Universal motor speed control and light dimmer
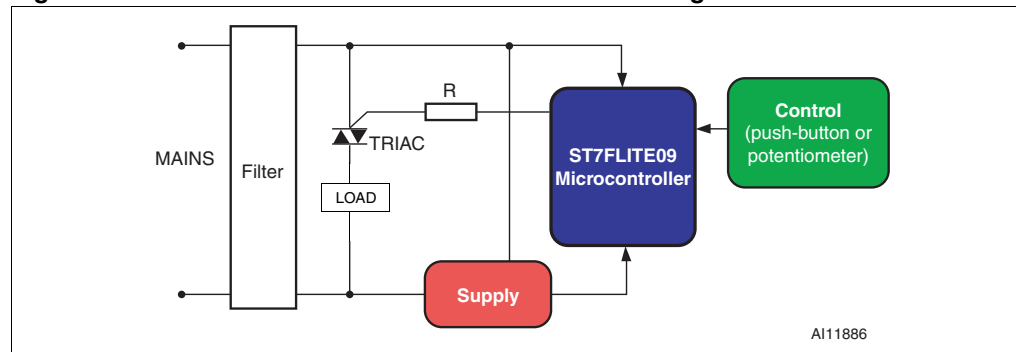with TRIAC and ST7LITE microcontroller

Introduction

This application note describes a traditional design solution for controlling a mono phase motor or any AC load based on phase-angle adjusting with a TRIAC or AC switch and a microcontroller as a driver. This solution is greatly improved with new software and ST components. This document contains information on the STEVAL-ILL004V1 evaluation board, including jumper settings, load connection, and device and software features. The electronic driver with a TRIAC and microcontroller presented in this document is cost effective and easy for designers to implement.

These electronic devices are typically used in home appliances or in industrial applications for various purposes, such as motor regulation in washing machines, vacuum cleaner control, light dimming in lamps, heating in a coffee machines, or motor regulation in ventilators. Analog solutions are being progressively replaced by microcontroller designs even in low-cost applications.

Advantages include fewer external components, easy adaptation through simple software modifications, control components can be designed with either a potentiometer or a pushbutton, easy feedback implementation, and flexibility. An analog IC's functionality is tied to its application and the designer is limited to fixed device functions.

Note: *The STEVAL-ILL004V1 was replaced by the new improved evaluation board STEVAL-ILL004V2 and therefore the STEVAL-ILL004V1 will not be orderable. The main difference between the two evaluation boards is the microcontroller; the STEVAL-ILL004V2 uses the smaller 8-pin ST7ULTRALITE microcontroller while the STEVAL-ILL004V1 uses a 16-pin ST7FLITE09 microcontroller.*

Figure 1.   STEVAL-ILL004V1 evaluation board block diagram

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1   Phase-angle adjustment motor control

Control techniques for mono phase motors or any AC load are based on phase-angle adjustment. This principle is shown in *Figure 2*. The TRIAC is turned ON by the control signal coming from the microcontroller with some delay after the zero crossing, and automatically turned OFF when its current reaches a zero value. This behavior is the same for positive and negative voltage.

There are only a few "turn ON" limitations along the zero crossing, when the current is not high enough (lower than the TRIAC's latching current), so the power to the load cannot be regulated from 0 to 100%. As the switch represents the main power component in these applications, the ACST switch family can improve the parameters of these devices. The ACST switch family embeds a TRIAC structure with a high voltage clamping device to absorb the inductive turn-off energy and withstand line transients such as those described in the IEC61000-4-5 standards. The main benefits of using the ACST switch are to enable equipment to meet IEC61000-4-5, high OFF state reliability with planar technology, it needs no external overvoltage protection, has direct interface with the microcontroller, and reduces the power component count.

Figure 2.   AC load control phase-angle adjustment
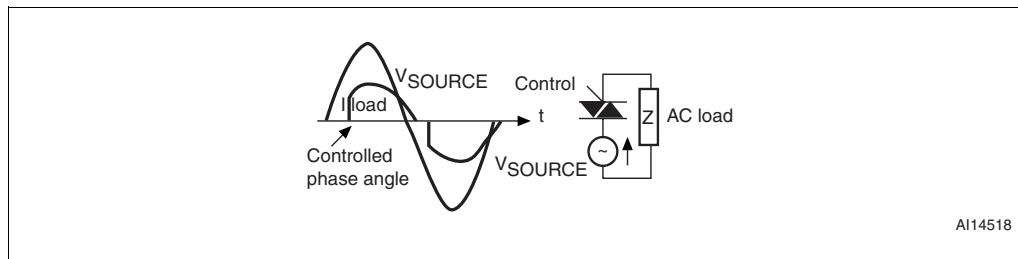
2 Universal motor speed control

The STEVAL-ILL004V1 Evaluation Board was developed to demonstrate ST's solution for driving a universal motor or other types of AC loads. The board is shown in *Figure 3*. On the left side there are two connectors:

● The mains connector for the input voltage supplied to the board
● The connector for the universal motor

Due to the versatility of the board, the load can be controlled by a push-button ("BUTTON") or a potentiometer ("POT."). The way it is controlled needs to be selected by using Switch S2 before the input voltage is connected.

Note: *The push-button should NOT be used to control the motor speed, but only for adjusting the brightness of a bulb when a lamp is connected as the load (the light dimmer). The potentiometer should be used to control motor speed.*

An additional feature that can be enabled on this board is temperature control through the Negative Temperature Coefficient (NTC) component. Although it is not a standard part of the board, the microcontroller has free ADC converters (PINs for the necessary thermistors are available). The maximum power range used on the evaluation board depends on the TRIAC and the size of its heat sink. For high power (higher than 350 W), it is necessary to use the heat sink on the TRIAC because of the power dissipation. The TRIAC heat sink can be as large as it needs to be because there is enough place on the board. For heat sink calculations, see *Section : How to calculate the size of the heat sink*.

The application is independent of the input frequency because of the switch frequency detection, so 50 Hz or 60 Hz can be selected without any problem. The input voltage can be from 110 V_{ac} to 240 V_{ac}.

Note: *The supply current for the microcontroller is obtained from the input voltage.*

The capacitive power supply in this application is designed to ensure that there is enough energy to run it, even with the input voltage of 110 V (IOUT = 6.11 mA) due to the fairly large capacitor being used (C4 = 330 nF). The output power also depends directly on the input voltage. For example, the brightness of a lamp for an input voltage of 110 V is almost half the brightness of a lamp for an input voltage of 230 V.

Figure 3.   STEVAL-ILL004V1 universal motor speed control evaluation board
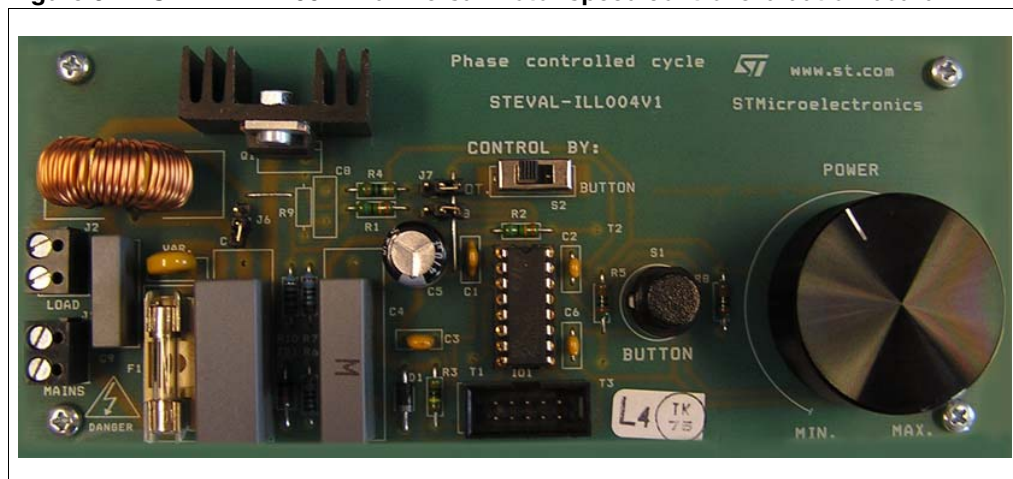
2.1 Block schematic

The 'heart' of this application is the ST7FLITE09 microcontroller which controls the TRIAC (see *Figure 4*). The synchronization required to switch on the TRIAC at the same time for each of the cycles is provided by zero crossing detection (ZCD). The microcontroller detects the zero crossing after each period of the input signal and sets the time to switch on the TRIAC in relation to the value of the potentiometer voltage.

Due to the low power consumption (approximately 5.5 mA), there is a capacitive power supply integrated into the design. Its calculation is described in the *Section 2.3*. The TRIAC produces a noise when it is turned ON or OFF, so the input Electromagnetic Interference (EMI) filter should be connected to the board as well. There is a passive C filter assembled and its value can be designed as required because there is enough place on the board for such components. Different packages for the input filtering capacitor can be used also.

Figure 4. STEVAL-ILL004V1 motor speed control block diagram
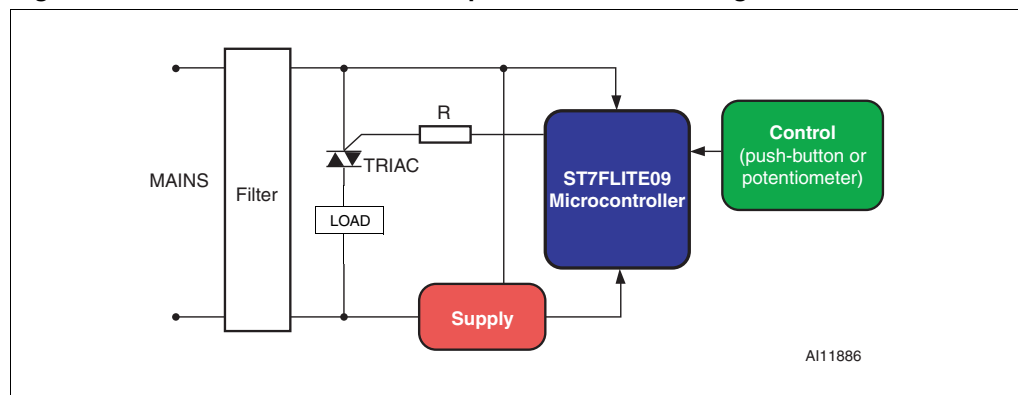
2.2 Application schematic

Figure 5 shows the universal motor speed control application schematic. In this case, components L1, C9, C8, and R9 are not necessary for motor speed control, so they are not used (see *Figure 3*).

2.2.1 EMI filter noise reduction

The versatility of the board allows for the EMI filter (C7, L1, and C9) to be designed as a CLC connection (Π element) to reduce the noise coming from the board to the mains. For motor control applications, it is enough to use only an input capacitor (for example: C7 = 470 nF) to guarantee the requested standards (see *Section 4* for details). If an input inductor is not required, a jumper is provided to disconnect it on the board.

2.2.2 TRIACs with integrated snubber

ST has a family of snubberless TRIACs, where the snubber is integrated, making it unnecessary to use external components for overvoltage protection. If the standard TRIAC is used, the snubber circuit (C8 and R9) should be assembled to prevent the TRIAC from spurious turn-on. The new ACST switch family embeds a TRIAC structure with a high voltage clamping device to absorb the inductive turn-off energy (motor) and withstand line transients such as those described in the IEC61000-4-5 standards. Recommended ST

TRIACs and AC switches for the light dimmer and motor speed control for mains voltage 230 V_{ac} are shown in the *Table 1* below.

Table 1. **Recommended ST TRIACs and AC switches**

Motor speed control applications			
Application requirements	**Power**	**Device**	**Feature**
- High (dI/dt) - Limited cooling conditions - High ITSM (non repetitive surge peak on-state current) due to inrush current	< 700 W	ACST8-8C	
	< 1200 W	BTB12-600BW	
		T1235H-600T	High Temperature (T_{JMAX}=150 °C)
	< 1600 W	BTB16-600BW	
	> 1600 W	T1635H-600T	High Temperature (T_{JMAX}=150 °C)
Light dimmer applications			
Application requirements	Power	Device	**Feature**
- Low IH (holding current=> sensitive gate TRIAC) to avoid risk of flickering due to LC filter oscillations - High ITSM (non repetitive surge peak on-state current) for cold filament effect and flashhover effect during bulb failure	60 to 600 W	BTA08-600SW	Insulated AC Switch
		BTA12-600SW	Insulated AC Switch
		BTB08-600SW	Non-Insulated
		BTB12-600SW	Non-Insulated

2.2.3 Power supply circuit

The power supply circuit (R6, R7, R10, C4, ZD1, D1, and C5) supplies the microcontroller. If both neutral and phase lines are available on the board, the maximum output current with the input voltage of 230 V is 11.08 mA (see the equations in section *Section 2.3*). The total power consumption of the microcontroller is about 5.5 mA (measured value), so 11.08 mA is really enough to supply it. It is also important to reduce consumption of the microcontroller, when the light dimmer is switched off. In this case, the microcontroller enters Halt mode and an ultra low power consumption is achievable. The consumption of the microcontroller on the evaluation board is 350 μA in halt mode. For this type of load (with the universal motor speed control elements connected to the board), it is possible to use the C4 lower-supply capacitor (220 nF).

