Four Steps to LEDs on the Mains

A guided approach

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Sure, there are many ways to power an LED from the mains. However, in good philosophical (and GPRS) tradition, the shortest way to success or any target for that matter is not necessarily the fastest — or, in *EE*-speak, the simplest circuits are not always the best. A lot can go wrong: a too small series resistor can vastly reduce the lifetime of the LED, while designing too many components into the circuit makes for a lot of wasted heat resulting in a really saddening efficiency figure.

Here's a four-step design guide we publish in reply to a question we hear a lot lately: *how do I make an LED light from the mains?* Read and think along with us, 'mind the steps' here and there and find inspiration for your own designs!

Warning. Components in the four circuits shown in this series are connected directly to the mains. To avoid electrification and risk of shock, the complete circuits must be encapsulated and insulated in accordance with all relevant electrical safety regulations. All component values are for a 240 VAC, 50 Hz mains voltage.

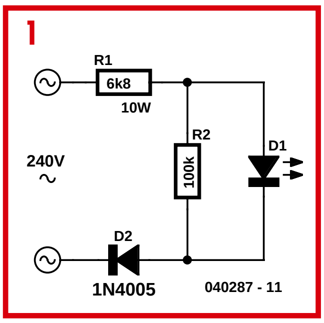
Step #1: free heating included

Running an LED from a dedicated power supply is not just inelegant, it is also, because of the transformer, a rather bulky and heavy solution. Where no low-voltage DC power is available and full isolation between the mains and the LED is not absolutely necessary, it is possible to avoid that extra supply.

To operate an LED directly from the mains we can, naturally enough, use a series resistor. Since the maximum reverse voltage of an LED is typically around 5 V, a mains-voltage rectifier diode is also required in series. Because the mains rectifier diode will exhibit some leakage, and to be on the safe side we also wire a 100 kΩ resistor in parallel with the LED which helps to prevent excessive reverse voltage appearing across the LED: the power dissipation of this resistor will be negligible. The simplest circuit therefore consists of four components, including the LED.

If we assume an LED current of 20 mA, we can calculate that the required series resistor is 240 V divided by twice 20 mA = 6 kΩ (the factor of two arising because we are only using one half-cycle of the AC waveform). A practical value is 6.8 kΩ (**Figure 1**). The total power dissipation will then be around 4.8 W, almost all used in heating the series resistor: the fraction used by the LED is less than 1 %. We might prefer to think of this circuit as primarily a generator of heat rather than of light, but nevertheless in principle it works.

We can derive some comfort from the fact that operation from a power supply is not particularly energy-efficient either. A quick back-of-the-envelope calculation: a typical small commercially-available transformer will be rated at 0.5 VA with a secondary voltage of 6 V; unloaded, the transformer will deliver nearer 7.5 V. After a bridge rectifier and smoothing we will have a DC voltage of about 9.5 V. If the LED is to be supplied with 20 mA with a forward voltage drop of 2 V, we must drop 7.5 V across the series resistor. The losses in the secondary side of the power supply total around 210 mW, when losses in the bridge rectifier are taken into account. Of this the LED sees only 2 V times 20 mA, or 40 mW. Things are actually even worse than this: the typical efficiency of



such a small transformer at full load is only about 55 %. Here, at less than full load, efficiency is worse, possibly only 45 %. Thus 210 mW at the secondary side corresponds to 467 mW at the primary, meaning that 427 mW, or 91 % of the total input power, is lost as heat!

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Step #2: series capacitor

To operate an LED directly from the mains we can, naturally enough, use a series resistor; this will, however, lead to about 99 % of the power used being dissipated as heat. So how about using the impedance of a capacitor instead of the resistor?

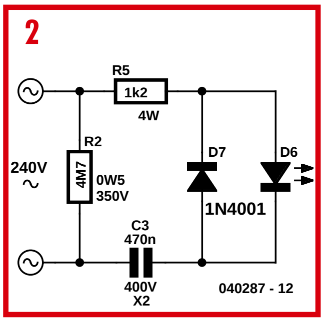
If we assume an LED current of 20 mA, we can calculate that the required series resistance is 240 V divided by twice 20 mA = 6 kΩ (the factor of two arising because we are only using one half-cycle of the AC waveform). The impedance of the series capacitor C1 must therefore also be 6 kΩ (**Figure 2**). Using the formula for the cutoff frequency of an RC-network, here set to 50 Hz, we arrive at a value of 530 nF for C1. We do not wish to overdrive the LED, and we choose the next available value in the E3 series for C1: 470 nF. The effective current through the LED over a full cycle of the mains waveform will be about 15 mA when the effect of protection resistor R1 is taken into account. This will generally give enough brightness. What then is the purpose of R1?

