# AN10803

## Triac dimmable CFL application using the UBA2028/UBA2014/UBA2027x

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### Document information

| Info | Content |
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| **Keywords** | UBA2028, UBA2014, UBA2027x, dimmable, CFL, Triac, dimmer, charge pump |
| **Abstract** | This application note describes how to design a dimmable CFL using the UBA2028, UBA2014 or UBA2027x. |

### Revision history

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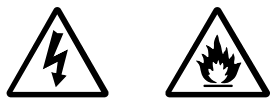
# 1. Introduction

**WARNING**

**Lethal voltage and fire ignition hazard**



The non-insulated high voltages that are present when operating this product, constitute a risk of electric shock, personal injury, death and/or ignition of fire.

This product is intended for evaluation purposes only. It shall be operated in a designated test area by personnel qualified according to local requirements and labor laws to work with non-insulated mains voltages and high-voltage circuits. This product shall never be operated unattended.

This application note describes how to design a dimmable Compact Fluorescent Lamp (CFL) circuit with the UBA2028, UBA2014 or the new UBA2027x series. The differences between the versions are the ones that have integrated MOSFETs and controller versions that use external MOSFETs. The versions with internal MOSFETs can drive burners to 18 W. Use the versions with external MOSFETs for larger burners. The control parts of the different versions are identical, so the same calculation tools can be used.

**Remark:** Unless otherwise stated all voltages are AC.

The design of a Triac dimmable CFL is a complicated task. Interaction between the dimmer and CFL, tolerances, aging of components and, last but not least the circuit must not be expensive affects the dimming behavior. Most components serve multiple purposes, so it is not always possible to choose the optimum value for each purpose. There is no guarantee that the designed circuit works with all dimmers, because it is not known in advance which dimmer type the CFL is connected to.

# 2. Triac dimmers

Virtually all domestic wall dimmers are phase cut dimmers. This means that the supply voltage to the lamp is reduced with cutting the phase see Figure 1. In practice, this condition is implemented by placing a switch. An example is a Triac in one of the supply lines that is not conducting during a certain part or angle (see φ Figure 1) of the mains period. Effectively, this reduces the RMS voltage supplied to the lamp.

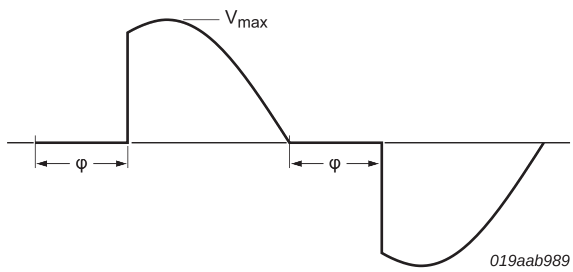



**Fig 1. Phase cut sine wave**

Phase cut dimming with a Triac works very well for dimming incandescent lamps. However, dimming CFL lamps with this principle is more complicated due to the interaction between the dimmer and the CFL. It is important to understand how a wall dimmer works before designing a dimmable CFL lamp. Figure 2 shows the circuit diagram of a basic wall dimmer with Triac.

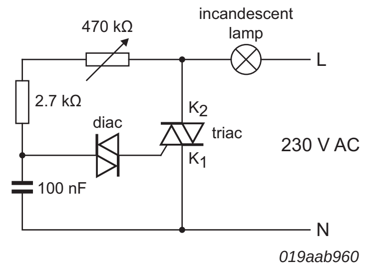



**Fig 2. Basic 230 V dimmer**

The capacitor is charged via the combination of a fixed and a variable resistor. The dimming angle is set with the variable resistor. When the resistance is low, the capacitor is quickly charged until the breakover voltage of the Diac. The Triac is then triggered and immediately a current starts to flow from $k_1$ to $k_2$. This current continues to flow until the Triac blocks when the current drops below the minimum hold current $I_H$. As the incandescent lamp is a resistive load, this occurs at the zero crossing of the mains input. The Triac is a bidirectional device that works in two quadrants (see Figure 3), so the same process is repeated during the negative half cycle.

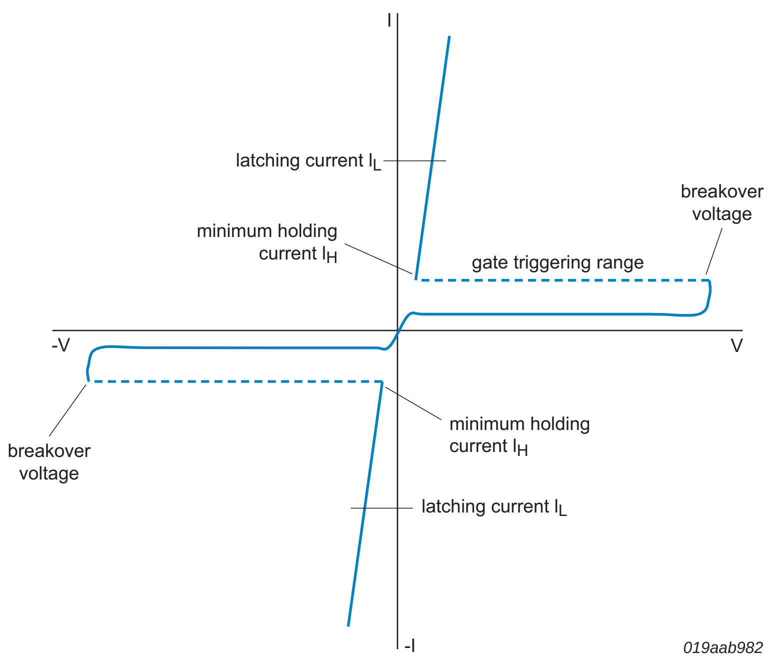



**Fig 3. Typical Triac VI characteristic curves**

Normal operation of the dimmer requires the presence of a conducting or charging path for $C_{dim}$ when the Triac in the dimmer is not conducting. It requires a low ohmic load for sustainable conduction of the Triac when the Triac is conducting. The incandescent light bulb see Figure 2 provides all of this. The situation is different when a CFL or other load that contains a bridge rectifier is connected. It depends on the moment of switch-on to determine if current flows through the Triac. This is only the case when the (momentary) input voltage is higher than the DC bus voltage. See Figure 5.

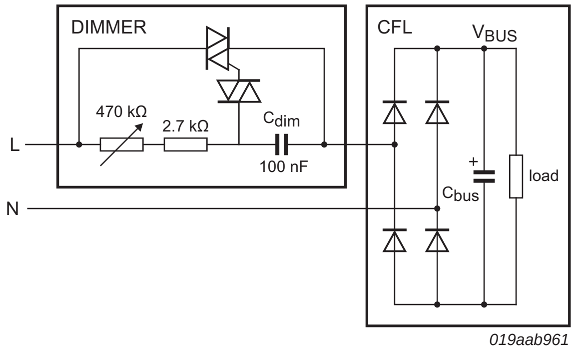



**Fig 4. Basic dimmer with CFL**

The Triac switches off when the current drops below the hold current $I_H$. Here it is not the moment at which the input voltage crosses zero, but the moment where the momentary input voltage drops below the DC bus voltage. In practice, this moment is soon after the Triac is switched on.

Most of the time, the bridge diodes are not conducting, so there is no conductive path to charge the capacitor in the dimmer. This is fine when the dimmer phase cut is set to a very small angle and $C_{dim}$ charges enough to trigger the Triac within the period that the mains is higher than the bus voltage. However, when the phase cut is set to a larger angle the charge of $C_{dim}$ is not completed in a single half cycle and triggering of the Triac is at irregular intervals as shown in Figure 5.

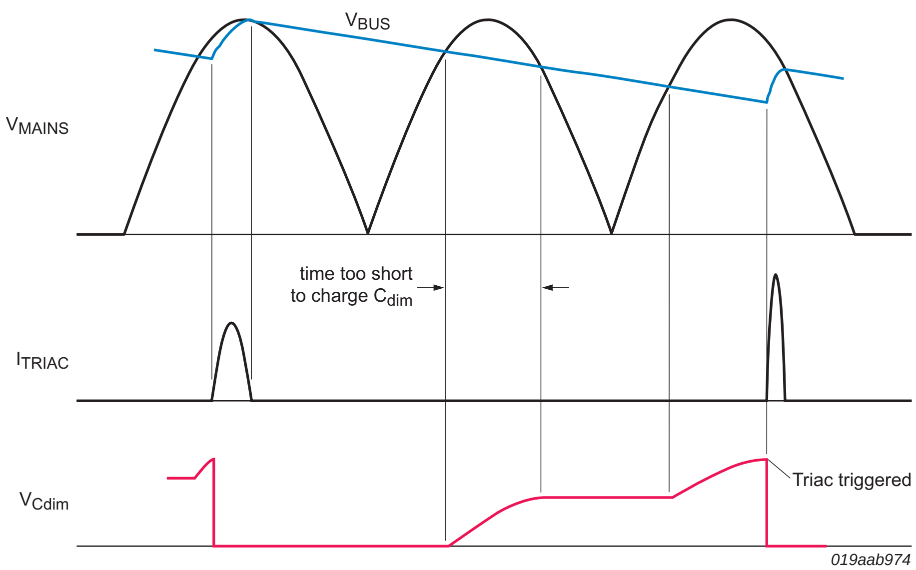



**Fig 5. Input voltage and current when large dimmer phase cut is set**

The result is that the Triac is triggered at irregular moments resulting in the input voltage of the CFL is irregular. The dimming level of the lamp is retrieved from the input voltage, so an irregular input voltage results in an irregular dimming level or lamp flicker.