2.2.4 Zero crossing detector

The ZCD is made from components R1, R2, and C2, and the signal is connected to the PA0 port of the microcontroller. The I_{CC} connector is provided on the board to program the microcontroller, making it easier to configure the switch feature (either push-button or potentiometer).

2.2.5 Driving the TRIAC

Several ports of the microcontroller (PA0, PA1, PA2, PA3, PA4 and PA5 are high sink) have high-current capability of up to 20 mA, which in some applications is enough current to drive the TRIAC directly with just one port. If it is not enough power to switch on the TRIAC, there

are two jumpers available to connect three of these ports in parallel configuration (see *Figure 5*). In this case, the maximum current capability is 60 mA, which should be enough power for any type of TRIAC.

Figure 5.   Application schematic
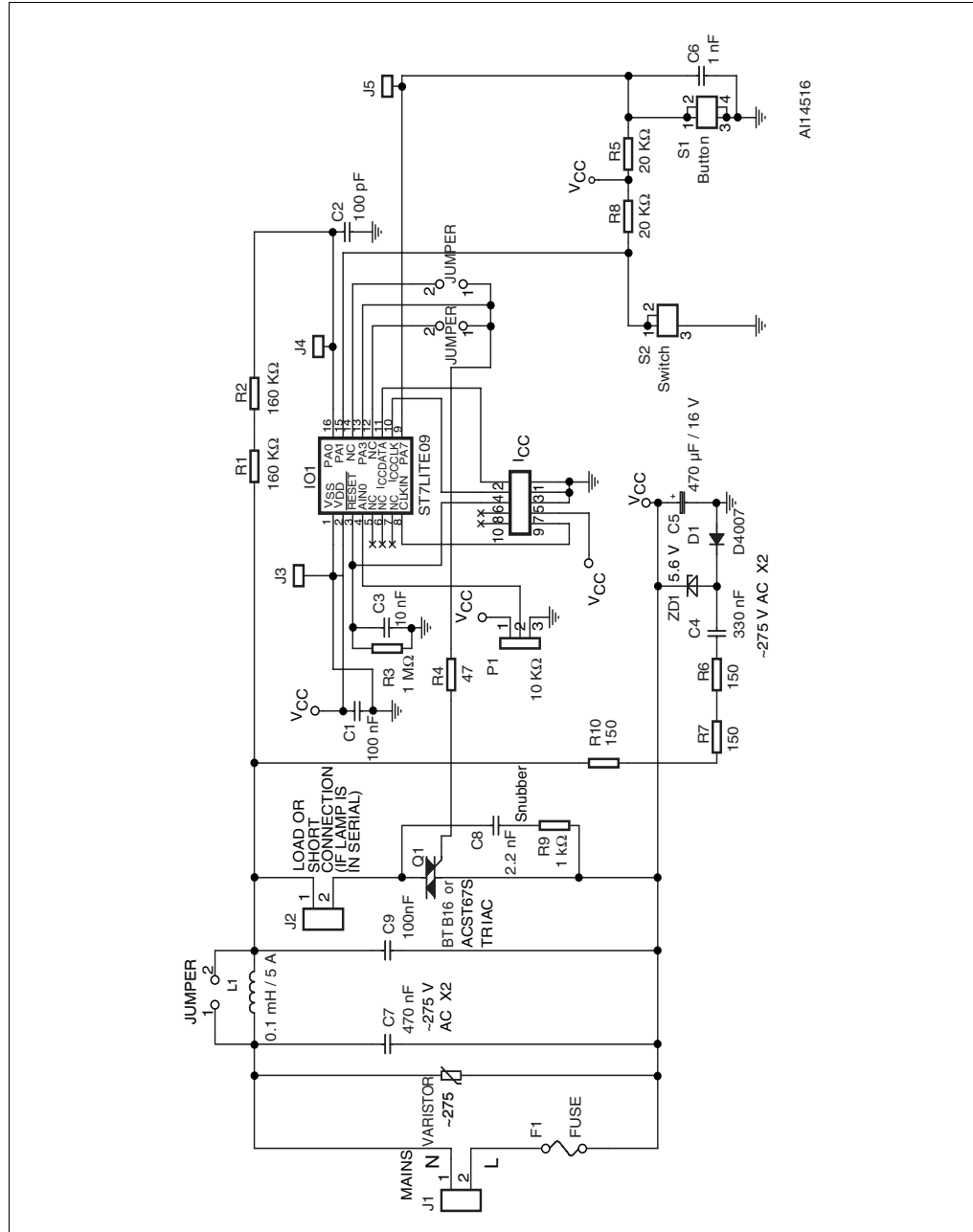
2.3 STEVAL-ILL004V1 application design procedure

Several considerations must be taken in account during the design procedure, including:

- The power supply circuit
- TRIAC power dissipation
- ZCD resistor values
- The size of the current-limiting resistor (R4)

2.3.1 Capacitive power supply circuit

The capacitive power supply is shown in *Figure 6*. The voltage at the output will remain constant as long as the output current I_{OUT} is less than or equal (in an ideal case) to the input current I_{IN}. I_{IN} is limited by R1 and the reactance of C1. The R1 resistor limits the inrush current, which must be lower than the maximum current through the capacitor C1.

The input current I_{IN} can be expressed by the following equation:

Equation 1

$$I_{IN} \geq I_{OUT} = \frac{V_{HPINRMS}}{X_{C1} + R_1} = \frac{\dfrac{V_{RMS} - V_{ZD}}{2}}{X_{C1} + R_1} = \frac{V_{RMS} - V_{ZD}}{2 \bullet \left(\dfrac{1}{2\pi f C_1} + R_1\right)}$$

where,

- $V_{HPINRMS}$ = the half period of the Root Mean Squared (RMS) Input Voltage, (because the output capacitor C2 is charged only in one half of the period)
- V_{RMS} = the RMS voltage of an AC sine wave
- V_{ZD} = the voltage drop across the Zener diode
- X_{C1}: the reactance of the capacitor C1.

Figure 6. Capacitive power supply circuit diagram
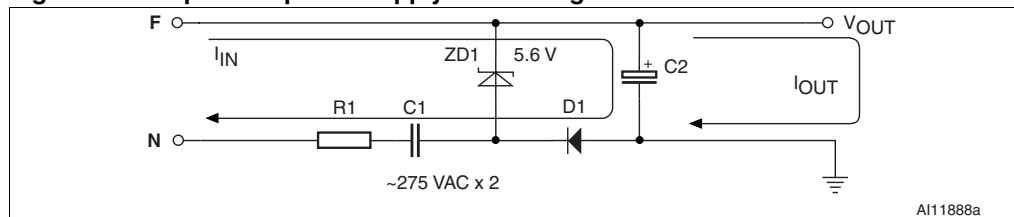
When the main voltage for the components used in this application is 230 V_{ac} / 50 Hz, the maximum output current is expressed as:

Equation 2

$$I_{OUT} = \frac{230 - 5.6}{2 \bullet \left(\dfrac{1}{2\pi 50 \bullet 330 \bullet 10^{-9}} + 450\right)} = 11.11 \text{ mA}$$

Note: *The real maximum current capability measured on the board is I_{OUT} = 9.5 mA. This real value is a little bit lower than the value coming from the equation, so the capacitive supply design has to be calculated with some reserve (approximately 20%).*

When the main voltage for the components used in this application is 110 V_{ac} / 60 Hz, the maximum output current is expressed as:

Equation 3

$$I_{OUT} = \frac{110 - 5.6}{2 \bullet \left(\dfrac{1}{2\pi60 \bullet 330 \bullet 10^{-9}} + 450 \right)} = 6.14\text{mA}$$

Note: *The real maximum current capability measured on the board is I_{OUT} = 5.6 mA. This real value is a little bit lower than the value coming from the equation, so the capacitive supply design has to be calculated with some reserve (approximately 20%).*

The output electrolytic capacitor C2 is charged through diode D2 from the voltage on the Zener diode. The output voltage is expressed as:

Equation 4

$$V_{OUT} = V_{ZD} - V_{D2}$$

Resistor R1 is used to reduce the inrush current and its power loss is expressed as:

Equation 5

$$P_{R1} = R_1 \bullet I^2 = R1 \bullet \left(\frac{V_{RMS}}{\left(\dfrac{1}{2\pi fC_1} + R_1 \right)} \right)^2 = 450 \bullet \left(\frac{230}{\dfrac{1}{2\pi50 \bullet 330 \bullet 10^{-9}} + 450} \right)^2 = 0.23 \text{ W}$$

Note: *Three thru-hole resistors of 150 Ω (R6, R7, and R10) are designed in this application to ensure their low temperature.*

2.3.2   TRIAC power dissipation

Calculating the maximum output power (maximum load) is one of the most important tasks in this design, and the power capability depends mainly on the TRIAC being used. The current capability of this TRIAC limits the maximum output power. The design is versatile, so designers are able to choose the best TRIAC that produces the maximum output power for their applications.

The BTB16-600CW is a 16 A TRIAC with a heat sink built into this evaluation board that controls the power-up to 1 kW. For power requirements less than 1 kW (e.g., light dimmers), the ACST6-7S (ST's 6A TRIAC) or similar can be used. Both TRIACs are snubberless, so they do not need any other external snubber circuitry as protection. Recommended TRIACs for motor speed control and light dimmer are in *Section 2.2.2*.

How to calculate the size of the heat sink

The current flowing through the TRIAC increases its temperature. If the current is too high (i.e., higher than 1.5 A for ACST6-7S), it is necessary to use a heat sink. A typical heat sink calculation is:

Equation 6

$$I = \frac{P}{U_{IN}} = \frac{1000}{230} = 4.35 \text{ A}$$

where,

P = the output power in the application (1 kW, for the ACST6-7S TRIAC), so the RMS current flow (I) through the TRIAC for 1 kW is 4.35 A.

Maximum power dissipation

The maximum power dissipation on the TRIAC versus the RMS ON state current (full cycle) is described in the ACST6-7S datasheet. *Figure 7* shows that the power dissipation on the TRIAC for 4.35 A of current is approximately 4.8 W.

