Mains Powered Soft-Start Circuit

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Introduction

The ESP soft-start circuit (Project 39 is over 20 years old now, and it's still (IMO) the best way to provide a reliable soft-start function for transformers over 300VA (especially toroidal types). Since publication, there are now countless variations available both as kits and designs. When it was published in 1999, there was almost nothing else available in any form. P39 remains my preferred option, as mains switching can be done at low voltage, with a small transformer (or even a small switchmode wall supply) providing the 'full-time' power that allows remote 12V switching or an internal switch.

> **Safety Warning:** This project is directly connected to the mains, and *all* parts are 'live' when in operation. No part of the circuitry can be left unprotected against accidental contact, and all wiring must be compliant with any regulations and/ or safety standards that apply where you live. ESP accepts no responsibility for damage, injury or loss of life. Should you build this project, you accept all responsibility for any consequences that arise for any reason. By continuing to read the material presented, you shall be deemed to have read this safety warning, and accepted the conditions herein.

For reasons that I must admit I don't understand, some people seem to like the idea of the entire soft-start circuit being mains powered, with all circuitry at the full mains potential. This is just as dangerous as it sounds, and everything has to be protected against accidental contact. There's no ability to use low-voltage switching, because the 'low voltage' supply is directly connected to the AC mains, and is not isolated. This is something I've avoided, because it *is* so dangerous, but if everything is done competently (and to the required standards) it's cheaper than using a transformer to power the circuit.

In the interests of completeness, the designs shown here *are* mains powered, with no mains transformer or other low voltage supply being used. Personally, I wouldn't recommend that anyone build these circuits, as the P39 board is far safer (it still has dangerous voltage at the mains end though). The PCB also includes the ability to use remote +12V switching. Because it has two relays (one for mains-on and the other to short out the ballast resistors), no additional front panel mains switch is necessary, but if used, it's at a (safe) low voltage. There should always be a 'proper' mains switch though, but it can be on the back panel.

Note: - the circuits shown do *not* include a mains fuse. This is always necessary, and will usually be located in the chassis-mount IEC mains input connector. The fuse rating depends on the transformer, and should be the type and value specified by the manufacturer or supplier.

Transformer Characteristics

It can be helpful to know the basics of your transformer, especially the winding resistance. From this, you can work out the worst case inrush current. This table is shown in Transformers, Part 2 and is abridged here. Transformers with a winding resistance of more than 10 ohms (230V types) don't need a soft start circuit. Although the peak current can reach around 30A, that's well within the abilities of a slow blow fuse and normally never causes a problem. Of course, if you *want* to use a soft start on smaller transformers, there's no reason not to, other than the added cost.

VA	Reg %	R_pΩ - 230V	R_pΩ - 120V	Diameter	Height	Mass (kg)
160	9	10 - 13	2.9 - 3.4	105	42	1.50
225	8	6.9 - 8.1	1.9 - 2.2	112	47	1.90
300	7	4.6 - 5.4	1.3 - 1.5	115	58	2.25
500	6	2.4 - 2.8	0.65 - 0.77	136	60	3.50
625	5	1.6 - 1.9	0.44 - 0.52	142	68	4.30
800	5	1.3 - 1.5	0.35 - 0.41	162	60	5.10
1000	5	1.0 - 1.2	0.28 - 0.33	165	70	6.50

Table 1 - Typical Toroidal Transformer Specifications

The maximum inrush current is roughly the mains voltage divided by the winding resistance. There's a lot more detailed info on this (including oscilloscope captures) in the Inrush Current article. It also includes waveforms with a rectifier followed by a large capacitance and a load, and will help you to understand the need for protection circuits with large transformers.

Project Description

The circuit is shown below. There's no transformer, so the easiest way to get the required voltage drop is via a capacitor (C1). This *must* be a Class-X cap, rated for continuous duty with a minimum of 270V RMS rating. To use the circuit with 120V (60Hz) supplies, C1 must be increased in value. A 330nF cap is suitable, and again, it must be a Class-X part. Many people seem to think that using a 630V DC capacitor with mains voltage is somehow ok, but it's *not*. Class-X (typically Class-X2) capacitors are designed to work with mains voltages, and the use of anything else is dangerous.