The latch current threshold of the Triac must be exceeded before the gate trigger current is removed. The current through the Triac must be maintained above the Hold current threshold $I_H$, until the next zero crossing of the mains voltage to ensure a smooth operation of the dimmer. A hold current of 15 mA to 20 mA is sufficient for most dimmers. A simple solution that generates the hold current, is to place a resistance across the input. However, the hold current must also flow at low input voltages, so the resistance must be very low resulting in huge losses. For that reason, a current source behavior is required. This can be realized with a Power Factor Corrector (PFC). It can either be a boost converter or a charge pump-based PFC. In the latter solution, a capacitor is used as an energy storage element to draw current from the mains at low voltages. The practical implementation consists of two diodes and a capacitor and is discussed in detail in Section 3.3. This application note addresses the charge pump solution because it is the most cost effective solution.

The charge pump circuit enables a conductive path as long as the lamp is on. However, if the phase cut angle is set too large, the supplied voltage becomes too low for the circuit to maintain the lamp current and the lamp turns off. Now there is no conductive path any more through the CFL to charge $C_{bus}$ in Figure 4. In practice, there is some leakage through the filter components in the dimmer, so after some time the Triac is fired. Then it depends on the potentiometer setting in the dimmer if the CFL starts, or begins in a flash mode. This start-up behavior heavily depends on the design of the dimmer.

# 3. Designing the application

## 3.1 Block diagram

Figure 6 shows the block diagram of the dimmable CFL with charge pump. The phase cut mains voltage is supplied to the CFL. The input voltage is rectified and supplied to the inverter, and also used for detecting the phase cut adjustment of the dimmer. This is done by measuring the average input voltage and supplying it to the control input of the inverter control IC. That is, the CSP pin of the UBA2014 or UBA2028 and the DCI pin of the UBA2027x. The dimmer phase cut detection must be non-linear. That is, the lamp must be dimmed to 10 % before the bus voltage becomes too low and the inverter switches off due to low supply voltage.

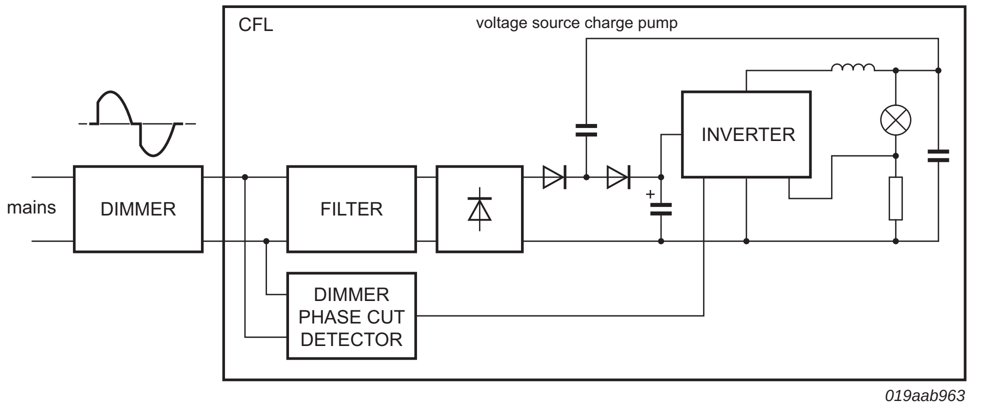



**Fig 6. Block diagram of the charge pump CFL dimmer**

In practice, the lamp must already be dimmed to 10 % at 120 degrees phase cut and preferably maintain the lowest dim level to 130 degrees. Beyond that value, the lamp is off, but the inverter is still switching and providing a charge pump current. Without the charge pump current, the CFL input is high (ohmic), and the input voltage is no longer a reliable representation of the dimmer position.

## 3.2 Resonant tank

Once the gas in the CFL tube is ionized however, its impedance becomes negative. This means that the more current is flowing through the tube, the more conductive it becomes The increased current increases the degree of ionization of the gas. Therefore, add some form of current limiter to the lamp to prevent the current increasing to a level where the tube is destroyed.

An inductor is placed in series with the tube therefore, the tube is supplied with a current, rather than with a voltage. A capacitor is placed in parallel to the tube that creates a resonant circuit or resonant tank in combination with the series inductor to ignite the tube. Before ignition, the lamp impedance is almost infinite, so the quality factor of the resonant tank is high. At start-up and before lamp ignition the switching frequency is above the resonance frequency and goes down in frequency until the tube ignites.

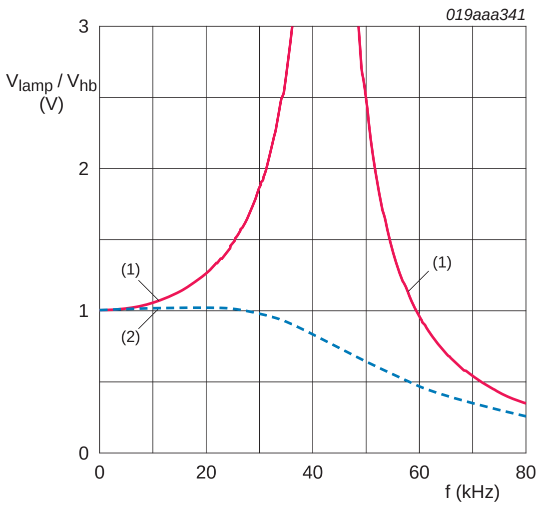



**Fig 7. Transfer of resonant tank versus frequency before and after ignition**

For the calculation of the resonant tank, the first harmonic approach is used. This approach works well, especially near the resonant frequency. Equation 1 shows the RMS value of the first harmonic of the half-bridge voltage.

$$V_{I(RMS)} = \frac{1}{\sqrt{2}}\frac{4}{\pi}\frac{V_{BUS}}{2} = \frac{\sqrt{2}}{\pi}V_{BUS} \quad (1)$$

The input parameters for the first estimation of the resonant tank are as follows:

- Nominal lamp current
- Nominal lamp voltage
- Nominal operating frequency
- Minimum bus voltage
- The phase angle $\varphi$ between the input voltage and current of the resonant tank

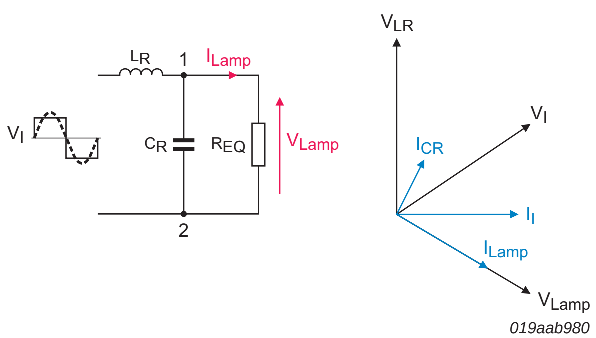



**Fig 8. Schematic resonant tank and vector diagram**

An equivalent resistor ($R_{EQ}$) is calculated from point 1 and 2. Equivalent resistance is only valid at nominal lamp power. The operating frequency ($f_{nom}$) at nominal lamp power, is set between 40 kHz and 50 kHz.

It is important to guarantee Zero Voltage Switching (ZVS) of the half-bridge stage to have low losses in the switching devices in the half-bridge driving the resonant tank. Therefore the resonant tank must have an inductive behavior, so the input current must lag the input voltage. The larger the phase angle between the input current and voltage, the easier it is to maintain ZVS. However, when the phase angle is made too large, the losses become potentially high. In general a value between 30 and 45 degrees is chosen.