Figure 7. Maximum power dissipation vs. RMS ON state current (full cycle)
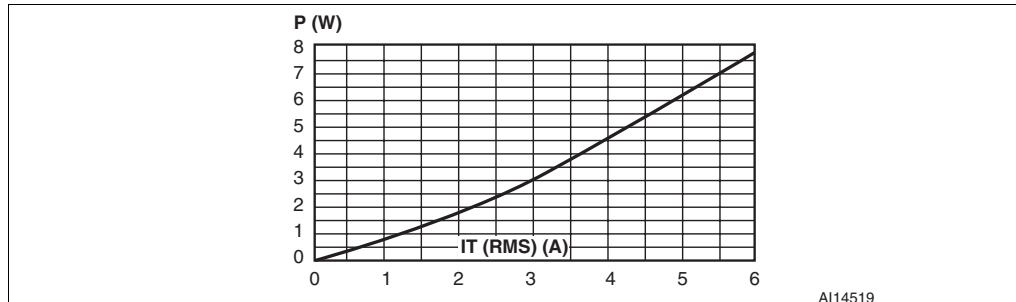
This power is lost in the TRIAC. The total power dissipation, when the heat sink is used, is expressed as follows:

Equation 7

$$P = \frac{T_J - T_A}{R_{thJC} + R_{thCH} + R_{thHA}}$$

where,

– T_J = maximum junction temperature [°C]
– T_A = ambient temperature [°C]
– R_{thJC} = junction-to-case thermal resistance [°C / W]
– R_{thCH} = case-to-heat sink thermal resistance [°C / W] (usually between 0.35 and 0.8 for the insulating washer)
– R_{thHA} = heat sink-to-ambient thermal resistance [°C / W]

After the heat sink-to-ambient thermal resistance is calculated from the equation above, the correct heat sink can be chosen from the value expressed as follows:

Equation 8

$$R_{thHA} \leq \frac{T_J - T_A - P \bullet R_{thJC} - P \bullet R_{thCH}}{P} = \frac{125 - 40 - 4.8 \bullet 2.5 - 4.8 \bullet 0.5}{4,8} = 14.7°\,C /\ W$$

For example,

the thermal resistance of the heat sink for the output power of 3 kW using a BTB16-600CW TRIAC is expressed as follows:

Equation 9

$$R_{thHA} \leq \frac{125 - 40 - 14 \bullet 1.2 - 14 \bullet 0.5}{14} = 4.37°\,C /\ W$$

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Note: *This calculation is done for an ambient temperature of 40 °C and the TRIAC that is on the evaluation board. The size of the heat sink can be dramatically decreased if the TRIAC is placed in a vacuum cleaner or any similar device which can cool it.*

2.3.3 ZCD resistor calculations

In order to synchronize the opening of the TRIAC with the input sinusoidal voltage waveform in each period, the microcontroller must make the zero crossing detection. Resistors R1 and R2, capacitor C2, and two internal clamping diodes (inside the microcontroller) provide this means of detection (see *Figure 8*). The power dissipation in the resistors with an input voltage of 230 V_{ac} can be calculated as follows:

Equation 10

$$P_{R1, \ R2} = \frac{V_{INRMS}^{2}}{R1 + R2} = \frac{230^{2}}{320000} = 0.1653 \text{ W}$$

The maximum voltage along the resistors is 325 V (RMS voltage value is 230 V_{ac}) therefore, it is necessary to connect at least two resistors in series in order to avoid overvoltage. For example, the maximum voltage for the 1206 Surface Mount Device (SMD) resistor is 200 V.

The actual ZCD circuit waveforms are shown in *Figure 9*:

The values were measured in the light dimmer application with a 60 W bulb (see *Section 3*).

Figure 8.   **ZCD circuit**
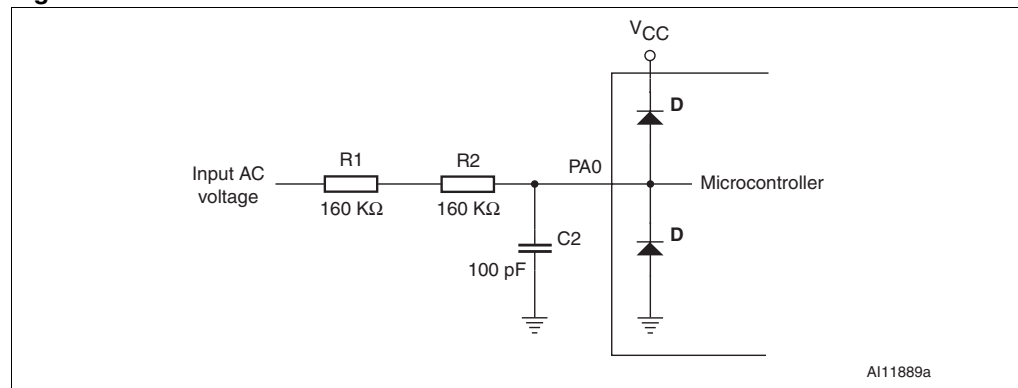
Figure 9.   ZCD circuit actual waveforms
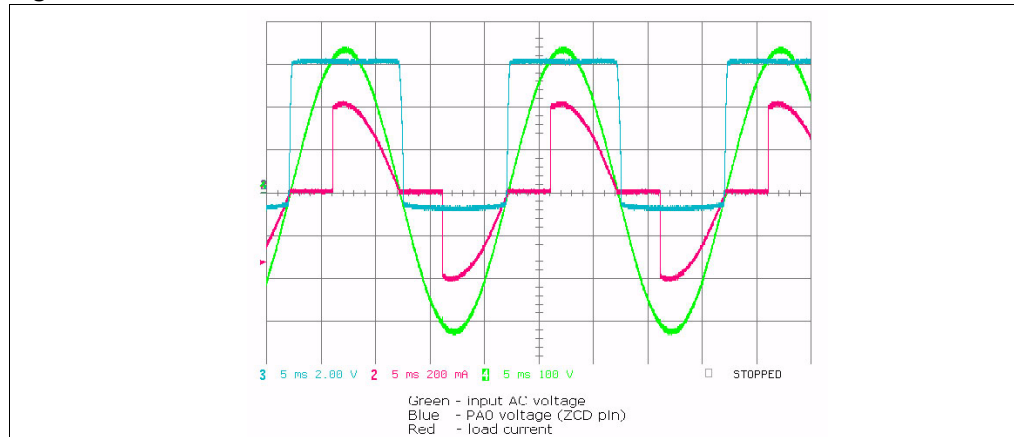
2.3.4   Gate-limiting resistor calculation

Connecting the resistor between the microcontroller and the gate of the TRIAC is recommended. This will limit the maximum driving current coming from the microcontroller. The following TRIAC parameters (from the datasheet) must be used to determine the resistor's value:

● TRIAC gate-triggering current (i.e., the BTB16-600CW is 35 mA and the ACST6-7S is 10 mA)

● The maximum I/O port driving current (the ST7FLITE09 is capable of high sink outputs, the maximum being 50 mA of current, but the recommended value is 20 mA).

The resistor's voltage drop is about 3 V because the rest of the supply voltage (V_{CC}) is in the TRIAC and microcontroller. To ensure that the TRIAC's gate opens under any circumstances, the maximum current going through the resistor should be at least the same or higher than the gate-triggering current. For example, a BTB16-600CW TRIAC with a maximum current of 40 mA would require the following resistor value:

Equation 11

$$R = \frac{V_{MAX}}{I_{GT}} = \frac{3}{0.04} = 75\Omega$$

Note: *It is better to connect two I/O pins in parallel to drive the BTB16-600CW and keep the recommended current capability from the high sink outputs of the microcontroller (20 mA).*

BTB16 TRIAC is assembled on the evaluation board with a gate-limiting resistor of 47 Ω which allows to fully open the TRIAC.

If an ACST6-7S TRIAC is used in the design, only one I/O pin from the microcontroller and a gate-limiting resistor of 180 Ω are required to guarantee the TRIAC's opening under any circumstances.

Warning: **The MCU is directly linked to the mains voltage supply. No insulation is ensured between the accessible parts and the high voltage. The STEVAL-ILL004V1 evaluation board must be used with care and only by persons qualified for working with electricity at mains voltage levels. Certain precautions have to be taken during emulation to avoid damaging development tools.**

3   Light dimmer design and load configurations

Figure 10 shows the STEVAL-ILL004V1 evaluation board that is configured for the light dimmer application. The basic design is the same as that of the motor speed control application (see *Section 2*). That is, all of the tasks and descriptions apply to the light dimmer application as well and include:

● *Block schematic*

● *Application schematic*

● *Capacitive power supply circuit*

● *TRIAC power dissipation*

● *ZCD resistor calculations*

● *Gate-limiting resistor calculation*

Otherwise, the only difference between the applications is the type of filter used in the design, which is a Capacitor-Inductor-Capacitor (CLC) filter. Capacitors C7 and C9 are both 100 nF, and L1 is 0.1 mH (see *Figure 5*).

A button is included in the design to enable the user to control the light as it is normally controlled in dimmer applications, including decreasing or increasing the light's intensity (brightness). If the button is pressed quickly (between 0 and 40 ms), nothing happens. If the time the button is pressed is between 40 ms and 240 ms, the device is turned ON or OFF.

When the lamp is turned OFF, the intensity level is stored in the microcontroller's memory. If the time the button is pressed is longer than 240 ms, the device is turned ON and the light intensity automatically increases until it reaches the maximum limit, and once the maximum intensity is reached, it automatically decreases (and vice-versa).

Figure 10. STEVAL-ILL004V1 light dimmer evaluation board

3.1 Phase and neutral lines unavailable

In many lighting applications, both phase and neutral lines are not available. For example, in a light switch on the wall, usually only the phase line is connected. A similar evaluation board application design is shown in *Figure 11*, where the lamp is in serial with the board and the energy supply for the microcontroller comes from the TRIAC voltage (when the TRIAC is turned OFF).

If the TRIAC is turned ON for a long time during half of the signal period, there is not enough time (voltage) to save the energy and the device will not work. Because of this limitation, it is not possible to switch the TRIAC ON for 100% of the time. With the power supply as it is applied in this design, the maximum opening time for the TRIAC is approximately 80% (see *Figure 12*). This measurement was done with 500 W halogen lamp connected in serial with the evaluation board.

Note: *If the load (lamp) is in serial with the board, the input filter must NOT be assembled (especially the input capacitors). This may produce a large time rate of change of the current (dI/dt) on the TRIAC, which can be damaged if the device is turned ON.*

Figure 11. Light dimmer-unavailable phase and neutral lines
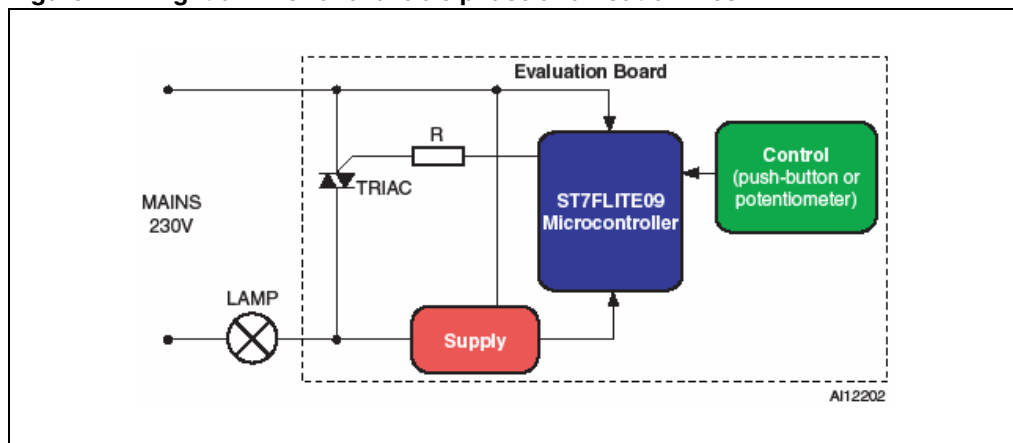
Figure 12. Lamp-in-serial TRIAC switch ON maximum time
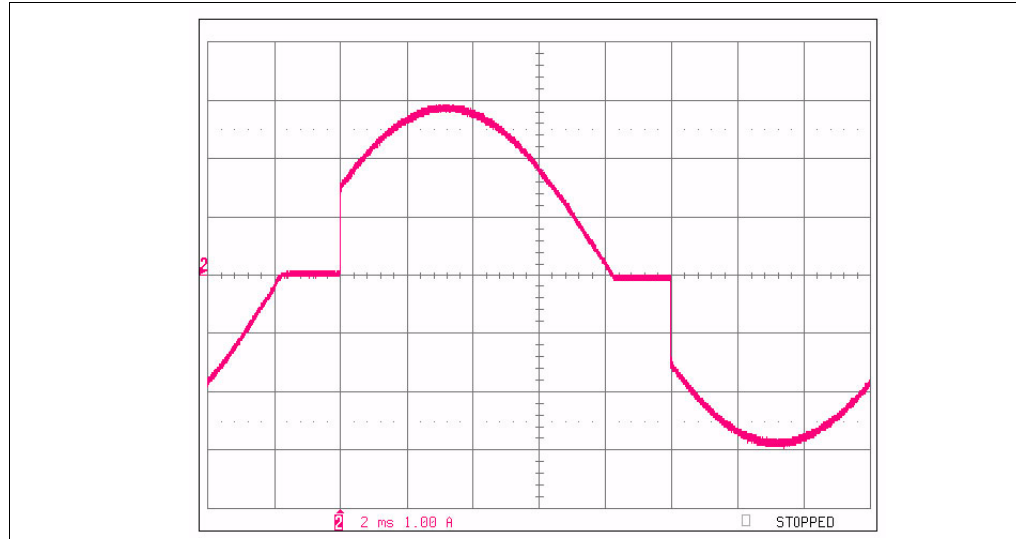
3.2 Phase and neutral lines available

In *Figure 13*, the lamp is directly connected to the evaluation board. The capacitive power supply is able to provide enough energy for the microcontroller because the phase and neutral are available, which provides the TRIAC with an unlimited amount of time to be open. Since there is very little difference between the light intensity of a switch designed with 95% TRIAC opening time and that of 100%, designing the switch to 95% (if needed) is sufficient.