A capacitor is ideal to reduce the voltage (actually the current), because it dissipates no power. At 50Hz, the 220nF cap has an impedance of about 14.5k, and a resistor of that value would have to dissipate almost 3.7W of heat. C1 provides a current of 15mA at 230V, or 20mA at 120V. There's no heat, because the capacitor is a reactive component, which (by definition) dissipates no power. The current through R1 and R2 is negligible and isn't considered.

The relay is important*!* The circuit is designed to use a 24V coil relay, having a coil resistance of not less than 820Ω These are very common, and are readily available from most suppliers. The contacts can be either normally open only, or the more common SPDT (single-pole, double-throw, aka CO [change-over] aka 1-Form C). The transformer (or other load) is connected directly to the mains after the timeout period, via the COM (common) terminal and the NO (normally open) contact. The NC (normally closed) terminal is not used.

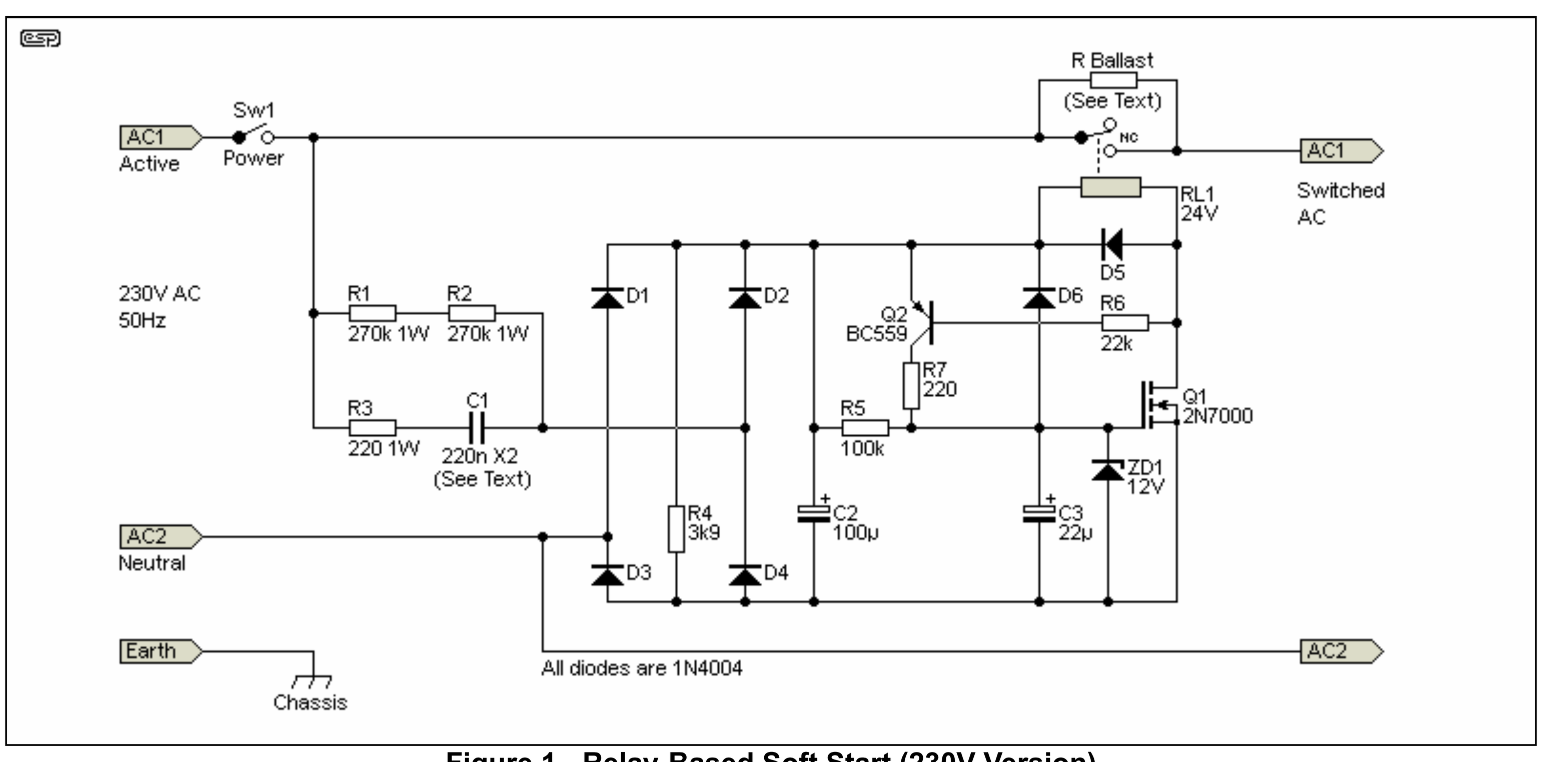

Figure 1 - Relay-Based Soft Start (230V Version)