The voltage transfer of the resonant tank is:

$$\frac{V_{lamp}}{V_{I(RMS)}} = \frac{1}{(1-\omega_{nom}{}^{2}LC) + j\left(\omega_{nom}\frac{L}{R_{EQ}}\right)} \quad \text{with} \quad \omega_{nom} = 2\pi f_{nom} \tag{2}$$

The tangent of the phase angle $\varphi$ between the input voltage and current of the resonant tank, is as calculated in Equation 3:

$$tan\varphi = \omega_{nom}\frac{L}{R_{EQ}} - \omega_{nom}R_{EQ}C + \omega_{nom}R_{EQ}LC^{2} \tag{3}$$

When these two equations are combined, the capacitance value can be calculated using Equation 4:

$$C = \frac{\sqrt{-V^{2}{}_{I(RMS)} + V_{lamp}{}^{2} + V_{lamp}{}^{2}\tan^{2}\varphi}}{V_{I(RMS)}R_{EQ}\omega_{nom}} \tag{4}$$

The value of the inductor is as calculated in Equation 5:

$$L = \frac{tan\varphi + \omega_{nom}R_{EQ}C}{\frac{\omega_{nom}}{R_{EQ}} + \omega_{nom}{}^{3}R_{EQ}C^{2}} \tag{5}$$

Now the inductor and capacitor values are fixed and the dimming behavior can be determined.

The control loop of the inverter works by setting a reference value for the lamp current. It adapts the half-bridge frequency until the desired lamp current is reached. Because of the negative impedance of a fluorescent lamp, the lamp voltage decreases when the lamp current increases. The exact relation between lamp current and lamp power depends on the lamp type. The lamp type must be known to calculate the relation between lamp power and frequency. The relation between lamp power and operating frequency is given in Equation 6:

$$V_{la}I_{la} = \frac{\frac{V_{la}}{I_{la}}\left(1 + \left(\omega\frac{V_{la}}{I_{la}}C\right)^{2}\right)}{\left(\frac{V_{la}}{I_{la}}\right)^{2} + \left(\omega L - \omega\left(\frac{V_{la}}{I_{la}}\right)^{2}C + \omega^{3}L\left(\frac{V_{la}}{I_{la}}\right)C^{2}\right)^{2}} \tag{6}$$

Solving Equation 6 yields:

$$f = \frac{1}{2\pi\sqrt{2LCV_{la}}}\sqrt{2LCV_{la}^{2} - L^{2}I_{la}^{2} + \sqrt{-4L^{3}CI_{la}^{2}V_{la}^{2} + L^{4}I_{la}^{4} + 4L^{2}C^{2}V_{la}^{2}V_{I}^{2}}} \quad (7)$$

With this equation, the power can be plotted versus frequency. See Section 5.

## 3.3 Charge pump circuit

The charge pump circuit is used in many applications to improve the power factor of the CFL. In this application, it is also used to draw hold current through the Triac to keep the Triac on, following ignition.

In an ordinary rectifier with an inverter, current is only drawn from the mains at around the maximum input voltage. Figure 9 shows an inverter with a voltage source charge pump. Adding two Hi-Speed $D_X$ and $D_Y$ diodes and a capacitor $C_X$, makes it possible to draw current from the mains during the whole cycle. The CFL inverter with charge pump power feedback (see Figure 9) is replaced by its equivalent circuit (see Figure 10). A voltage source represents the lamp voltage, the rectified mains voltage and the voltage across the bus electrolytic capacitor.

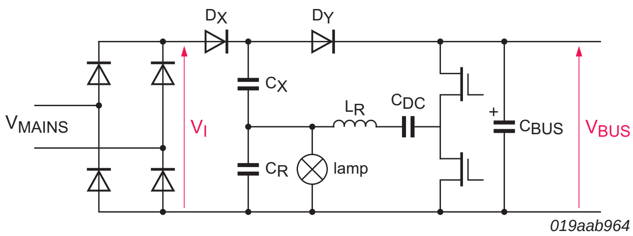



**Fig 9. CFL inverter with charge pump power feedback**

The lamp voltage or equally the voltage across $C_R$ (see Figure 9) can also be considered a high-frequency voltage source. Therefore $V_{la}$ is equal to the lamp voltage and $C_x$ can be connected to this point.

The capacitance $C_x$ is charged from $V_I$ via $D_x$ and is discharged to $V_{BUS}$ via $D_Y$. A charge package is “pumped” from $V_I$ to $V_{BUS}$ in each inverter switching cycle of $V_{la}$. $V_I$ is the rectified mains voltage that has a ripple that is twice the mains frequency.

The parameter of interest is the average current during one inverter switching cycle ($I_{I(ave)}$) that is drawn from the mains. In Ref. 1, it is shown that this current is calculated with the following equation:

$$I_{I(ave)} = C_x f_s (V_I + 2V_{lamp} - V_{BUS}) \quad (8)$$

Where:

- $f_s$ is the inverter switching frequency
- $V_{lamp}$ is the amplitude of the lamp voltage

Equation 8 shows that the input current is following the input voltage when the peak-to-peak lamp voltage (= 2 $V_{lamp}$) is equal to the bus voltage. The power factor is equal to 1 in this situation (unity power factor condition).

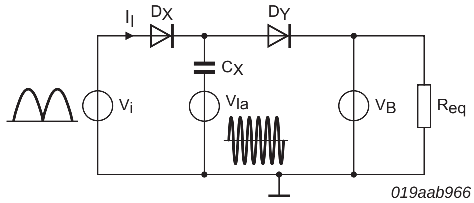



**Fig 10. Equivalent circuit of a voltage source charge pump**

When $C_{bus}$ Figure 9 is directly charged from the mains, both diodes $D_x$ and $D_Y$ are conducting and $C_x$ is then directly in parallel with $C_R$. Therefore by connecting $C_x$ to the resonant tank, $C_x$ highly modulates it during a switching cycle. The total capacitance that is in parallel to the lamp is given in Equation 9.

$$C_{EQ} = C_R + C_X\frac{(V_I + 2V_{lamp} - V_{BUS})}{2V_{lamp}} \tag{9}$$

Equation 9 reduces to Equation 10 when 2 $V_{lamp}$ = $V_{BUS}$:

$$C_{EQ} = C_R + C_X\frac{V_I}{V_{BUS}} \tag{10}$$

The use of a voltage source charge pump circuit has some drawbacks:

Unity power factor is only obtained when $V_{bus}$ = 2 $V_{lamp}$. However, this can only be fulfilled when the lamp is operating at a constant level and is not dimmed. When the lamp is dimmed, the frequency goes up and the tube voltage rises because of negative incremental impedance of the tube. The unity power factor condition is not fulfilled any more. The voltage across the tube is not only much higher when the lamp is dimmed, but also when the lamp is in the preheat or ignition phase.

Both are considered as low-power situations and cause the charge pump to absorb a lot more energy from the mains than the load consumes. This extra energy is stored in the buffer capacitor $C_{bus}$. It causes the bus voltage to exceed 800 V which is much higher than the voltage rating of the bus capacitor and driver IC.

Another drawback is the modulating effect of $C_x$ on the resonant tank. This causes the crest factor of the lamp to become as high as 2.6, reducing lamp life and increasing the possibility of visible lamp flicker. A crest factor of 1.7 is preferred.

A way to reduce these problems is to place an extra capacitor across $D_Y$. This capacitor improves the crest factor to a value of 1.6. It reduces bus voltage stress by 60 % while still providing a cost effective way to produce the necessary hold current for a dimmable CFL application.

This all comes at a price of 1.6 times higher current stress on the half-bridge switches so this technique is most suited for the drivers with external output devices. See Ref. 3 for more information on the voltage source charge pump with improved crest factor (VSCP with ICF).

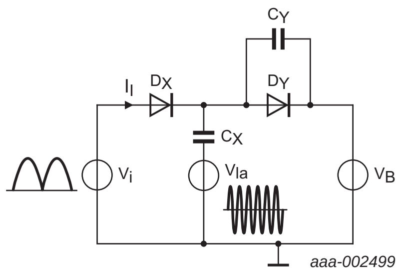



**Fig 11. VSCP with ICF**

Another voltage source charge pump which can be considered is the voltage source charge pump with low-frequency second resonance (VSCP with LFSR). This topology uses more components and two inductors. However, it has a good power factor and a low bus voltage stress over the full dimming range:

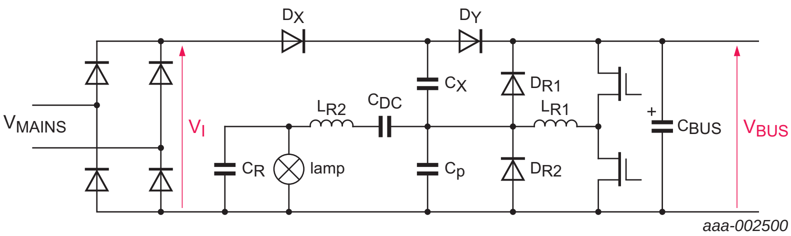



**Fig 12. VSCP with LFSR**

## 3.4 Voltage doubler and charge pump for 120 V input

When the mains voltage is 120 V, then the bus voltage is too low to supply the lamp. For that reason, a voltage doubler is used instead of a full bridge rectifier. Figure 13 shows the voltage doubler circuit. $C_H$ is charged during the positive half-cycle and during the negative half-cycle $C_L$ is charged. If there is no load, the bus voltage becomes equal to the mains peak-to-peak voltage.