Due to the versatility of the evaluation board (e.g., motor speed control, lamp-on-board or lamp-in-series), the switch is designed to limit the TRIAC opening time to 80%. This guarantees functionality for a lamp-in-series with the evaluation board. However, if both phase and neutral lines are available for the application, this limit may be changed.

Figure 13. Light dimmer-available phase and neutral lines
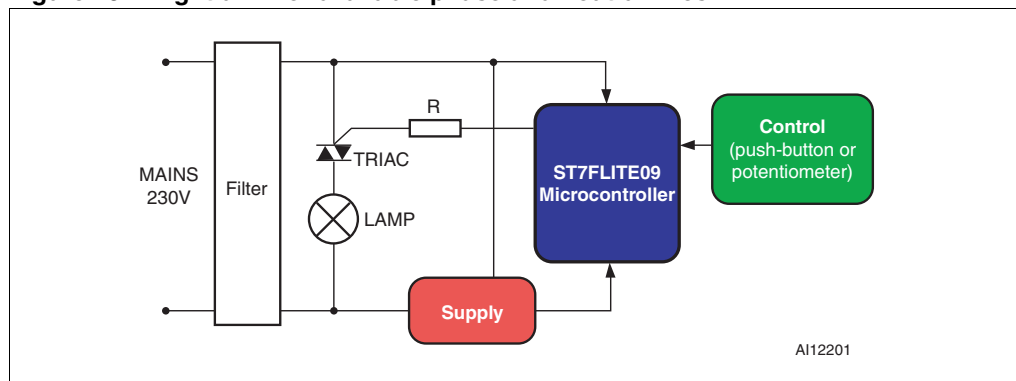
4 Electromagnetic compatibility (EMC) tests

European standards impose restrictions on EMC to reduce electrical pollution of the environment. The proliferation of non-linear loads and the consequential increase in harmonics pollution in power distribution lines have induced various technical committees to establish maximum limits on the harmonic content produced by all industrial and domestic devices. Manufacturers of these devices are required to conform to this new standard and develop products which function with new operational characteristics.

For the purposes of this application note, EMC standard is tested for the light dimmer (EN55015), and two standards for the motor speed control (EN55014-1 and EN61000-3-2 class A).

- EN55015 describes the limits and methods of measurement of radio disturbance characteristics for electrical lighting and similar equipment.
- EN55014-1 describes EMC requirements for household appliances, electric tools, and similar devices (part 1, emission).
- EN61000-3-2 describes the limits for harmonic current emissions (equipment input current up to and including 16 A per phase), and includes four categories (Class A, B, C, and D) divided by the equipment used (see *Table 2*).

All of the standards described above were tested on the evaluation board.

Note: 1 For any other design of these applications (light dimmer or motor control), the results will not be the same and the tests must therefore be repeated.

2 Only a certification laboratory can provide and approve the standards for the products to be sold on the market.

Table 2.   The classification of EN61000-3-2

Class	Version of EN61000-3-2	Amendment prA14
Class A	Balanced three-phase equipment and all other equipment, except that stated in either Class B or Class C.	– Balanced three-phase equipment – Household appliances excluding equipment identified as Class D – Tools excluding portable tools – Dimmers for incandescent lamps
Class B	Portable tools	Portable tools
Class C	Lighting equipment, including dimming devices	Lighting equipment
Class D	Equipment having an input current with a "special wave shape" and an active input power ≤ 600 W	Equipment having a specified input power ≤ 600W, of the following types: – Personal computers and personal computer monitors – Television receivers and video cassette recorders – Multimedia devices which are not professional equipment – Printers which are not professional equipment – Fax machines which are not professional equipment
Equipment not specified in one of the above classes shall be considered as class A equipment.		

4.1   EN55015 for the light dimmer application

A CLC input filter is used to guarantee this standard. The filtering capacitors C7 and C9 each have the value of 100 nF (~275 V_{ac} x2), and the inductor L1 has the value of 0.1 mH (see *Figure 5*).

The load is 100 W and it consists of two lamps (40 and 60 W). The load is connected on the board, which means the phase and the neutral lines are available for the power supply circuit (see *Section 3.2*). Since the output power can be regulated by the switching time of the TRIAC, there are many states available for testing, but only the worst case (highest noise) measurement is provided. This occurs when the TRIAC is turned on in the maximum voltage of the sinusoidal waveform. Two measurements are required by this standard:

● Quasi-peak value (*Figure 14*)
● The average value (*Figure 15*)

Both of the actual waveforms are under the requested limits, proving that this type of EMI filter is suitable for the light dimmer application.

Figure 14.   Light dimmer quasi-peak measurement
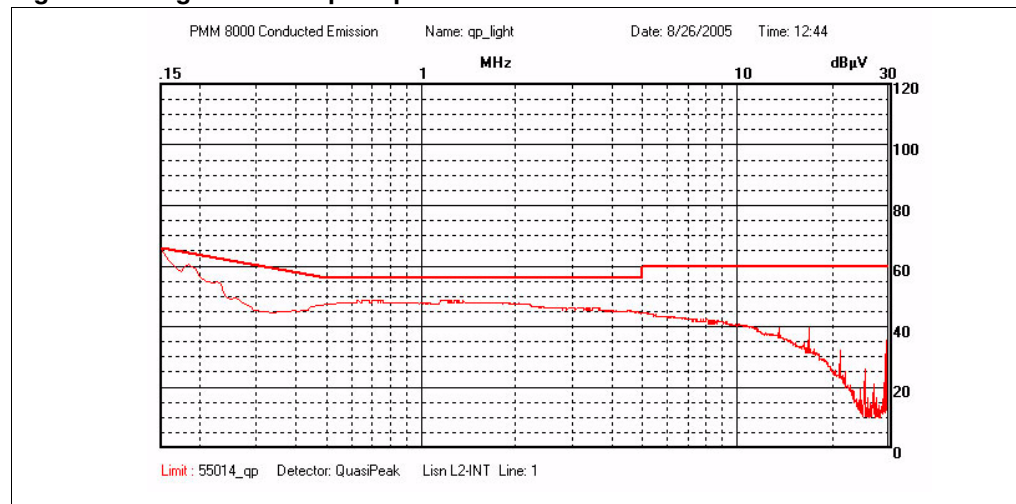
Figure 15. Light dimmer average value measurement
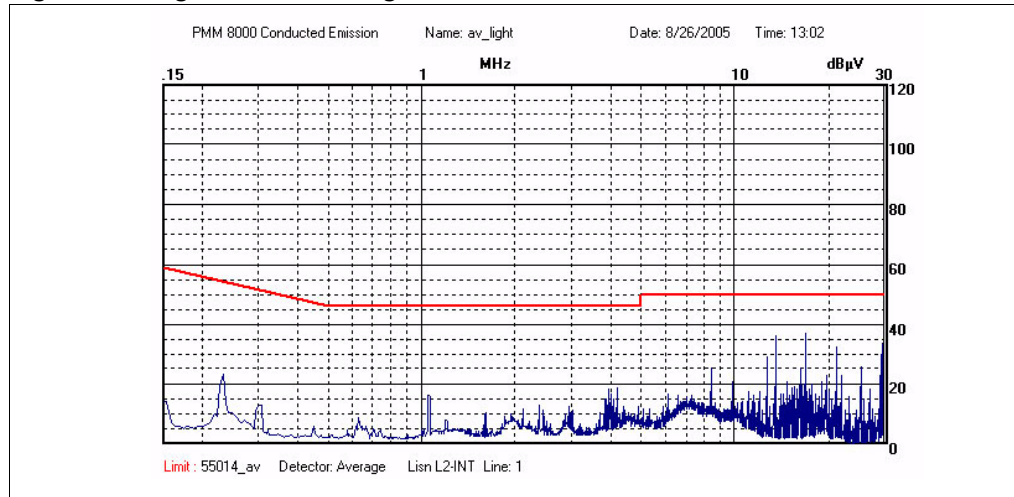
4.2   EN61000-3-2 class A for light dimmer

Phase-controlled dimmers up to 1 kW do not need to be tested for harmonic current emissions, because harmonic current limits are not specified in this standard for independent dimmers for incandescent lamps with a rated power less than or equal to 1 kW. The STEVAL-ILL004V1 evaluation board with with heatsink is designed to deliver output power up to 1 kW and therefore it is not necessary to test it.

4.3   EN55014 for motor speed control

Only one input capacitor (C7 = 470 nF) connected in parallel is required to obtain waveform results below their limits, so this standard can be guaranteed just with this type of filter. When an AC motor is used as a load, the serial inductor is not needed in the application.

For the testing, a load of 1600 W from a vacuum cleaner motor has been used. The motor was connected to the board so the phase and neutral lines were available for the power supply circuit. Since the output power can be regulated by the switching time of the TRIAC, there are many states available for testing, but only the worst case (highest noise) measurement is provided. This happens when the TRIAC is turned on in the maximum voltage of the sinusoidal waveform. Two measurements are required in this standard:

1. Quasi-peak value (*Figure 16*)
2. An average value (*Figure 17*)

Both of the actual waveforms are under the requested limits, proving that this type of EMI filter is suitable for the AC motor application.

Figure 16.   Motor speed control quasi-peak measurement
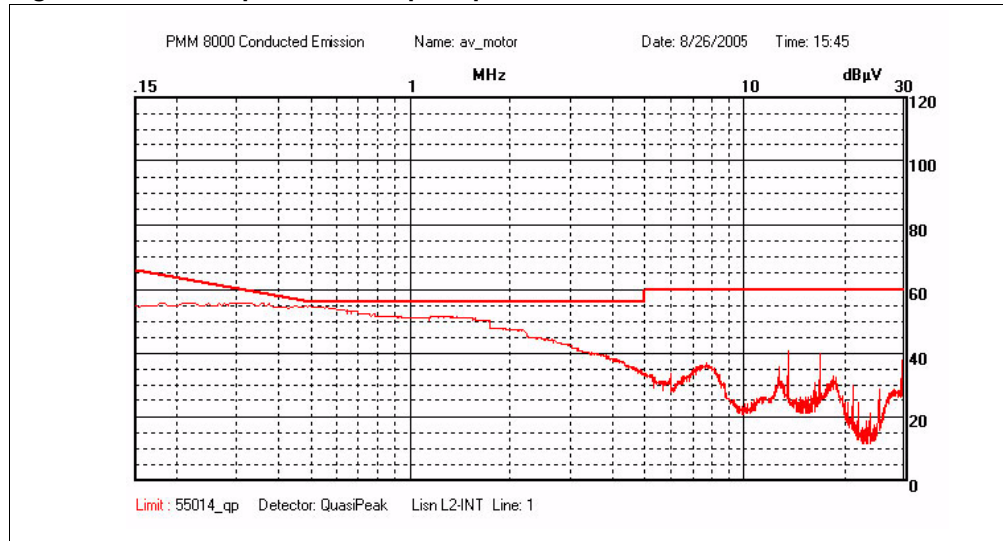
Figure 17.   Motor speed control average value measurement
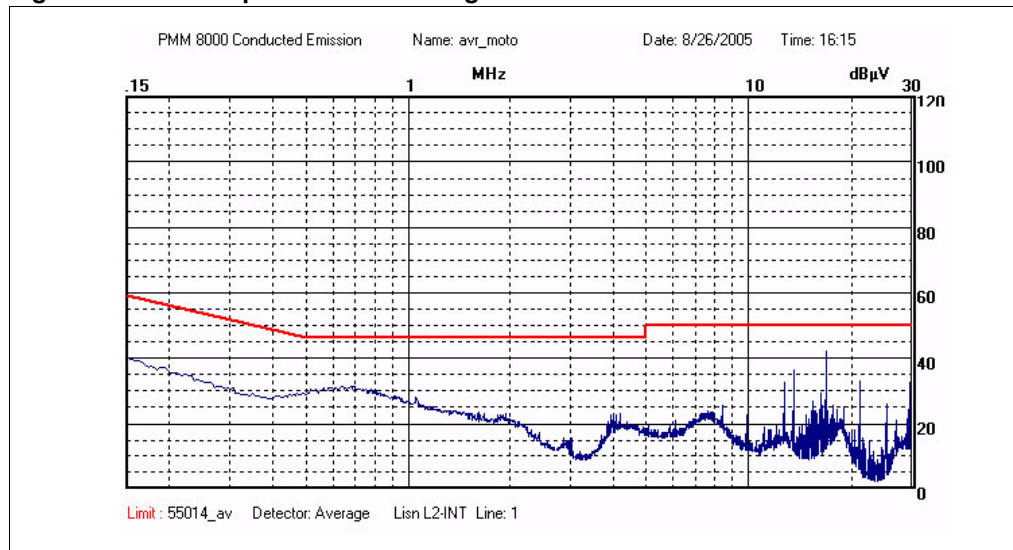
4.4   EN61000-3-2 class A for motor speed control

Only one input filter (capacitor C7 = 470 nF) is used to guarantee this standard since the 1900 W AC motor load is connected to the board.