C1 is used to drop the voltage, and with 220nF (at 230V, 50Hz) it passes 15mA. R1 and R2 discharge the cap so the mains pins can't 'bite' after the unit has been unplugged (this is a requirement in many countries). R3 limits the peak current. I recommend that these three resistors should be 1W - not because they dissipate much power, but to ensure that they can withstand the voltage. Resistors have a voltage rating (which is often not stated) and if that's exceeded they may be subject to internal breakdown. The current-limited AC is then rectified, with C2 charging to 33-36V (limited by R4). Note that the current through C1 is less than that needed by the relay, but C2 stores enough energy to activate the relay reliably. Minimal current is needed to keep the relay closed after it's been activated.

Given that a 24V relay is specified, you may wonder why the voltage is allowed to rise to over 30V. This both simplifies the circuit, and ensures that the relay will pull in reliably. Once the relay activates, the voltage falls to about 11V. This is more than enough to keep the relay energised, since most 24V relays won't release until the voltage falls to less than 4V. Despite any misgivings you may have, C2 only needs to be rated for 35V - if that's exceeded it's momentary, and the cap will not be damaged. If you prefer, R4 can be replaced with a 30V zener diode, which (predictably) sets an absolute maximum voltage of 30V.

The specification for a typical relay of the type recommended is shown in the Datasheet on the ESP website (© Tyco Electronics Corporation) and it's linked here because suppliers keep moving their material so external links keep breaking. The TE product code is OMI-SS-124LM1 (high sensitivity, 540mW) or OMI-SS-124D1 (standard sensitivity, 720mW). The 540mW coil is preferred as it draws less current. Equivalent relays are very common from multiple manufacturers (TE, Omron, Panasonic, etc.) and suppliers.

The time delay is set by R5 and C3, with some additional delay created by C2. With the values shown, the delay is about 300ms. Q2 is essential. When the voltage across the relay starts to increase (as Q1 turns on), Q2 also turns on with a regenerative action (positive feedback). This ensures that the relay is turned on very quickly, which gives much greater certainty that it will activate reliably. The suggested (and recommended in P39) time delay is around 100ms, but this circuit is limited to a minimum of about 250ms.

The timing can be changed by varying the value of R5. Mostly, it should be about right as shown, but you can increase the time delay if you wish. It should *not* be reduced to anything less than 250ms, as there may not be enough charge in C1 to ensure that the relay activates reliably. I've run extensive tests for switching, and a 100µF capacitor will turn on even the most robust relay, but *only* when the switching speed is fast enough.

It is possible to do away with the MOSFET and most of the other parts, but then you have a very poor circuit indeed. You need a much larger capacitor for C2, and that creates the time delay. The timing is anything but precise, and it takes a lot longer for the circuit to reset after power is disconnected. Many of the 'alternative' circuits you may come across rely solely on the filter cap and a slowly increasing relay voltage to bypass the ballast resistor. These circuits need much more current, and provide no means to achieve both 'snap' action plus the relay power reduction that this circuit provides.

Unfortunately, it's more difficult to ensure that the relay releases (very) quickly after power is turned off by Sw1. The release time is likely to be quite acceptable in normal use, and the additional complexity is not warranted. There is a good reason to have fairly fast recovery though. If power is turned off and back on again quickly, the soft start won't operate and this may cause a blown fuse. With this design, it will drop out (and the timer will reset) in under 300ms after power-off. This is only a little slower than the P39 unit.