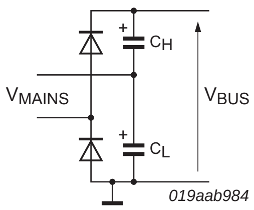



**Fig 13. Voltage doubler circuit**

The electrolytic capacitors in this circuit have a double capacitance and half the voltage with reference to the 230 V circuit. Figure 14 shows the voltage doubler combined with the charge pump circuit. A symmetrical voltage source charge pump replaces both rectifier diodes. The two top left diodes charge energy into $C_H$ at the positive half cycle of the mains. The two left bottom diodes charge energy into $C_L$ during the negative half cycle of the mains (see Figure 14). Instead of using two high-voltage charge pump capacitors driving each charge pump from the resonant tank, a single high-voltage charge pump capacitor and an AC coupling capacitor between the two charge pumps are used. Because only one set of diodes is conducting during each half mains cycle, the energy stored in $C_p$ is automatically stored to either $C_H$ or $C_L$ only, depending on the mains polarity.

A coupling capacitor of 100 nF is more than sufficient to have a neglecting influence compared to the value of $C_p$. By using only a single capacitor $C_Y$ a charge pump with improved crest factor is created.

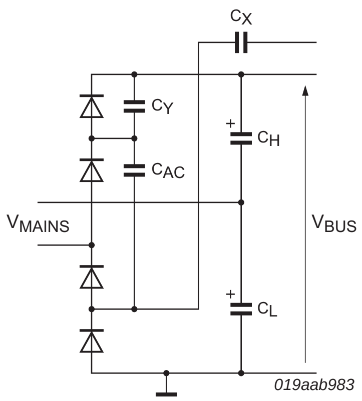



**Fig 14. Voltage doubler with charge pump circuit**

## 3.5 Current feedback control loop

With the UBA2014 or the UBA2028, it is easy to control the lamp current as a controller is implemented in the IC.

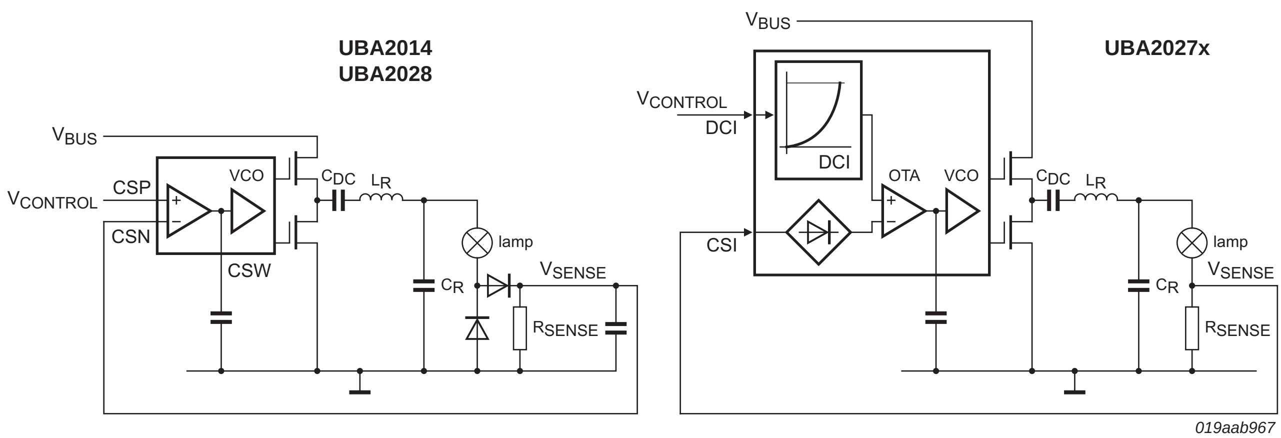



**Fig 15. Current feedback control loop**

The lamp current is measured across a sense resistor. The UBA2014 and UBA2028 are single-sided rectified externally. The UBA2027x family is double-sided rectified internally. The measured value is compared with a control voltage that is applied to the CSP pin. The control loop changes the half-bridge frequency until the measured voltage is equal to the control voltage, so the RMS lamp current can be calculated with:

For UBA2014 and UBA2028:

$$I_{lamp(RMS)} = \frac{\pi}{\sqrt{2}} \frac{V_{control}}{R_{SENSE}} \quad (11)$$

Due to UBA2027x families' overpower protection, the maximum RMS lamp current is limited to:

$$I_{lamp(RMS)} = \frac{1}{R_{sense}} \quad (12)$$

In the Triac dimmable CFL application, the control voltage is derived from the average mains voltage in the dimmer position detector.

## 3.6 Dimmer phase cut detector

The control voltage for the current feedback control loop is derived in the dimmer phase cut detector. The dimmer phase cut detector is based on average voltage detection of the phase cut mains voltage and converted to a lower voltage average reference voltage. The average reference voltage is supplied to the CSP pin in case of UBA20214/UBA2028 and the DCI pin in case of the UBA2027x family.

Ideally, the lamp lumen is linear with the position of the dimmer control. Figure 6. The human eye is more sensitive to small light changes at low lumen level, than to large light changes at high lumen levels. The lamp current has a direct linear relation to the lamp lumen output. When the phase cut dimming angle is detected by using an average voltage detection, the result is that the average control voltage curve follows a cosine function. The cosine slope has a small level change at the high lumen levels and a large change at mid to low lumens.

Typically the UBA2014 and UBA2028 have a linear control voltage to lamp current transfer (see Figure 16 left image). The response to a dimmer is observed as less natural because the dimmer must be set halfway to notice response in the lumen output of the lamp. Also, the lower dim levels are more difficult to control. A way to overcome this problem is using extra diodes in the lamp current sense which helps at the lower dim rage. However, a better solution is to make the control voltage to lamp current transfer function non-linear.

This is what has been implemented in the UBA2027x family, its transfer function is shown on the right of Figure 16. It is called the natural dimming transfer function and makes better use of the control rage of the dimmer.

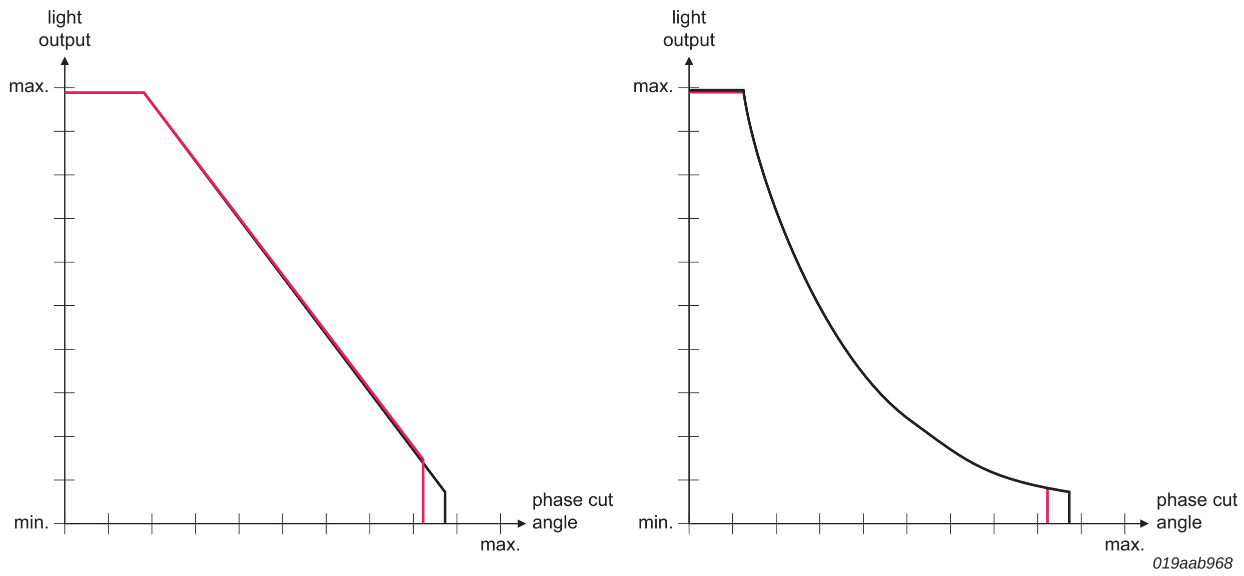



**Fig 16. Dimming curve UBA2028 versus UBA2027**

Figure 17 shows the phase cut angle detection for a double sided rectified mains voltage, typically used in 230 V applications and 120 V applications that sweep up the lamp voltage in the resonant tank.