3 measurements (cases) must be provided:

1.   Minimum power (*Figure 18*)
2.   Opening the TRIAC at 90° (*Figure 19*)
3.   Maximum power (*Figure 20*)

The red columns are the limits and blue columns are measured results.

It seems there may be issues with guaranteeing this standard because when the TRIAC is opened at 90°, the results are above their limits (the third and fifth harmonics failed, see *Figure 19*). However, the standard indicates that the arithmetic average of the individual harmonic should be compared with the applicable limits. Taken exactly from the standard description in the EN61000-3-2 standard,

> "The arithmetic average of the individual harmonic currents observed during the three operating modes is computed for each harmonic order. This arithmetic average is compared against the applicable limits".

The arithmetic average for the three cases (minimum, 90°, and maximum) for third harmonic is 2.13 A (the average of 1.2 A, 3.4 A, and 1.8 A, respectively) and for the fifth harmonic is 0.7 A (the average of 0.7 A, 1.2 A, and 0.2 A, respectively). Since the limits for the third harmonic is 2.3 A and the fifth harmonic is 1.15 A (see *Figure 18*), the average values are under these limitations, proving that this type of EMI filter (with only the input capacitor C7 = 470 nF) is suitable for AC motor speed control.

Figure 18. EN61000-3-2 results (minimum power)
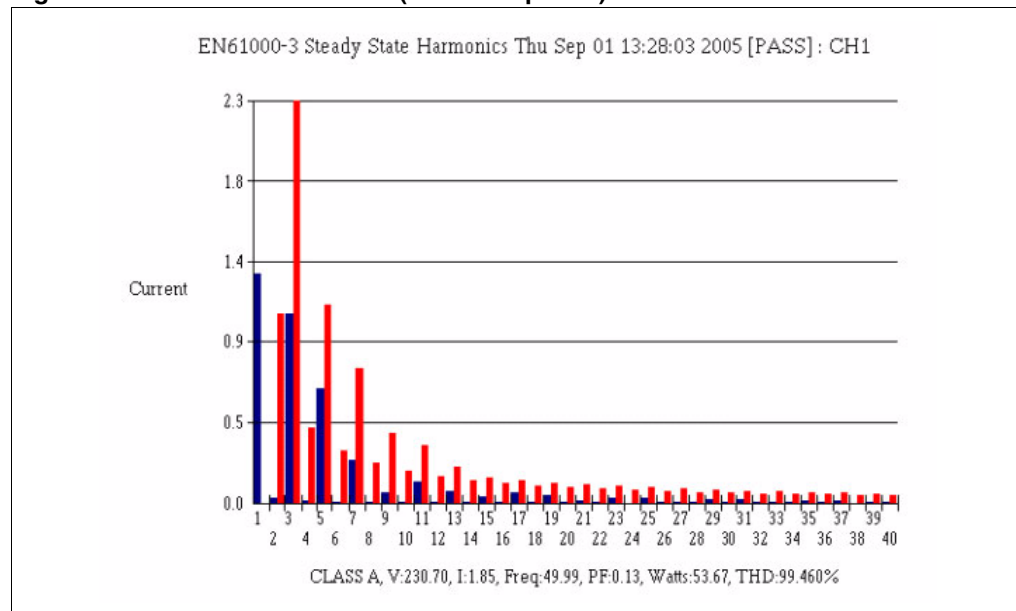
Figure 19. EN61000-3-2 results (TRIAC at 90°)
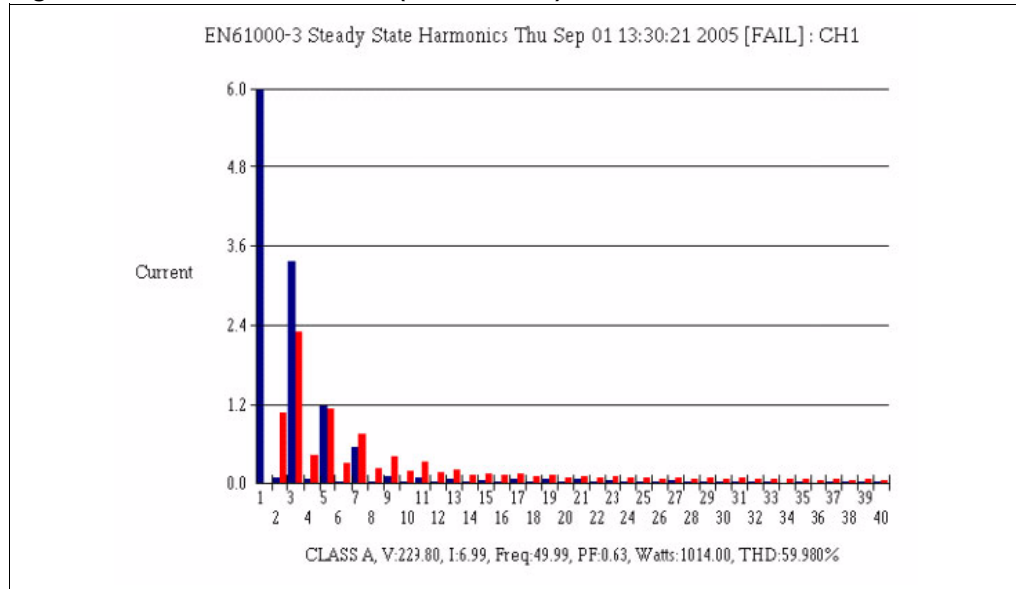
Figure 20. EN61000-3-2 results (maximum power)
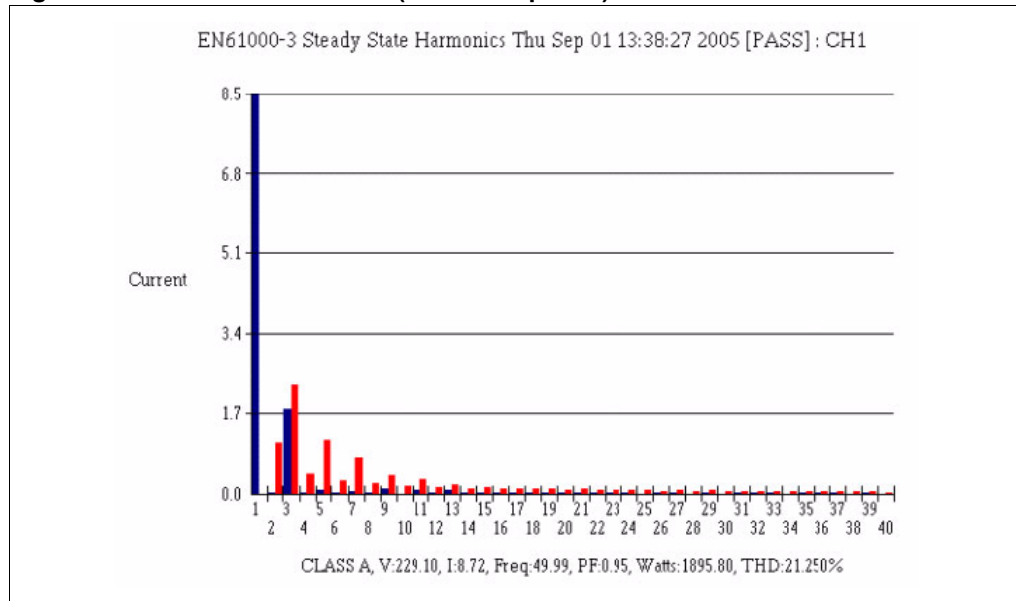
5 Size optimization design procedure

The evaluation board size is often one of the most important considerations during the design procedure. There are ways to shrink the board size smaller than those shown in *Figure 3* or *Figure 10*.

The main size-limiting components of the board are the C4 capacitor, the R6, R7, and R10 resistors, the heat sink on the TRIAC, and the EMI filter.

Note: *Since it is not possible to optimize the evaluation board for these devices, the original design uses the 16 A BTB16-600CW TRIAC, a heat sink for the output power of up to 1 kW, and an input CLC filter (C7 = 470 nF, L1 = 0.1 mH, and C9 = 100 nF). In fact, users can design the board with any EMI filter or even any heat sink for the TRIAC because there is enough space to do so.*

To minimize the size of the board:

● Resistors R1, R2, R3, R4, R5, and R8, capacitors C1, C2, C3, C5, and C6, diodes ZD1 and D1, or the ST7FLITE09 microcontroller need to be assembled in SMD version

● The switch and button can be situated in another place (for example, a switch on the wall)

● The I_{CC} connector is not needed in the manufacturing process either because the microcontroller can be programmed anywhere

If all of these points are taken into account, and the EMI filter and large power supply are not required (small or no heat sink), the optimal design can achieve an evaluation board about the size of 3 cm x 3 cm.

6 Software

The software is written in C language, structured, and well-commented. It contains several modules, but the main functions necessary for the proper operation of the evaluation board reside in the following:

- main.c
- ports.c
- pwm_ar_timer_12bit.c
- lite_timer_8bit.c
- adc_8bit.c

Note: *The overall code has less than 1.34 KB so that it will fit the ST7FLITE09 memory.*

The working principle of using the TRIAC to drive either the incandescent lamp or one-phase AC motor is to switch ON the TRIAC at the exact time in both half-periods of the sinus wave. The TRIAC is closed automatically upon zero crossing detection. The minimum and maximum opening time for the TRIAC is set as a constant value inside the software and it can be easily modified in order to guarantee the requested power range for different applications (see *Section 3* for more details).

The main idea of the software is to synchronize the internal timer inside the ST7FLITE09 microcontroller with the Zero Crossing (ZC) events of the mains sinusoidal waveform. The voltage from the mains is applied on the PA0 pin which is set up as input interrupt in a pull-up configuration. In the case of an internal counter that is not synchronized with the ZC event, the user may have difficulty with the performance of the following interrupts:

1. Interrupt from the input pin
2. Interrupt from the timer (e.g. overflow interrupt)

Note: *This can influence the driver stability, if in one period the TRIAC is switched ON at a different time, compared to the second one.*

The 12-bit Auto-reload Timer (AT timer) is used in Output Compare (OC) mode. AT timer is overflowed on address FFFh to the value set in Auto-reload (ATR, in this configuration, 0x000).

At each ZC event (see *Figure 21*), the DCR register is filled by the actual counter state from CNTR plus the value corresponding with the 0.2 ms interval (0x640). At that time, the ZC is synchronized on the mains. After that, each 0.2 ms OC interrupt occurs, where DCR = DCR + the value corresponding with the 0.2 ms interval (0x640). Each OC interrupt is incremented by the software counter (see *Figure 22*).

The biggest advantage of this is that the CNTR register is readable at any time and the new value can be written immediately to the DCR register without any delay. The 0.2 ms interval is the smallest step required for firing the TRIAC.

To increase power on reliability and EMC robustness, a HW watchdog and the highest LVD is used (option byte setting).

