is -95.6. The $\overline{x'}_f$ moves to 55.92kHz. The result is shown in TABLE VI. By recalculates the $W_P$, It also results the correct 32W.

Fig. 12 shows the operation process result of this proposed algorithm applied with 36W lamp. The oscilloscope is setup with 0.5A/div in channel 1 ,200V/div in channel 2 and 800ms/div for time. The recognition process take approximately 2.8 seconds after striking or 4 seconds from startup. The algorithm has 3 step of lamp regulated consist of 16W, 30W and 34W. This process will take longer that in case of higher lamp rate. The maximum classification time is with 70W lamp rating is less than 6 seconds from startup.

From the detection results with another tested lamp outcome the correct answer with L variation is less than 5% compare to not more than 1% with only frequency detection. With the variation of lamp resistance or capacitance is different. The tolerance of changing them is significantly dropped. This algorithm allows R and C to be varied with in 5%. Compare to the previous methods the previous one has higher tolerance for both C and R values shifting by 10-15%. But for the L it has only 1% tolerance. And comparing to the voltage consideration method, this frequency and phase consideration method can classify the lamp that has very close impedance like 58w and 32w in the tolerance region.

## V. CONCLUSION

An automatic lamp detection method by considering the frequency and phase shift has been tested for T8 fluorescent lamps. The results show the correct classification; especially, for the lamp that has very close impedance like 58W and 32W lamps. But the very weak point of this method is such a frequency is much depended on resonant parameters. This becomes a low tolerance of resonant circuit parameters especially the inductor. With the proposed phase compensation, the tolerance of inductance varied to 5%. This is in exchange with the lower tolerance with capacitance and lamp resistance variation dropped down to around 5%. Although this does not affect the normal condition lamps, the end of life and the near end of life lamps are affected. An unpredictable result occurred for such this kind of lamp. Thus, the end of life protection should be applied in order to shutdown the ballast when connected to the end of life lamp.

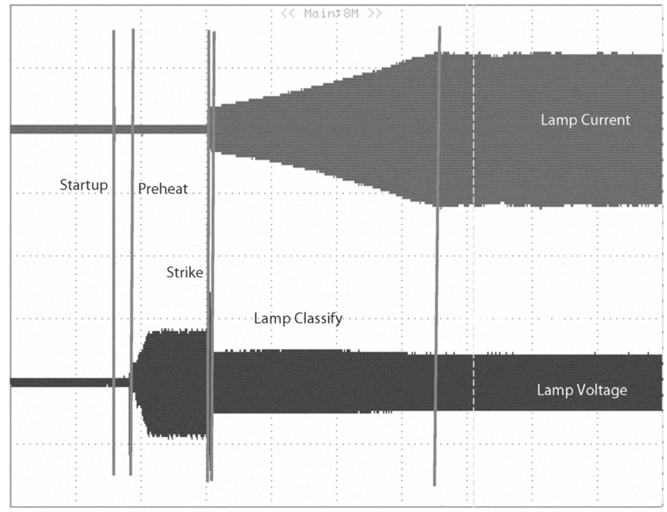


Fig. 12. The tested lamp output waveform running with this proposed algorithm

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