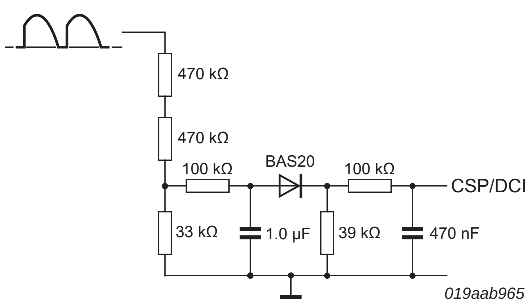



**Fig 17. Dimmer phase cut detector circuit for rectified mains supply**

Figure 18 is a typical circuit that is used for single side rectified 120 V voltage doubler applications.

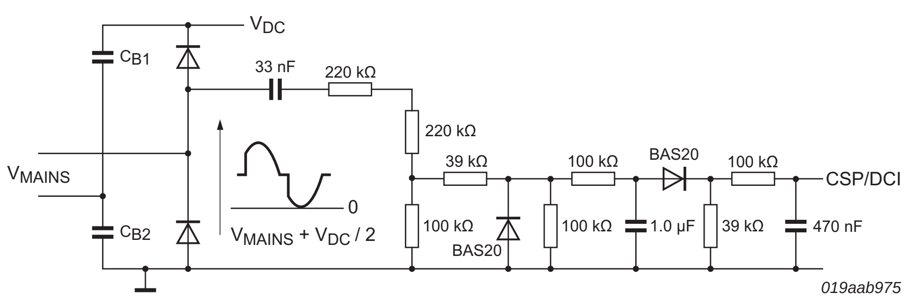



**Fig 18. Input voltage measurement in voltage doubler**

## 3.7 Supply of the IC and ACM for UBA2028 and UBA2014

Before start-up the supply electrolytic capacitor is charged via the start-up resistor to the DC bus voltage. The IC starts when the supply voltage exceeds $V_{DD(start)}$. Then the half-bridge starts to switch and the IC is supplied via the dV/dt capacitor that is connected to the half-bridge. The supply current of the IC and the charge required to drive larger MOSFETs determine the value of this capacitor. The IC needs more supply current which requires a larger dV/dt capacitor.

On the other hand, if the dV/dt capacitor is too large, the half-bridge can be hard switching at the higher frequencies. In most cases, a value of 470 pF is a good compromise between these two mechanisms. A larger CdV/dt also has a positive influence on the EMI as it slows down the rise and fall times of the half-bridge switching pulses. A small capacitor is placed in parallel with the 12 V Zener diode, so it does not overload if $C_{dV/dt}$ is larger than required to supply energy to the IC. This capacitor also determines at which bus voltage level the IC stops oscillating. This to create a flicker free operation of the lamp by using the hysteresis on the $V_{DD}$ pin of the IC.

A Zener diode clamps the voltage, which is supplied to the supply electrolytic capacitor via a diode. This must be a diode with a fast recovery.

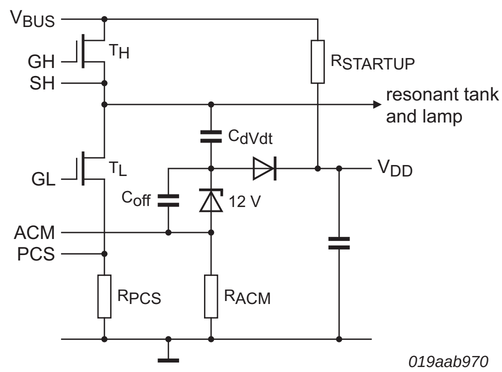



**Fig 19. IC supply circuit**

The UBA2014 and UBA2028 have an adaptive non-overlap function and a capacitive mode detection that measure the charging current of the dV/dt capacitor by measuring the voltage across $R_{ACM}$. This voltage is supplied to the capacitive mode detection input. For more information on this function, consult the respective data sheet.

## 3.8 Preheating

Before ignition, the tube resistance is infinite. However, the resonance inductor has two auxiliary windings that are used for heating the filaments, so the quality factor of the resonant tank is high, but not infinite. The half-bridge frequency starts at $f_{max}$ and is swept down until the voltage on the PCS/SLS pin reaches the $V_{PH}$ level of 0.6 V. The frequency sweep stops. The current in the resonant tank is kept constant for the duration of the preheat time, which is defined with the value of the preheat capacitor connected to the CT/CP pin.

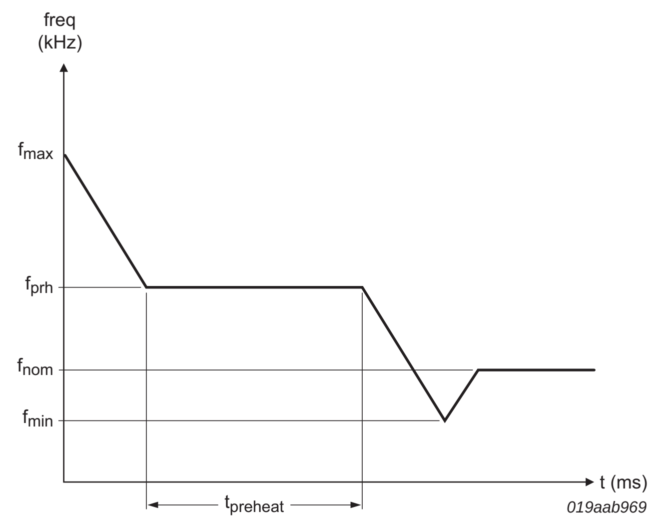



**Fig 20. Frequency versus time during start-up**

During the preheat time, the current is controlled by regulating the half-bridge frequency so that the voltage on the PCS/SLS pin stays constant. This means that the half-bridge current is kept constant. The value of this current can be adapted by changing the vale of the PCS/SLS resistor. Take care that the tube voltage does not become too high during preheat time. Generally, it must be less than half the ignition voltage. Tube voltage that is too high can cause an early uncontrolled ignition in the preheat phase.

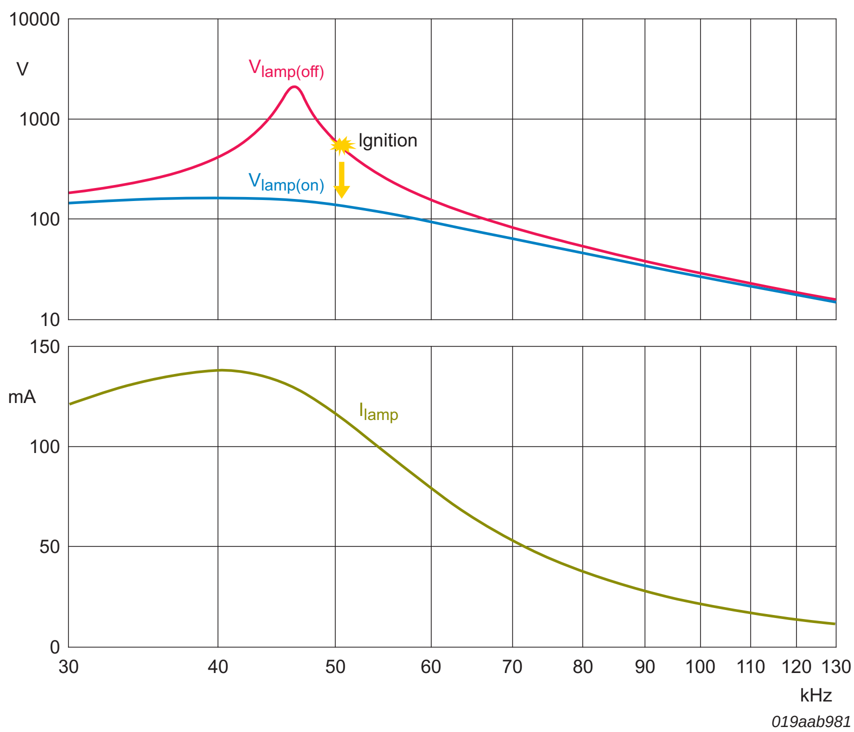



**Fig 21. Transfer of the resonant tank**

After preheating, the frequency sweeps down and during this part of the sweep the voltage across the lamp rises further and the lamp ignites. The UBA2014 and UBA2028 always sweep down to $f_{min}$. The UBA2027 detects a lamp current and stops the sweep and immediately goes to $f_{nom}$ (see Figure 20). The tube is now a resistive element in parallel to the capacitor in the resonant tank. This changes the quality factor of the resonant tank. Figure 21 shows this situation (blue line ($V_{lamp(on)}$)). After the frequency reaches $f_{min}$ or the current in the tube has been detected, the lamp current control loop takes over the tube current control.