Figure 21. Zero crossing (ZC) events diagram
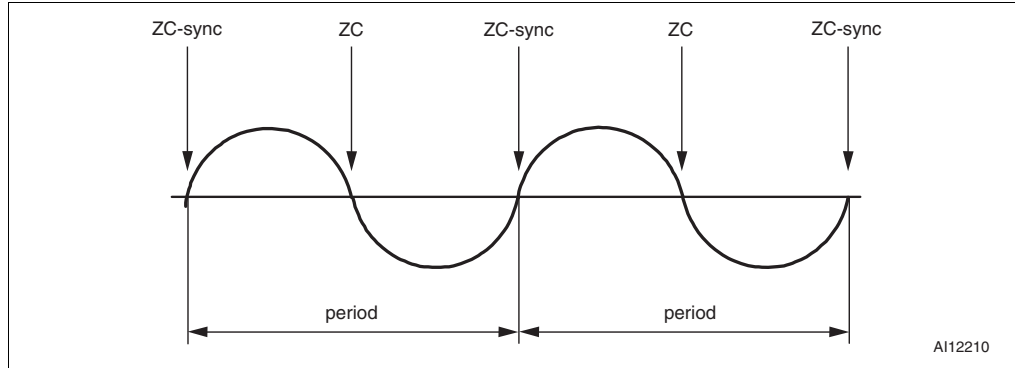
Figure 22. Auto-reload timer principle
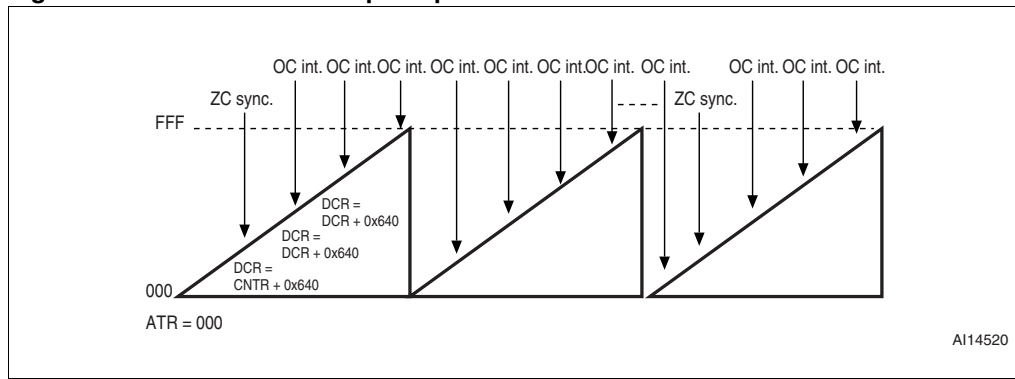
6.1   Main.c module

After the MCU is turned ON, all of the peripherals in use (e.g., Ports, LITE Timer, and 12-bit Auto-reload and ADC) are set up in "Main" program in this module. After this, all of the variables are set up and the MCU will go into the Wait For Interrupt (WFI) mode. This leads to minimum power consumption because the program is executed only in interrupts (from ZC and the OC timer, see *Figure 23*).

Figure 23.   Main programming flowchart
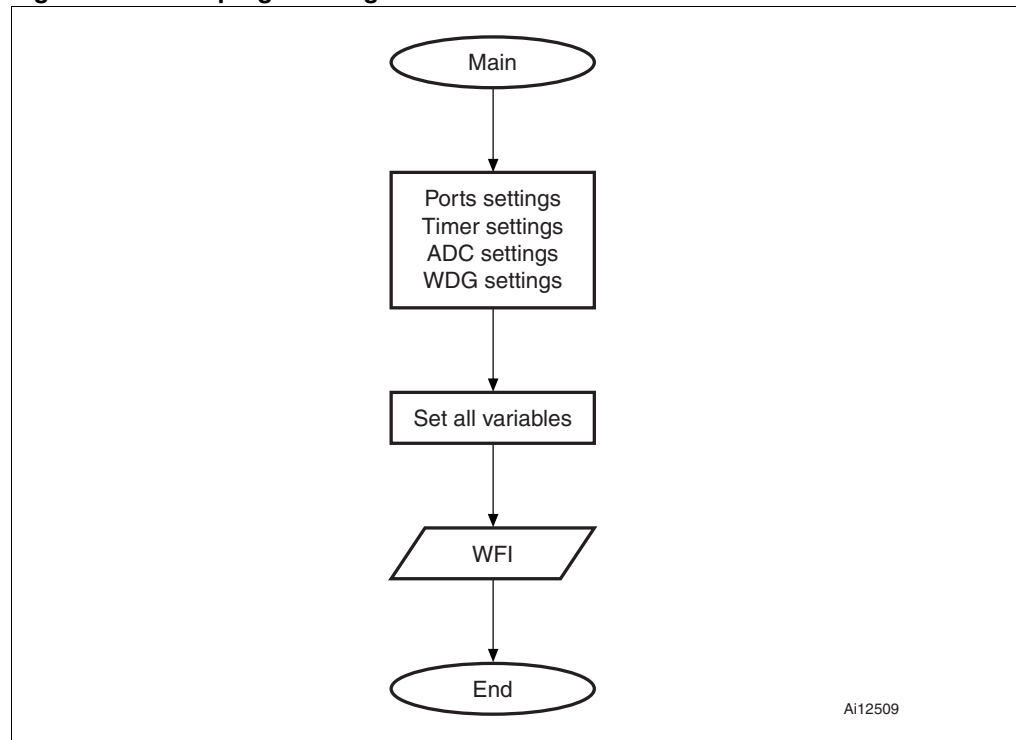
6.2   Ports.c module

All timers are switched off until the first ZC event occurs. This interrupt is handled in the ports.c module by the PORTS_0_Interrupt routine (see *Figure 24*) which checks the Port A pin 0 (PA0) on the falling edge. This pin is set up as the input interrupt that is in pull-up configuration. After catching the first interrupt, the AT timer is switched ON and the DRC is loaded with the 0.2 ms value for the compare interrupt.

The timer is then synchronized with the ZC event. The ZC window is set up either for 50 Hz or 60 Hz mains supplies to filter out all spikes. From this point, the AR_TIMER_OC_Interrupt routine is performed every 0.2 ms (see *Figure 25*).

After the 50 / 60 Hz mains has been ON for a certain period of time (about 20 ms to 16.7 ms), the second ZC interrupt occurs. At this point, the interval between two ZC events is measured and, based on this value, the corresponding flags are set (50 or 60 Hz). If this event does not fit either the 50 or 60 Hz parameters, all of the timer flags and the counter are reinitialized for another synchronization attempt. ZC event is expected at each 20 ms and filtered out in time frame of +/− 1.2 ms in order to ignore all other spikes. At the end of this

synchronization phase, a new ZC event is set up and the software watchdog is enabled. After a successful synchronization phase, the next ZC event is monitored during the following ZC interrupt and checked to see if the ZC interval passes synchronization parameters, or if the timer needs to be synchronized again. In this case, a new ZC interval is measured and the new value is used to fire the TRIAC (via the 'Read from' button or potentiometer). If the ZC interval is missed the first time, the program continues with the synchronization and measured period from the previous ZC interrupt, in case the next ZC interval is missed again the microcontroller is reset by the WDG.

6.3 Pwm_ar_timer_12bit.c module

The AT timer in OC mode is used as the main time counter. This interrupt is handled in the AR_TIMER_OC_Interrupt routine in the pwm_ar_timer_12bit.c module. This routine generates the 0.2 ms time base, push-button handling, TRIAC firing, WDG refresh, and software counter incrementing (see *Figure 25*). The button checking and handling routine checks the state of the button driving pin every 0.2 ms.

If you switch OFF the dimmer using the push button, the microcontroller enters Halt mode, reducing power consumption to the minimum. Switching back ON the light dimmer using the the push button restarts the microcontroller to synchronize on the mains. It means that the light dimmer starts again with the maximum power.

Figure 24. PORTS_0_interrupt routine flow diagram
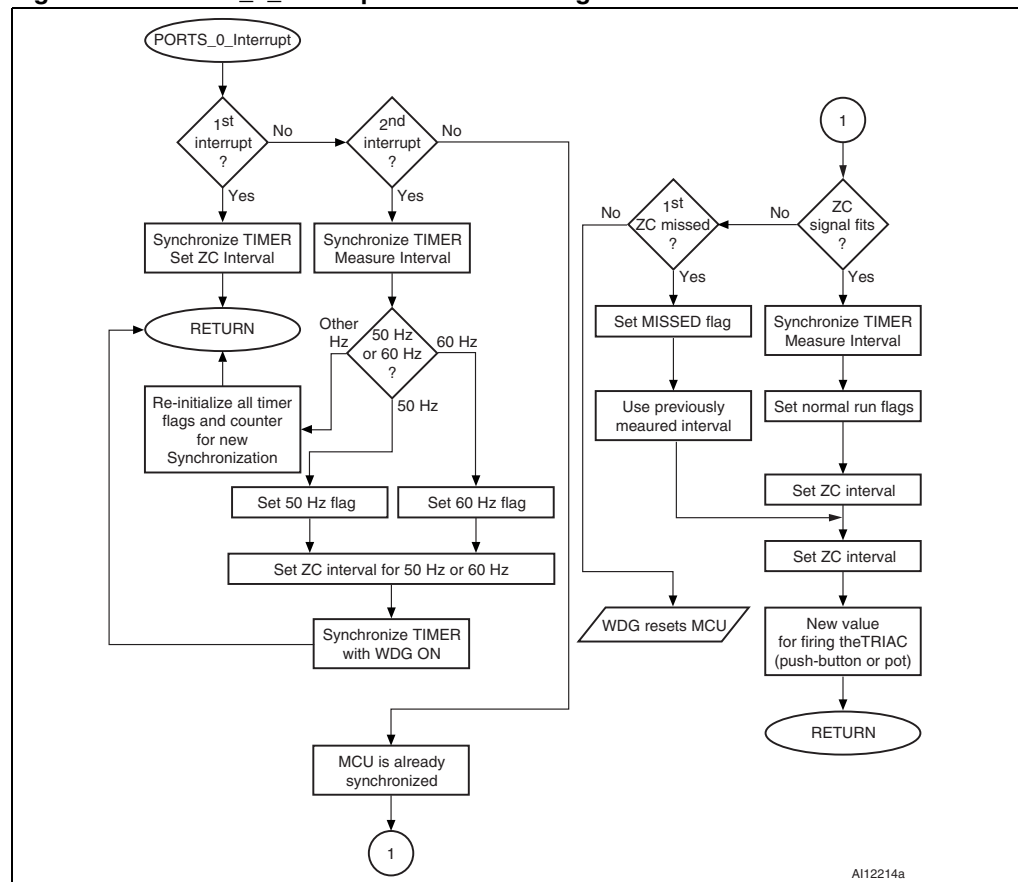
Figure 25. AR_TIMER_OC_interrupt routine flow diagram

```
                    ┌─────────────────┐
                    │  AR_TIMER_OC    │
                    │   _Interrupt    │
                    └────────┬────────┘
                             │
                    ┌────────┴────────┐
                    │  Set next 0.2 ms │
                    │     period       │
                    └────────┬────────┘
                             │
                         ◇───────◇           ┌──────────────┐
                        / 1st ZC  \   YES     │ Recount edges│
                       <  missed?  >─────────>│ for firing the│
                        \         /           │    TRIAC     │
                         ◇───┬───◇            └──────┬───────┘
                            NO│                       │
                    ┌────────┴────────┐               │
                    │     Button      │<──────────────┘
                    │  checking and   │
                    │    handling     │
                    └────────┬────────┘
                    ┌────────┴────────┐
                    │    Dimming      │
                    │    direction    │
                    │    handling     │
                    └────────┬────────┘
                         ◇───────◇   YES     ┌──────────────┐
                        /  Is it the\─────────>│Fire the TRIAC│
                       < time to fire>        └──────┬───────┘
                        \the TRIAC?/                  │
                         ◇───┬───◇                    │
                            NO│<─────────────────────┘
                         ◇───────◇   YES     ┌──────────────┐
                        / 2nd ZC  \─────────>│  Reset the   │
                       <  missed?  >          │     MCU      │
                        \         /           └──────────────┘
                         ◇───┬───◇
                            NO│
                    ┌────────┴────────┐
                    │   Counter++     │
                    └────────┬────────┘
                    ┌────────┴────────┐
                    │   WDG refresh   │
                    └────────┬────────┘
                    ┌────────┴────────┐
                    │     RETURN      │
                    └─────────────────┘
                                            Ai12510a
```
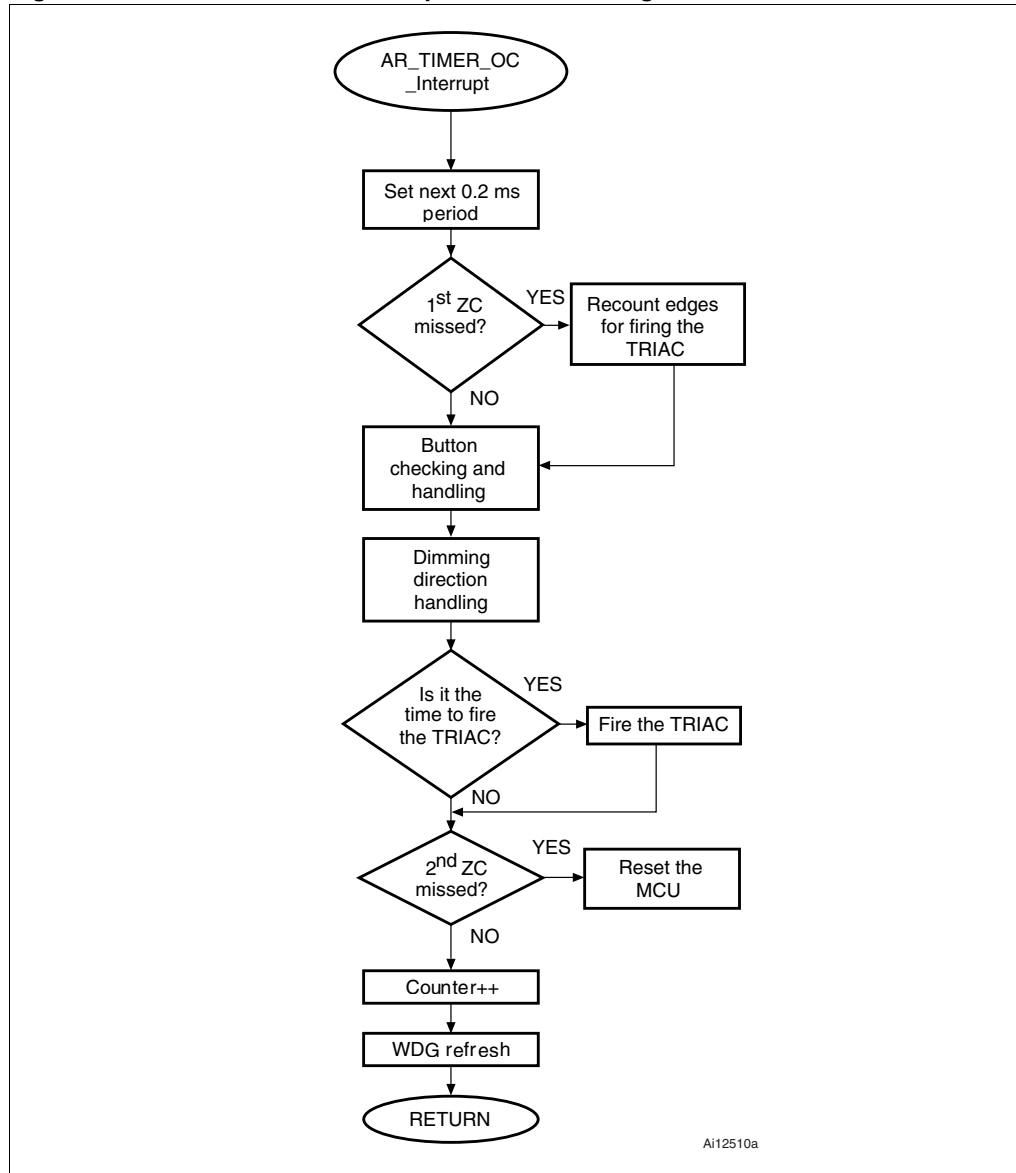
7 Small light dimmer