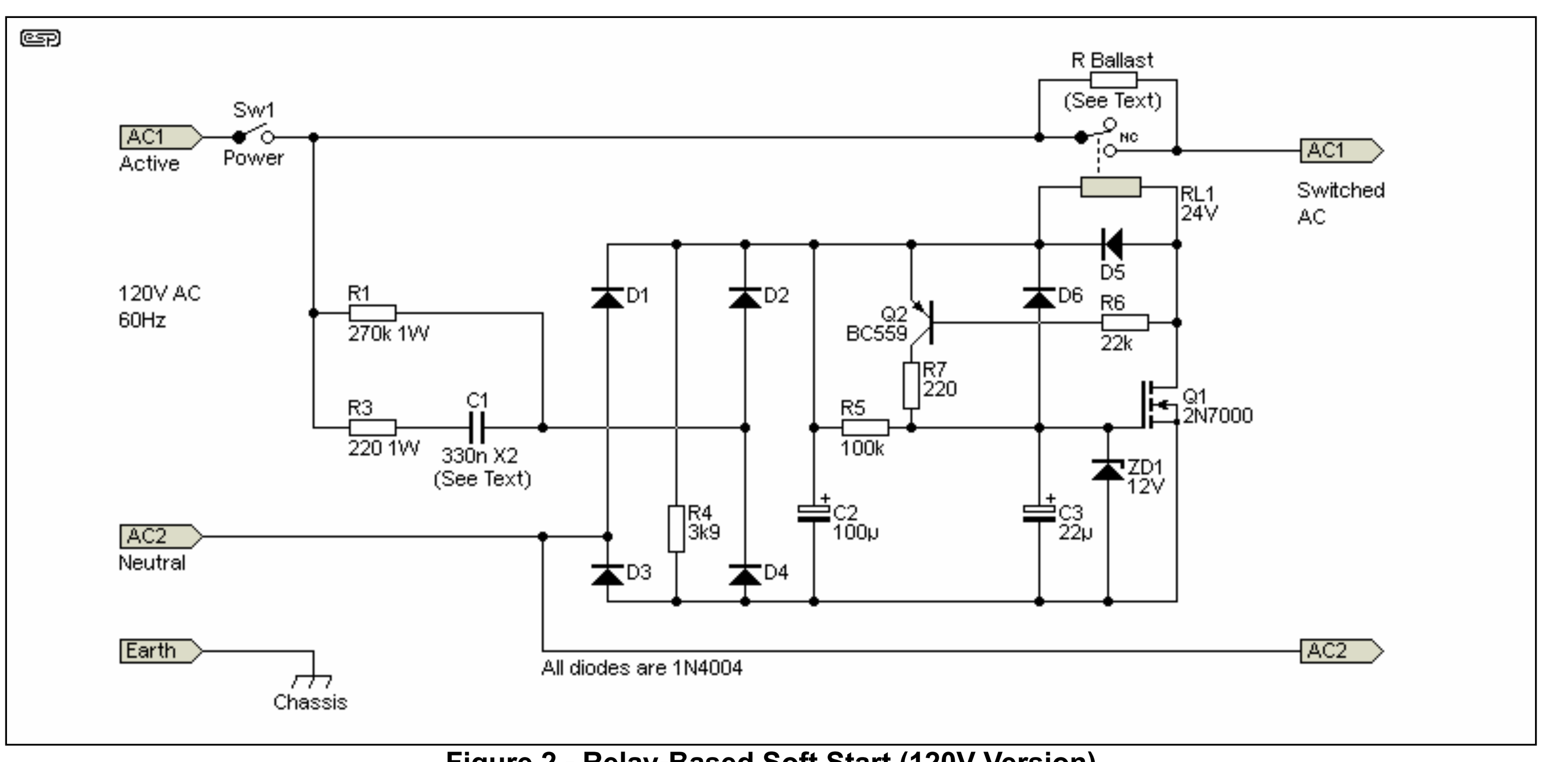

Figure 2 - Relay-Based Soft Start (120V Version)

There's not much difference between the two versions. R2 isn't necessary, and C1 is increased to 330nF. Everything else stays the same, since the changes don't affect the low voltage DC provided for the relay. Ideally, C1 would be 390nF, but Class-X2 caps are only available within limited values from most suppliers. If you can get a 330nF X2 cap, that's what I'd use for 120V, 60Hz. The supply current is 1mA less than you'd get with 390nF, but that's of no consequence. If you can't get a 330nF or 390nF X2 cap, you can use 470nF. The current is higher, so I suggest that R4 be reduced to 1.8k.