When inductive preheat is used (the only option for the UBA2027), the resonance inductor is in fact a three winding coupled inductor. A series capacitor can be used for tuning the preheat current into constant power to the filament during preheat. A resistor and a capacitor in parallel to the resonance inductor can represent the preheat circuit. The coupling between the windings is assumed to be perfect.

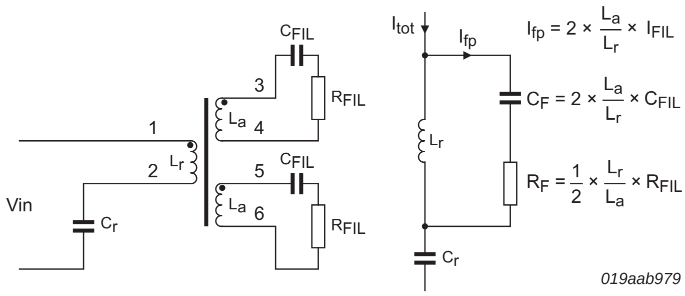



**Fig 22. Preheat circuit**

The equation of interest is the relation between the half-bridge current ($I_{tot}$) and the preheat current ($I_{fil}$), because the value of $I_{tot}$ during preheat is fixed with the value of the PCS/SLS resistor. The resulting value of $I_{fil}$ can be calculated with Equation 13:

$$\frac{I_{fil}}{I_{tot}} = \frac{\frac{1}{2}\frac{L_r}{L_a} i_{fp}}{I_{tot}} = \frac{\frac{1}{2}\frac{L_r}{L_a} j\omega L_r}{j\omega L_r + \frac{1}{j\omega C_f} + R_f} \qquad (13)$$

Equation 13 leads to:

$$\left|\frac{I_{fil}}{I_{tot}}\right| = \frac{1}{2}\sqrt{\frac{\omega^4 L_r{}^4 C_f{}^2}{L_a{}^2(L_r{}^2 C_f{}^2 \omega^4 + R_f{}^2 C_r{}^2 \omega^2 - 2L_r C_r \omega^2 + 1)}} \qquad (14)$$

This equation does not contain $C_r$.

The total current that is drawn from the half-bridge is:

$$I_{tot} = \frac{C_r C_f R_f \omega^2 + j(L_r C_r C_f \omega^3 - C_r \omega)}{L_r C_r \omega^2 + L_r C_f \omega^2 - 1 + j(L_r C_r R_f C_f \omega^3 - R_f C_f \omega)} V_I \qquad (15)$$

The resistance of the filament is not constant. During preheating, the resistance of the filament becomes ideally 4.75 times higher than the cold resistance. Changing the value of the resistance in the equations above shows that the filament current is almost independent of the filament resistance. However, the filament current strongly depends on the frequency, and the voltage across the inductor is almost a square wave. This means that the preheat current contains numerous higher harmonics that are present in the half-bridge voltage. High dV/dt gives a high preheat current. So if the bridge is hard switching, then there is a large preheat current flowing through the filaments. It is more practical to simulate the preheat circuit in spice than to calculate it in a spreadsheet application. A simulation also shows the switching behavior of the half-bridge.

During dimming, the lamp current decreases and subsequently the current through the filaments also decreases. The result is that the filaments become colder and the emission of electrons becomes more difficult. For that reason additional heating of the filaments is required, which the auxiliary windings provide. The way of connecting the auxiliary windings to the lamp is important: depending on the connection the additional current is added or subtracted from the lamp current that also flows through the filaments (see Ref. 2.). This mechanism can be used to adapt the heating current to the specification of the lamp.

## 3.9 Input filtering

The half-bridge, and to a larger extent the charge pump, are drawing a high frequency current from the mains. Filter out the HF current because it causes EMI problems.

Figure 23 shows a basic input filter. The inductor is blocking the high frequent current the charge pump circuit is drawing. The capacitor is providing a low ohmic path for this current.

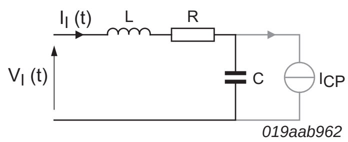



**Fig 23. Basic input filter**

The damping of the HF components is calculated using Equation 16

$$Damping = 20log\left|\frac{I_I(\omega)}{I_{CP}(\omega)}\right| = 20log\frac{1}{(1+\omega^2 LC)^2 + (\omega RC)^2} \tag{16}$$

Assuming that:

- L = 10 mH
- C = 47 nF
- R = 10 Ω

For 50 Hz, the damping is 0 dB, for 50 kHz the damping is 66 dB.

For CFL lamps that are not placed behind a dimmer, this circuit works well. However due to the voltage steps in the phase cut input voltage, there is ringing of the input current. When the input current drops below the hold current during this ringing (or even crosses zero), then the Triac is turned off. After some time, the Triac is triggered again and switches off again. This process repeats until the load current is so large that there is no more zero crossing of the mains current. This phenomenon is called multiple triggering or firing and it is shown in Figure 24

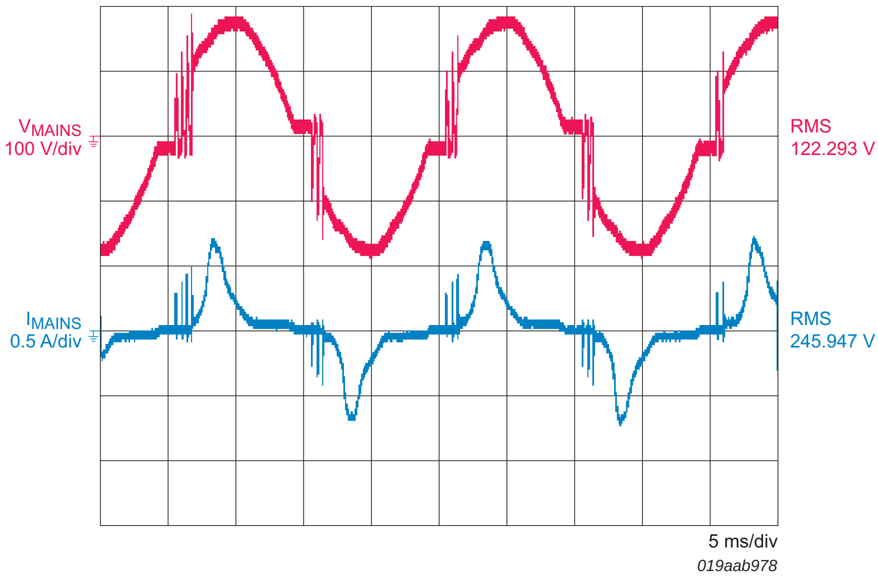



**Fig 24. Mains voltage and mains current with multiple firing of the Triac**

The mains current when a voltage step $V_{step}$ is applied to the system is calculated as shown in Equation 17: and Equation 18

$$i(t) = \frac{V_{step}}{\omega_{res} L} e^{-\frac{R}{2L^2}} \sin(\omega t) + I_{CP} I \tag{17}$$

with

$$\omega_{res} = \sqrt{\left(\frac{1}{LC} - \frac{R^2}{4L^2}\right)} \tag{18}$$

If the charge pump circuit current ($I_{CP}$) rises very quickly after the voltage step and $I_{CP}$ is larger than the negative amplitude of the ringing, there is no zero crossing and hence no multiple firing.

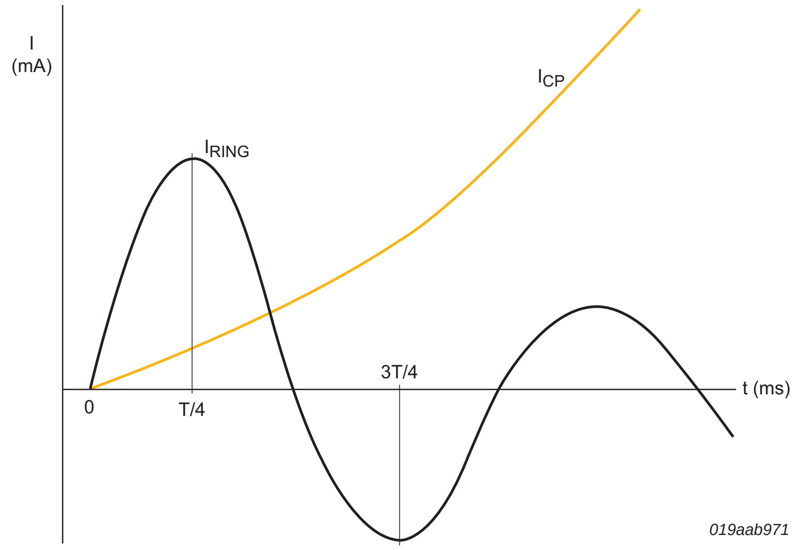



**Fig 25. Input current ringing**

Example:

- $V_{step}$ = 40 V
- L = 10 mH
- C = 47 nF
- R = 10 Ω
- $\omega_{res}$ = 46126
- $f_{res}$ = 7.3 kHz
- T = 136 μs
- 3T/4 = 102 μs

The peak current at 3T/4 is: 40 × 2.16 × 10 – 3 × 0.95 = 82 mA.