The objective of this design is to show how the size of the STEVAL-ILL004V1 or STEVAL-ILL004V2 evaluation board can be reduced in order to fit a light dimmer to the switch box on a wall. The design is based on the STEVAL-ILL004V1 evaluation board using the 16-pin microcontroller ST7FLITE09. The size of small light dimmer is demonstrated in *Figure 26*, where the dimmer is placed in a standard plastic switch box. Also shown is the size of the noise suppression choke inductor for power ranges from 140 W to 1000 W. The size of the evaluation board is 39 x 42 mm. The through-hole components are assembled from the top side and the SMD components are assembled from button side only (see *Figure 27*).

Figure 26. Small light dimmer inside standard plastic box

a) Noise suppression choke inductor   b) Small light dimmer reference board
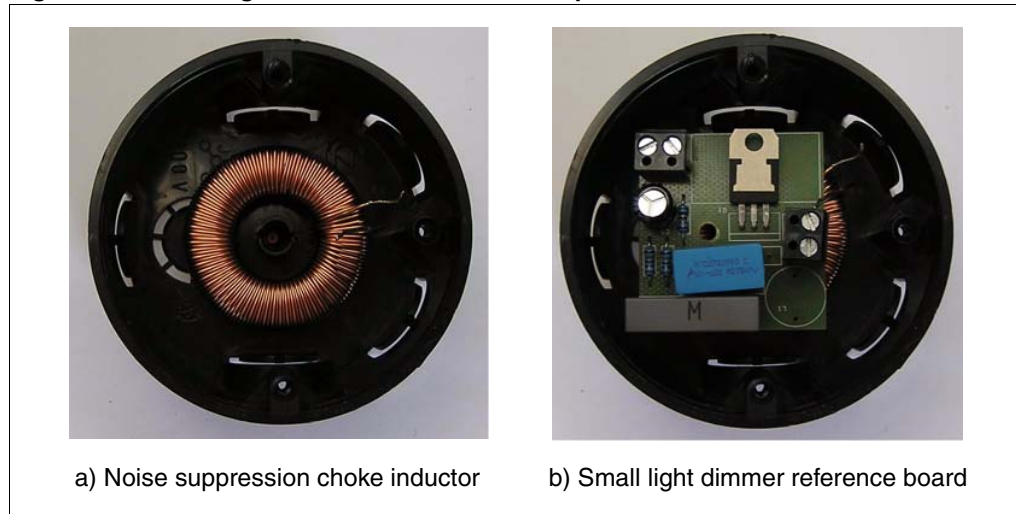
Figure 27. Small light dimmer

a) Top side   b) Bottom side

7.1 Schematic diagram

The schematic diagram of the small light dimmer is shown in *Figure 28*. The load (lamp) is connected in series with the board, as previously described in *Section 3.1*. The button is not connected to the board, but there is a connector available for greater flexibility. The maximum load power mainly depends on the TRIAC and heatsink used. Power up to 350 W can be delivered to the load using the ACST67S TRIAC, if there is no heatsink connected. A heatsink must be used if the power is higher than 350 W. How to connect the heatsink to the board is mainly a mechanical issue and it is not within the scope of this document to demonstrate the small light dimmer with a heatsink (the heatsink calculation is in *Section 2.3.2*). The type and size of the noise suppression choke inductor needed to fulfill the required standards is described in *Section 7.3*.

Figure 28.   Small light dimmer - schematic diagram

7.2 PCB

The PCB layout is shown in *Figure 29* and *Figure 30*. The layers shown are the bottom layer, solder mask bottom layer, silk screen bottom layer and the silk screen top layer.

Figure 29.   Small light dimmer PCB layout

| a) Bottom layer (BOT) | b) Solder mask bottom layer (SMB) |
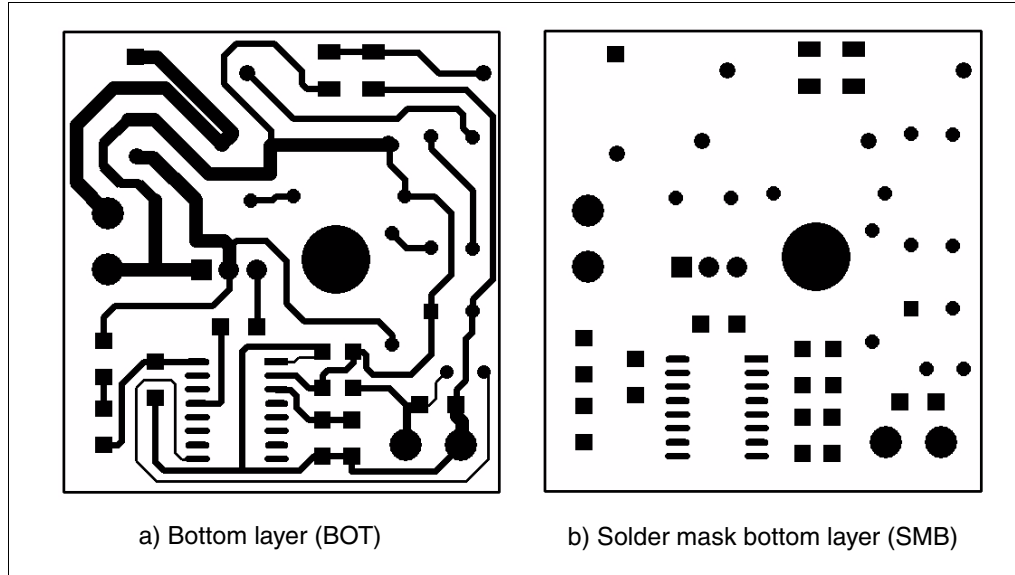
Figure 30.   Small light dimmer PCB layout

| a) Silk screen top layer (SST) | b) Silk screen bottom layer (SSB) |
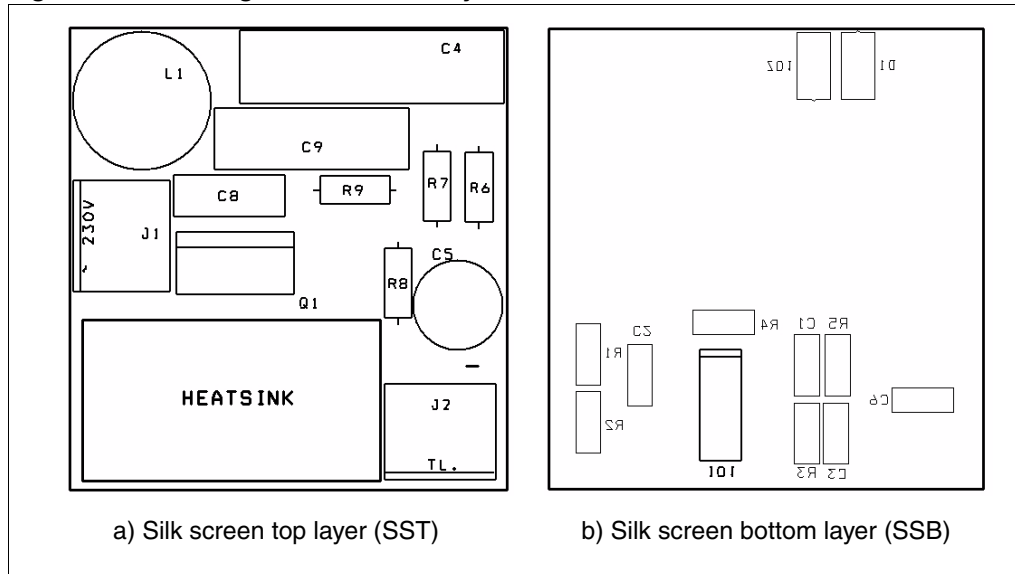
7.3   EMC measurement - EN55015 for the small light dimmer

A C-L input filter is used to guarantee the standard requirements. Filtering capacitor C9 has a value of 220 nF (~275 V_{ac} X2). The noise suppression choke inductor L1 is used for power between 140 W and 1000 W and its size is 42.5 mm x 13 mm (tested power is 330 W). The component size as a function of power is shown in *Figure 31* (the figure is from the VOGT electronic components catalogue). *Figure 32* shows the exact type of inductor used with the dimensions and the order code. The inductor with order code 5730806700 has been used on this evaluation board during the EMC test measurements. Users can select the appropriate filtering capacitor and inductor combination depending on their power range specification in order to fulfill the standards (*Figure 31*).