Imagine switching on the circuit, with R1 missing, at the instant when the mains voltage reaches its peak value. A large current spike will pass through the LED via C1, and it will light brightly — but only very briefly, before it turns into a wire link, or possibly a firecracker. Modern LEDs can only withstand a maximum current peak of around 0.5 A, and then only for a few microseconds. Exceeding this value will reduce the life expectancy of the LED, which rather cancels out its advantage in terms of long life in comparison with its incandescent cousins. Since this current surge can occur each time the circuit is switched on, we should limit it for safety to half of the maximum permitted value. C1 must therefore have a series resistor added to limit the surge current to around 250 mA. The peak value of the mains voltage is around 340 V, and so a resistance of 1360 Ω is suitable. A sufficiently accurate value for R1 from the E12 series is 1.2 kΩ. Anyone familiar with this type of circuit will immediately see that this value is higher than usual: 330 Ω is a more commonly-seen value. It is easy to appreciate that the LED will from time to time be driven outside its specification.

Rectifier diode D1 is logically connected in parallel with the LED. R2 is a discharging resistor for C1, preventing the pins of the pulled mains plug carrying enough energy to cause an electrical shock when touched. At 4.7 MΩ, R2 is able to discharge C1 to about 2/3 within about two seconds. The resistor has to be dimensioned for 350 V minimum! In case of doubt, it is best to connect two 2.2-MΩ resistors in series.

Because C1 must carry alternating current, D1 is connected in parallel with the LED, rather than in series. Since no more than about 2 V will appear across D1 in the reverse direction, we can use a low-voltage type such as the 1N4001. We can now take a look at the energy budget. Twice the LED current flows through R1, and so a voltage of about 36 V is dropped across it. R1 thus dissipates almost 1.1 W and so over 97 % of the total power taken by the circuit is lost as heat: not exactly a stunning performance!

This is also a reason why lower values are frequently seen for R1. At 330 Ω, for example, the losses are practically divided by four, although the LED is then driven outside its specification: this affects reliability, leading to a greater probability of failure and shortened operating life. The theoretical lower limit for R1, without leaving any significant safety margin, is 680 Ω. In this case 0.5 W of power is dissipated as heat.



A metal film resistor should not be used for R1. With a value of 1.2 kΩ the peak dissipation will be nearly 100 W for a period of a few hundred microseconds: carbon film resistors are better able to withstand this treatment. The most tolerant are the ceramic wirewound types: the small 4 W versions are suitable. Even if a value of 680 Ω is used, the ceramic 4 W types are preferred. Resistors rated at less than 0.5 W generally do not have a sufficiently high working voltage.

What happens if we use a low current LED? Our remarks on peak currents still apply, but R1 can be made even smaller. The capacitance of C1 must be adjusted to suit the LED. A low current LED will operate on about 5 mA, corresponding to a value of 100 nF for C1.

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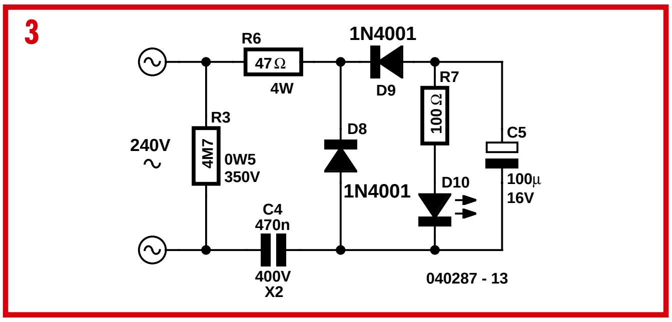
Step #3: flicker-free

Apart from their low efficiency, both the ohmic and the capacitive 'voltage dropper' suffer from another major deficiency. Because a rectifier diode is required in series or anti-parallel with the LED (the allowable LED reverse voltage being limited to about 5 V) a decisive disadvantage is created: current flows through the LED only during one half-cycle of the mains waveform, leading to a somewhat flickery light. Since LEDs do not share the thermal inertia of light bulbs, the 50 Hz flicker is clearly visible to many people. This is annoying if a white LED is to be used as a night light.