In order to prevent ringing, the charge pump must switch on immediately and draw a current larger than 82 mA after 102 m. If the charge pump circuit does not rise fast enough, some other measures can be taken to reduce multiple firing. One solution is to place an RC combination can be placed across the input. In that way, a current is added to $I_I$ (see Figure 26).

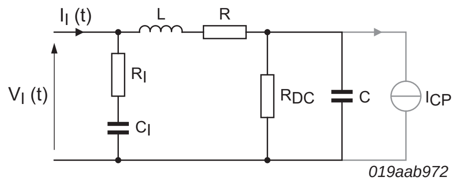



**Fig 26. Input filter with AC load**

The drawback of the circuit in Figure 26 is that the filter capacitor $C_I$ is very large, as it must be a high-voltage type. The resistor is large too because it must handle a power of 1 W. Furthermore, it adds some reactive power slightly decreasing the power factor.

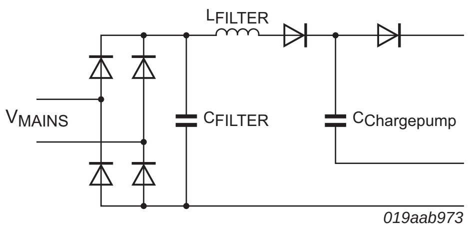



**Fig 27. Input filter placed after rectifier bridge creates the Constant Input Current (CIC) topology**

In Figure 27, resistor $R_{DC}$ is in parallel to the filter capacitor. This resistor can be added to provide a DC path for charging the capacitor or supplying current to electronics inside a dimmer that fires the Triac.

## 4. Circuit diagrams

The next three paragraphs show the circuit diagrams for the dimmable CFL applications for 230 V and 120 V mains voltage. These circuit diagrams were tested with one burner type and with different dimmers. So with a different burner or specific dimmers some components have to be adapted. In most cases, it means modifying the resonant tank and the charge pump capacitor. Section 5 shows a calculation example for the resonant tank. In this example, the lamp voltage is assumed to be constant during dimming. Take the lamp characteristics into account when more accurate results are required.