Figure 31.   Component size as a function of power - VOGT catalogue

Figure 32.   VOGT Inductor type - catalogue datasheet

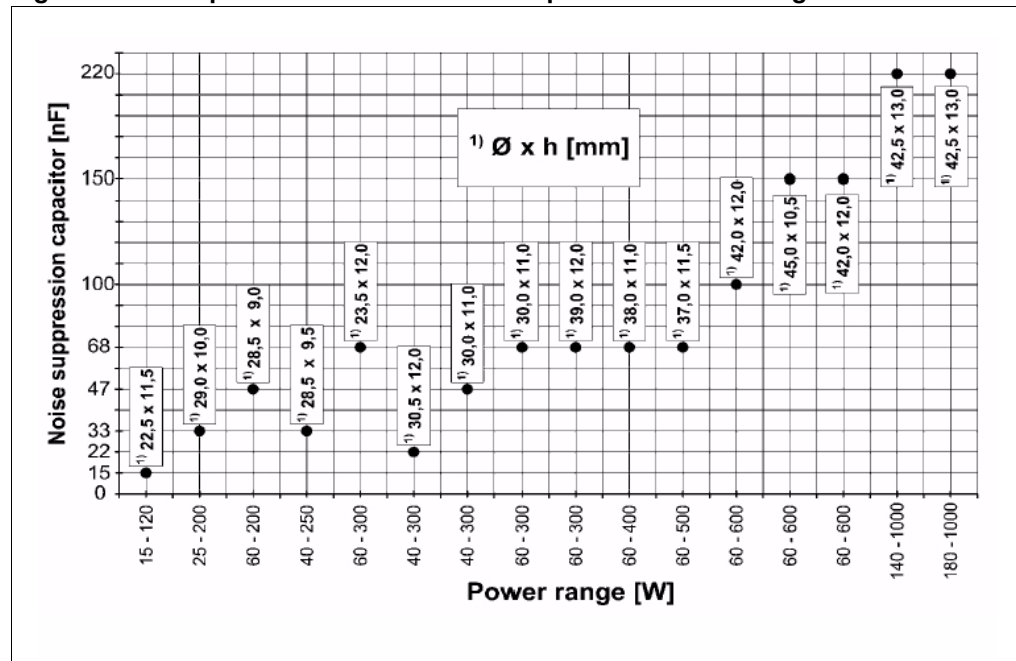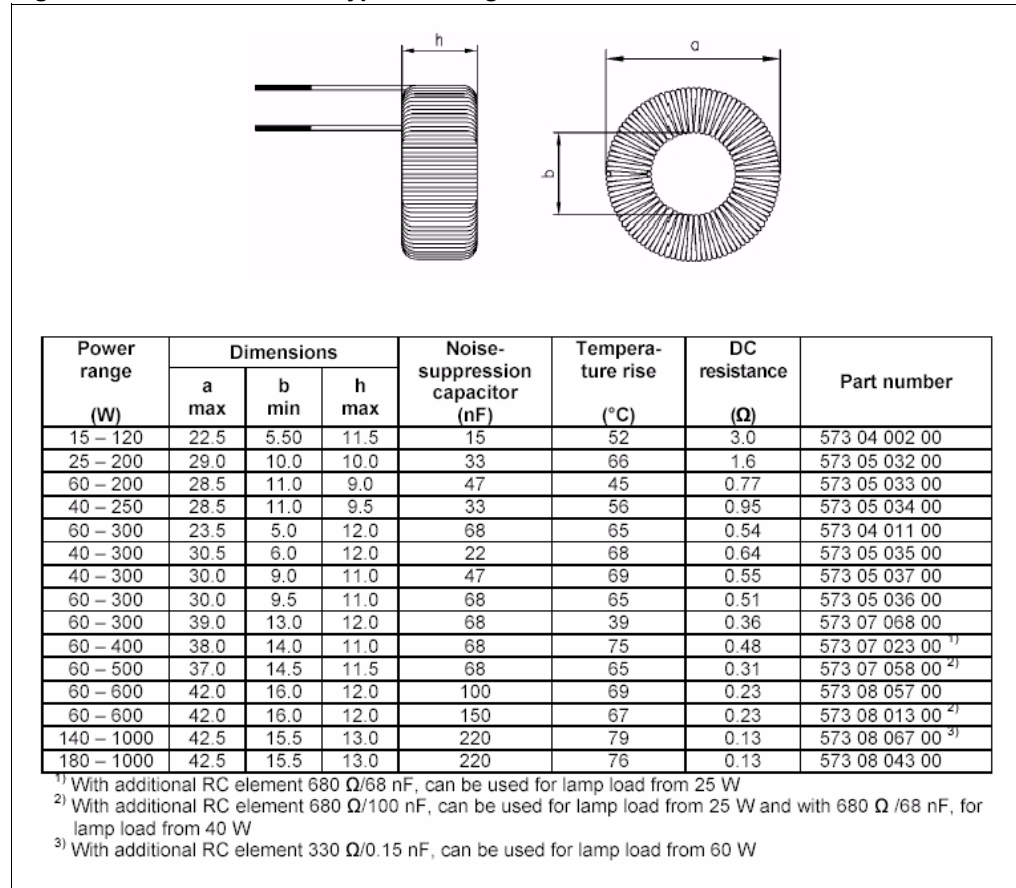| Power range (W)	Dimensions			Noise-suppression capacitor (nF)	Tempera-ture rise (°C)	DC resistance (Ω)	Part number
	a max	b min	h max				
15 – 120	22.5	5.50	11.5	15	52	3.0	573 04 002 00
25 – 200	29.0	10.0	10.0	33	66	1.6	573 05 032 00
60 – 200	28.5	11.0	9.0	47	45	0.77	573 05 033 00
40 – 250	28.5	11.0	9.5	33	56	0.95	573 05 034 00
60 – 300	23.5	5.0	12.0	68	65	0.54	573 04 011 00
40 – 300	30.5	6.0	12.0	22	68	0.64	573 05 035 00
40 – 300	30.0	9.0	11.0	47	69	0.55	573 05 037 00
60 – 300	30.0	9.5	11.0	68	65	0.51	573 05 036 00
60 – 300	39.0	13.0	12.0	68	39	0.36	573 07 068 00
60 – 400	38.0	14.0	11.0	68	75	0.48	573 07 023 00 [1]
60 – 500	37.0	14.5	11.5	68	65	0.31	573 07 058 00 [2]
60 – 600	42.0	16.0	12.0	100	69	0.23	573 08 057 00
60 – 600	42.0	16.0	12.0	150	67	0.23	573 08 013 00 [2]
140 – 1000	42.5	15.5	13.0	220	79	0.13	573 08 067 00 [3]
180 – 1000	42.5	15.5	13.0	220	76	0.13	573 08 043 00

[1] With additional RC element 680 Ω/68 nF, can be used for lamp load from 25 W
[2] With additional RC element 680 Ω/100 nF, can be used for lamp load from 25 W and with 680 Ω /68 nF, for lamp load from 40 W
[3] With additional RC element 330 Ω/0.15 nF, can be used for lamp load from 60 W

The load is 330 W and it consists of four lamps (150 W and 3 x 60 W). The load is connected on the board in series. Since the output power can be regulated by the switching time of the TRIAC, there are many states available for testing, but only the worst case (highest noise) measurement is provided. This occurs when the TRIAC is turned on in the maximum voltage of the sinusoidal waveform. Two measurements are required by this standard:

● Peak value (*Figure 33*)

● Average value (*Figure 34*)

Both of the actual waveforms are under the requested limits, proving that this type of EMI filter is suitable for the light dimmer application.
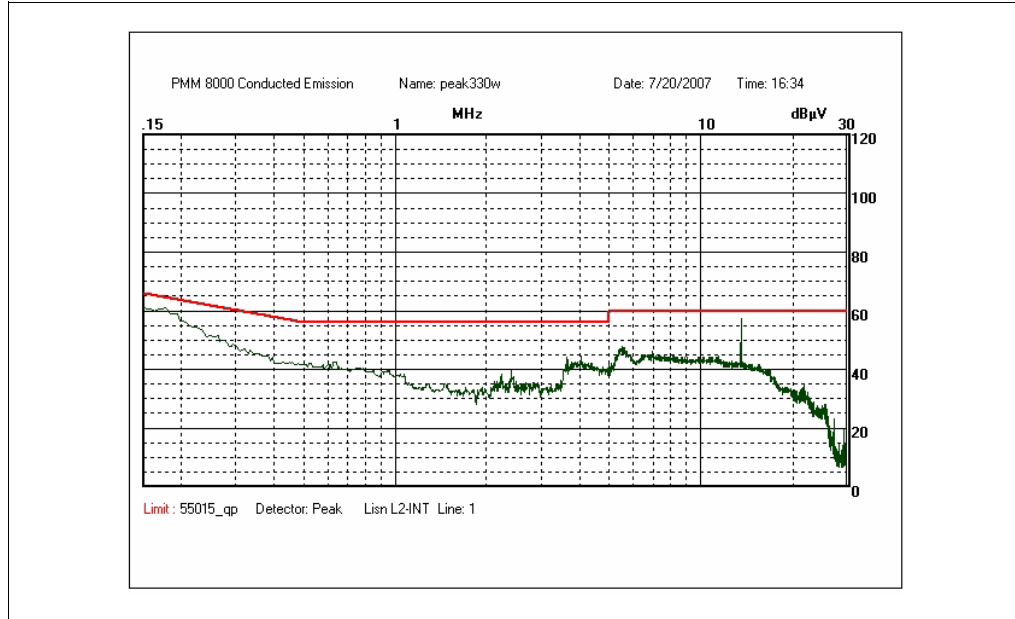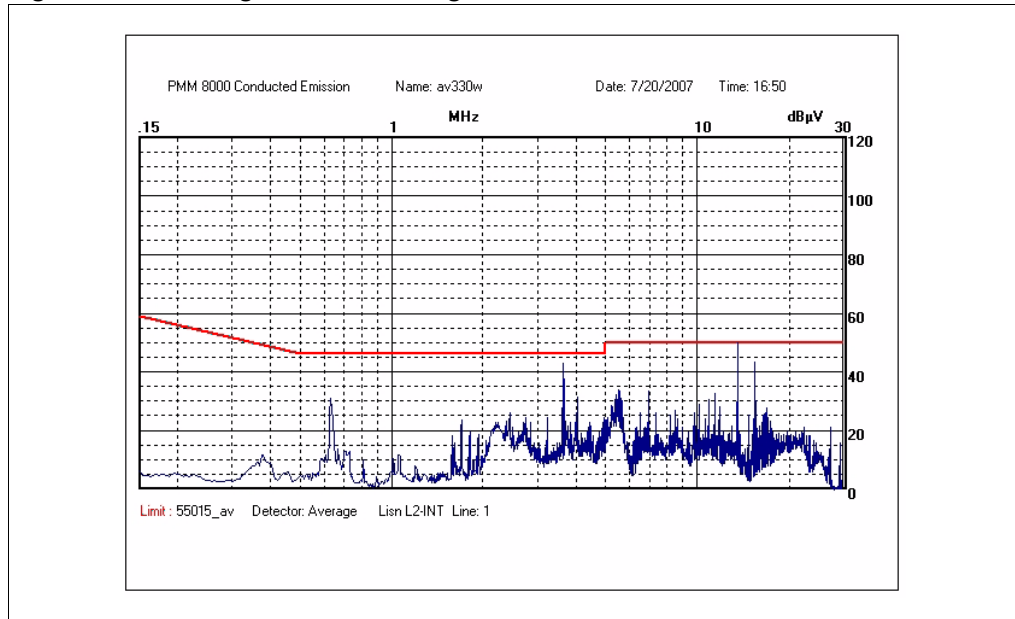
Figure 33. Small light dimmer peak value measurement

Figure 34. Small light dimmer average value measurement

Appendix A STEVAL-ILL004V1 bill of material

Table 3. **Bill of materials**

Item	Qty	Reference	Part	Ordering code
1	1	CONNECTOR2	I_{CC}	
2	1	C1	100 nF / 50 V	
3	1	C2	100 pF / 50 V	
4	1	C3	10 nF / 50 V	
5	1	C4	330 nF / ~275 V_{ac} X2	
6	1	C5	470 µF / 16 V	
7	1	C6	1 nF / 50 V	
8	1	C7	470 nF / ~275 V_{ac} X2	
9	1	C8	2.2 nF	
10	1	C9	100 nF / ~275 V_{ac} X2	
11	1	D1	D4007	
12	1	F1	FUSE-10 A	
13	1	IO1	ST7LITE09	ST7FLITE09Y0B6
14	2	J1, J2	CON3	
15	3	J3, J4, J5	CON1	
16	3	J6, J7, J8	JUMPER	
17	1	L1	0.1 mH / 5 A	
18	1	P1	10 kΩ	
19	1	Q1	BTB16	BTB16-600CW
20	2	R1, R2	160 kΩ	
21	1	R3	1 MΩ	
22	1	R4	47 Ω	
23	2	R5, R8	20 kΩ	
24	3	R6, R7, R10	150 Ω	
25	1	R9	1 kΩ	
26	1	S1	Button	
27	1	S2	Switch	
28	1	ZD1	5.5 V	
29	1	~275	Varistor	

8 Revision history

Table 4. Document revision history

Date	Revision	Changes
12-Dec-2005	1	Initial release
07-Jun-2006	2	Minor editing for figures, schematics and text.
23-Oct-2007	3	– Document reformatted – Modified: *Introduction* – Added: *Section 7: Small light dimmer*.

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