First we turn to the problem of low efficiency. The circuit shown in **Figure 3** limits the maximum surge current by connecting a capacitor in parallel with the LED. A diode (D2) is therefore also required. Now the value of the protection resistor R2 can be made small. Ideally we would reduce it as far as we can while protecting the other components adequately. First of all we need to consider the surge tolerance of the two diodes. Typical rectifier diodes in the 1N4000 series have a half-cycle surge tolerance of 30 A. In order not to overly stress conductors, fuses (if any) and switches we should keep the current to less than 10 A. With R1 at 47 Ω we have a peak current of around 7 A.

The diodes and C2 can all cope with 7 A. R1 now dissipates only



50 mW. Because of the peak power, which is over 1 kW (!) for around 1 µs, a ceramic wirewound type is absolutely essential. A carbon film resistor rated at, for example, 0.5 W will be destroyed in the blink of an eye in this application.

Now to the problem of flickering: the capacitor value can be chosen to be sufficiently large that it produces a reasonably smooth DC voltage. Resistor R2 linearises the resistance of the LED and thus stabilises the current through it. The dynamic resistance of an LED is relatively low: only a few ohms. Choosing a value of 100 Ω for R2 gives an acceptably steady current. When choosing C2 we observe that in order to limit the peak current through the LED to, for example, 250 mA, we need a value of roughly speaking twenty times that of C1. If C1 is 470 nF, (see under 'Series capacitor') then 10 μF is adequate for C2. When smoothing a half-wave rectified AC voltage a larger capacitor would usually be used: the rule of thumb states that we should use at least 2 μF per mA. This would give a theoretical value of 33 μF for C2, and in practice we would choose 100 μF from the E3 series in order to have something in reserve. Note that for a low current LED a current of 5 mA suffices: C1 should then be 100 nF and R2 should be increased to 270 Ω.

Of course, everything has its price: electrical energy is wasted as heat in R2. With a voltage drop of 1.65 V and an average current of 16.5 mA we are spending an extra 27 mW for the sake of a steady light. To this we can add the losses in the two diodes, which at 0.75 V and 16.5 mA come to about 25 mW. In total the circuit therefore takes around 134 mW and delivers about 33 mW to the LED for its operation. With about 75 % of the power wasted as heat the efficiency of the circuit is already considerably better than using just a series resistor or capacitor. This advance requires a grand total of eight components. The upshot is that although the circuit might be a little more expensive, it does not generate significant quantities of heat yet produces a steady light.

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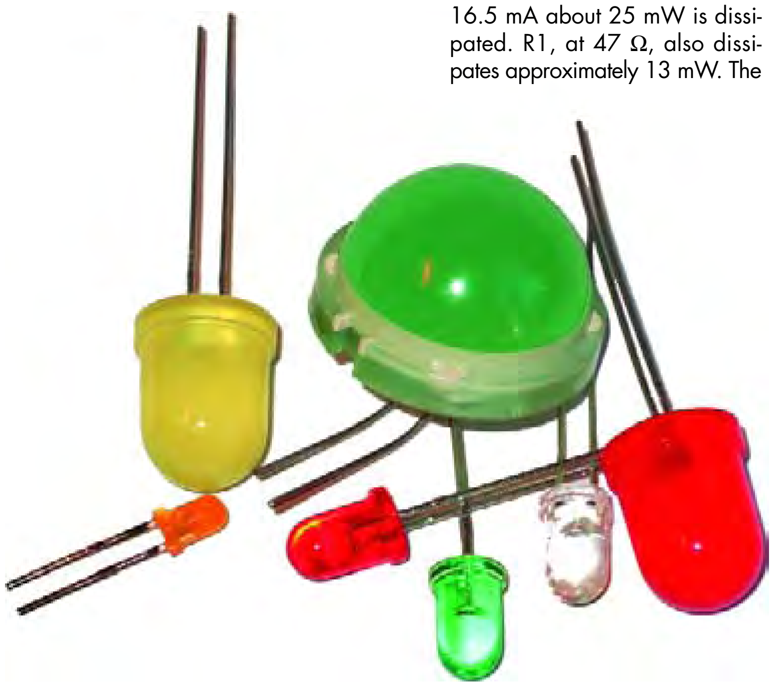
Step #4: the 100 Hertz LED

'Why use one component when a dozen will do?' might be your first thought on seeing this circuit. After all, we only need a series resistor to connect an LED to the mains. Simple circuits unfortunately have decisive disadvantages, including poor efficiency and flickering (see the other circuit descriptions). Compared to the 'Flicker-free' circuit, Step #4 (**Figure 4**) is improved in an important way: the supply to the LED is full-wave rectified.