### 4.1 Circuit diagram for the UBA2027 application

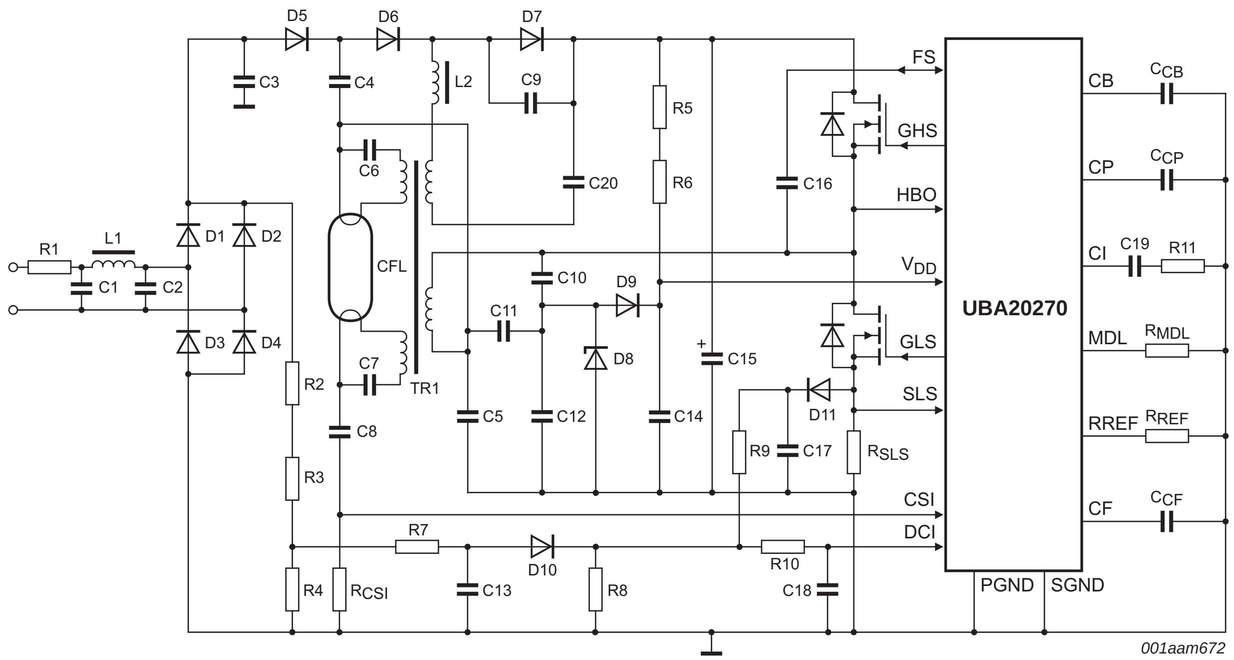



**Fig 28. UBA2027 circuit diagram**

## 4.2 Circuit diagram 230 V input for the UBA2014 application

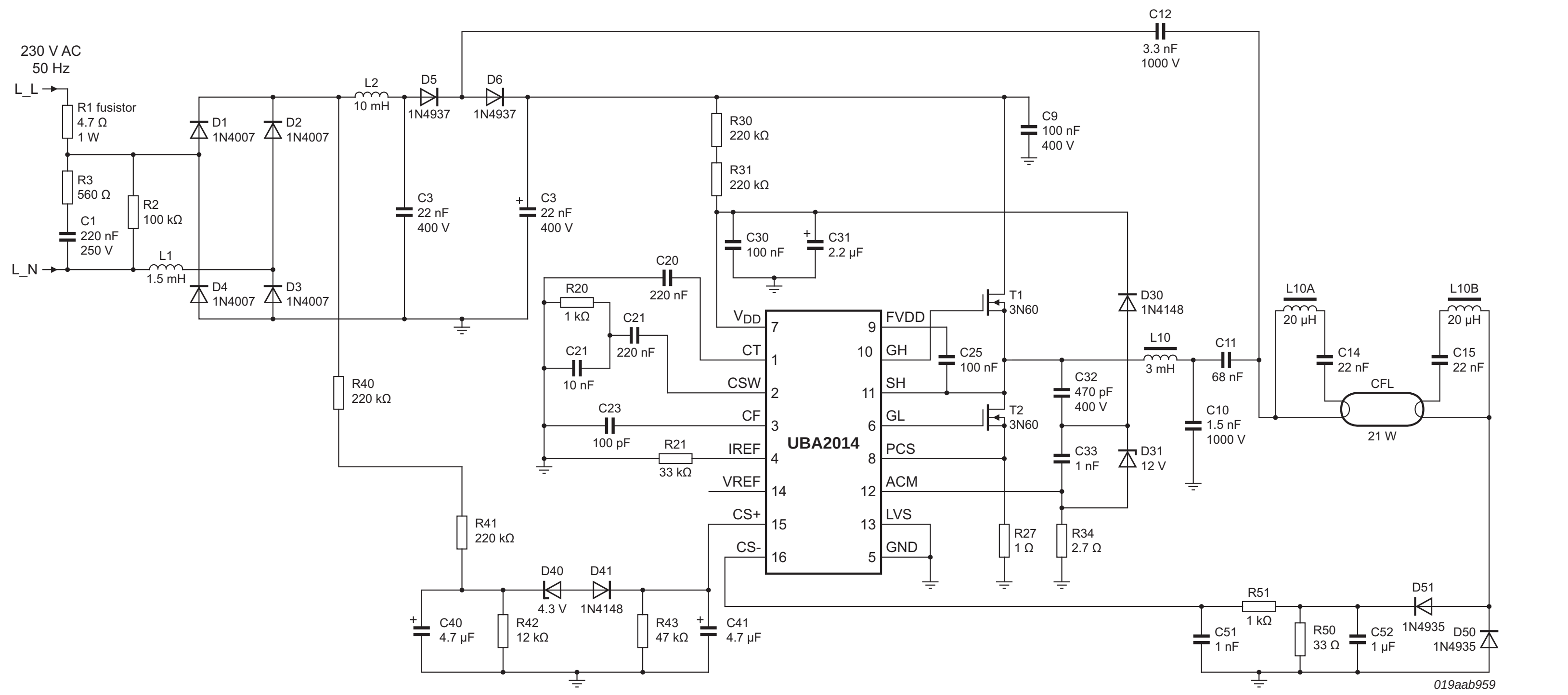



Fig 29. 230 V circuit diagram

## 4.3 Circuit diagram 120 V input for the UBA2014 application

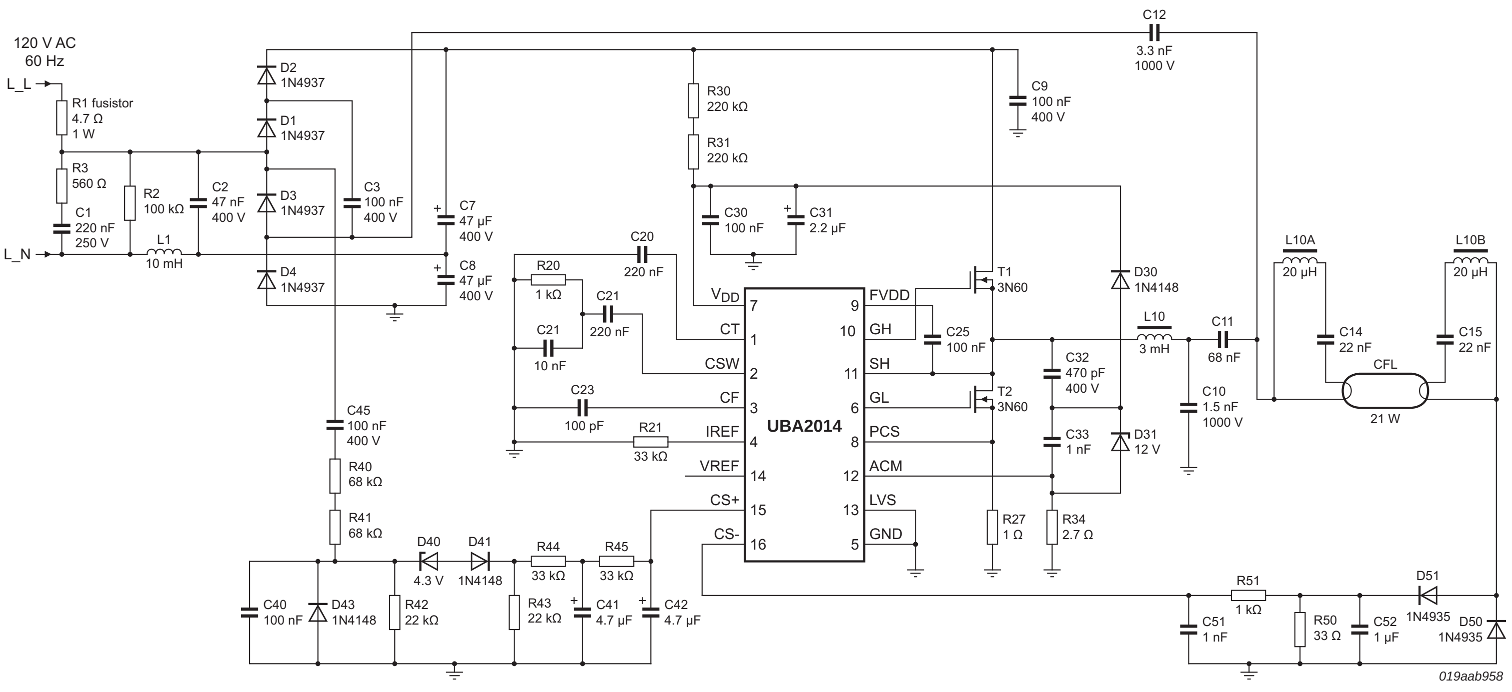



**Fig 30. 120 V circuit diagram**

# 5. Resonant tank calculation example

Typical lamp power versus frequency calculations as used in a mathematical design application are as follows:

**Input data:**

$V_{bus} = 300$, $f_{op} = 45 \times 10^3$, $I_{lamp\_nom} = 140 \times 10^{-3}$, $V_{lamp\_nom} = 130$, $\varphi = 35$

$$V_{1\_RMS} = \frac{1}{\sqrt{2}} \frac{4}{\pi} \frac{V_{bus}}{2} \quad (19)$$

$V_{1\_RMS} = 135.047$, $\phi = \frac{\varphi}{180} \pi$, $\phi = 0.611$, $\omega_{op} = 2\pi \ f_{op}$, $\omega_{op} = 2.827 \times 10^5$

$P_{lamp} = I_{lamp\_nom} \ V_{lamp\_nom}$, $P_{lamp} = 18.2$, $R_{eq} = \frac{V_{lamp\_nom}}{I_{lamp\_nom}}$, $R_{eq} = 928.571$

$$C = \frac{\sqrt{-V_{1\_RMS}^2 + V_{lamp\_nom}^2 + V_{lamp\_nom}^2 \tan\langle\phi\rangle^2}}{V_{1\_RMS} R_{eq} \omega_{op}}, \ C = 2.351 \times 10^{-9}$$

$$L = \frac{\tan(\phi) + \omega_{op} R_{eq} C}{\frac{\omega_{op}}{R_{eq}} + \omega_{op}^3 R_{eq} C^2}, \ L = 3.133 \times 10^{-3}, \qquad f_{res} = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}, \ f_{res} = 58.64 \times 10^3$$

The lamp voltage is assumed to be constant: $V_{la} = 130$, $I_{la} = 0.001, 0.011. 0.3$

$$f(I_{la}) = \frac{1}{2\sqrt{2}\,\pi\, L\, C\, V_{la}} \sqrt{2\, L\, C\, V_{la}^2 - L^2 I_{la}^2 + \sqrt{-4\, L^3\, C\, I_{la}^2\, V_{la}^2 + L^4\, I_{la}^4 + 4\, L^2\, C^2\, V_{la}^2\, V_{l\_RMS}^2}}$$

$$P_{la}(I_{la}) = V_{la}\, I_{la}$$

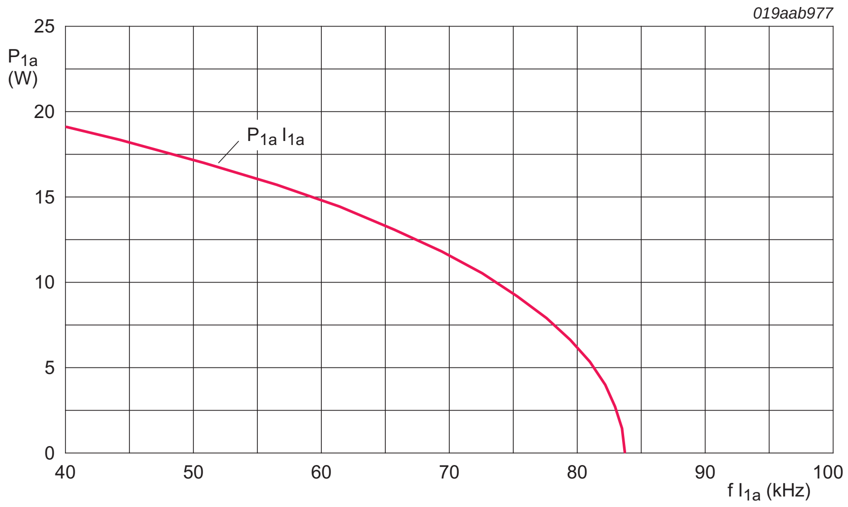



Fig 31. Lamp power versus frequency graph

# 6. Abbreviations

Table 1. Abbreviations

| Acronym | Description |
|---|---|
| CFL | Compact Fluorescent Lamp |
| CMP | Capacitive Mode Protection |
| EMI | ElectroMagnetic Interference |
| MDL | Minimum Dimming Level |
| PFC | Power Factor Correction |
| RMS | Root Mean Square |
| ZVS | Zero Voltage Switching |

# 7. References

[1] Charge Pump Power-Factor-Correction Dimming Electronic Ballast Jinrong Qian, Fred C. Lee, Tokushi Yamauchi. IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL.14, NO. 3, MAY 1999

[2] Standardized data for dimming of fluorescent lamps L.H. Goud, J.W.F. Dorleijn IEEE-IAS Conference 2002

[3] Application note: AN10962

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## 10. Contents





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