Ballast Resistor

When power is applied, the mains transformer is powered via the ballast resistor(s), with a value of around 50Ω being about right for 230V, and 23Ω for 120V. My suggestion is to use 3 x 150Ω 5W resistors in parallel for 230V, and 3 x 68Ω 5W resistors in parallel (22.6Ω) for 120V. These values have proven to be very reliable, with many hundreds of P39 boards having been built. The majority have used my suggested values, and I've yet to hear of a failure.

You can use NTC thermistors, with a pair of 20Ω types being fine for 230V operation, or a pair of 10Ω types for 120V. These *must* be rated for the peak current, and there's a lot of other useful info in the Project 39 article. The requirements are identical, regardless of the drive circuit used.

Like the original project, I suggest a relay as the switching device. A TRIAC can be used, but it will almost always need a heatsink (TRIACs dissipate power in operation, approximately 1.5W/ Amp), and that makes everything harder due to the safety requirements. Even providing insulation between a TRIAC and a heatsink is irksome. You can use a silicone pad, but you can't use a metal screw to hold the TRIAC down because the creepage and clearance distances are too small. Creepage is the distance across an insulating surface, and clearance is the physical distance between conductive connections (e.g. between device pins and the heatsink). Use of a 'hot' (live) heatsink is discouraged, as it's very dangerous with mains voltages applied.

While I could easily include a TRIAC based switch here, I don't intend to do so due to the inherent risks involved. TRIACs can also have problems with the transformer's current waveform, and because they are an electronic switching component, they can also generate electrical noise. Coupled with the inherent danger of having a heatsink, IMO using a TRIAC simply isn't worth the trouble. You could use a dedicated TRIAC SSR which will generally alleviate mounting and heatsinking issues, but if it's used with the circuit shown here, all the other components are live anyway.

Conclusions

This is not intended as a replacement for the P39 soft start circuit, and PCBs will not be made available. It's shown here purely in the interests of showing how it can be done, and it's not meant to imply that it's a good idea. Because everything is at mains potential, if built, it should be in its own plastic enclosure, with ventilation for the resistors or thermistors. The reset time is longer than I'd like (around 250ms, which is much longer than the Project 39 circuit).

Naturally, everything about the circuit's operation can be improved, but at the expense of greater complexity. Since this isn't a circuit I recommend that anyone should build, making it more complex would be (IMO) a waste of my time. However, the principles as described have been simulated, and bench-tested, so I know it will do exactly what's claimed for it. Id does have one advantage over the P39 circuit, in that it doesn't need a transformer because of the 'off line' capacitor-fed supply. However, it can't be switched remotely, and the supply voltage cannot (and *must not*) be used for anything else.

However, it's handy to know that it can be done well, with comparatively simple circuitry. It's even alright to build it on Veroboard, with the *absolute exception* of C1, R1, R2 (if used) and R3. Veroboard cannot withstand mains voltages safely, so these parts have to be mounted 'off-board', but in a way that they can't move or short out under any conditions. You can use a terminal block to mount and connect these parts, and I leave the details to the constructor.

I also ran some tests, but using a 12V relay (I didn't have a 24V version handy). The relay remained closed with only 3.4V across it, well below the voltage that will be available when a 24V relay was used. The test was run using a 470nF X2 cap and 120V input. Relay activation was positive every time, even when operated once each second (or thereabouts). With the combined results from simulations and bench testing, it's very doubtful that anyone will find the circuit lacking in any way. A 470nF X2 cap can also be used with 230V, but I'd strongly recommend that R4 be replaced with a 30V zener diode (or 2 x 15V zeners in series if you have them to hand), otherwise there's nothing to stop the voltage rising too high before the timeout. The resistor (R4) could be reduced, but that's less than ideal when you have more current available.

This project is intended more as a learning exercise than something you should build. There's a great deal of scope for experimentation (such as using a 48V relay for even lower power dissipation), but I leave this as an exercise for the reader. Quite a few values will need to be changed, and you must ensure that Q1 and Q2 are rated for the maximum voltage you obtain. In short, the circuit topology is very flexible, it provides true 'snap-action' for the relay, and doesn't rely on the voltage at which the relay chooses to close. I still don't recommend it of course.

References

There are no references, since the basic principles have already been described in Project 39, and this design uses circuit ideas that you won't find elsewhere.

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