The supply voltage for the LED pulses at 100 Hz in this circuit. Flicker at this frequency is almost imperceptible to the human eye. Because we are using 100 Hz, we can halve the value of smoothing capacitor C2. But there is a more attractive alternative: we can leave C2 at 100 μF and instead halve the value of R2 to 47 Ω.

As a consequence of the improved rectification using both half-cycles of the waveform we have to halve the series resistance, or halve the value of C1. Film capacitors with suitable working voltage are easier to come by at 220 nF than the theoretically correct 270 nF (under 'Step #2' we calculated a value of 530 nF for an LED current of 20 mA), and so we use that value. The LED current, with the reduced value for R1, will still be around 16.5 mA. Note that for operation with a low current LED around 5 mA is required. A value of 47 nF will then be suitable for C1, and R2 should be increased to 150 Ω.

R2 now dissipates only about 13 mW. The diodes together have a total forward voltage drop of around 1.5 V, and so at 16.5 mA about 25 mW is dissipated. R1, at 47 Ω, also dissipates approximately 13 mW. The



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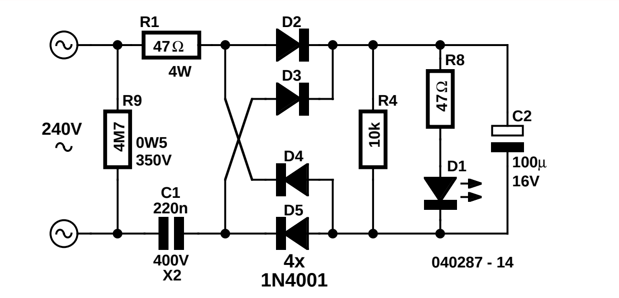

LED itself takes 33 mW. The overall efficiency is thus considerably improved: at 51 mW only 60 % of the total power is lost to heating the environment.

What part do R3 and R4 play in this circuit? R3 is a discharge capacitor for C1. This prevents, for example, the possibility of a finger receiving a dangerous shock from the pins of the plug after it has been removed from the wall. Using a value of 4.7 MΩ for R3 means that C1 is two-thirds discharged within one second. Do you remember the 2-times-2.2-MΩ-in-series-trick in Step #2? Good! R4, on the other hand, ensures that C2 is discharged when power is applied so that it can have full effect in limiting the surge current through the LED. Its dissipation is negligible at under 1 mW. A small potted bridge rectifier (such as type B40C1000; 40V piv, 1A) can of course be used in place of D1 to D4.

The circuit is designed to be especially suitable for use as a low-power, flicker-free night light for a child's bedroom. In this case three series-connected high-efficiency white LEDs can be used in place of LED1. Each of these LEDs will drop a voltage of about 3.6 V. Maximum light is obtained with an operating current of 25 mA, for which C1 will need to have a capacitance of 330 nF. Since values in the E3 series are easier to obtain, it is possible to use a 220 nF capacitor in parallel with a 100 nF capacitor instead.

The working voltage given for C2 is adequate, but in the interests of reliability might be increased to 25 V. There will be 11 V across the LEDs at 24 mA, for a total power of 260 mW, adequate for a normal-sized bedroom. The energy budget is as follows: R1 and R2 together dissipate about 52 mW. Adding the 12 mW dissipated by discharge resistor R3 and we reach 64 mW. The total operating power is therefore about 324 mW, of which less than 20 % is wasted. Total energy consumption is only 2.85 kWh per year. At only a few pence in estimated electricity cost per year, even our most parsimonious reader should be happy to leave the circuit plugged in. Finally, a note on safety: not forgetting general-purpose safety guidelines and regulations, electronics installed in a child's bedroom should be childproof!

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