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An Automatic Mains Voltage Switch Protector for Domestic Appliances

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Abstract

Electronic and electrical appliances used in most homes in the country are designed to operate at a nominal 230 V AC, which ought to be acceptable within certain tolerable upper and lower limits. Excessive fluctuations beyond these limits may cause the appliance to malfunction or get irreparably damaged. Most protective devices are imported as well as expensive. The circuit presented is a relatively cheap automatic mains voltage switch (AVS) protector that senses undesirable and harmful fluctuations in mains voltages and disconnects the appliance whenever the mains voltage supply goes above or below pre-settable and safe tolerable limits or 'window'. The appliance is automatically reconnected when mains power returns to normal within that 'window'. The design features anti-surge protection, a transformerless power supply for the circuitry, a window comparator for the detection of low and excessively high mains voltages to the load and a switching relay capable of switching high currents, ideal for compressor-based appliances. A delay section for control of spurious low voltage drops as well as mains stability is incorporated. The design provides a safe operating voltage range of 180V to 250V and offers practically the same functions as those of the imported brands. Basically, the design consists of various circuit building blocks and circuit techniques that would be of interest to the electronic hobbyist.

Keywords: transients, surge, over-voltage, window comparator, monostable, transformerless power supply.

INTRODUCTION

Mains electricity supply in Nigeria is anything but smooth and stable. Electrical and sensitive electronic equipment are not immune from noisy and detrimental mains power supply. Voltage surges, spikes and transients in excess of kilovolts and hundreds of amperes in very short duration of microseconds, (Fig. 1), power outages, brownouts, mains under- and over-voltage conditions can cause unprotected appliances either in the home or office to malfunction. A huge number of domestic and industrial appliances have sustained irreparable damage as a result of either excessively high (>280 V), low (<160 V) or unstable and noisy fluctuating mains supplies. Typical casualties in the homes are TV sets, computers, video players, refrigerators, Hi-Fi, air conditioners, and other sensitive electrical/electronic consumer products. The epileptic nature of the electricity supply can be attributed to the failure of the power company to cope with the rising electrical energy demands and its inability to modernise existing and deteriorating infrastructure. Moreover, as in some cases, high frequency interference or improper earthing have been found to also contribute to unstable power supply. Heavily populated areas or communities close to industrial layouts are prone to brownouts, which are short duration sags in power lines causing poor equipment performance. Overhead power lines exposed to natural or climatic disturbances, like lightning, have voltage spikes induced on them, which result in power surges as well (Waddington, 1993). One of the ways by which domestic appliances are protected in the country is the use of automatic voltage stabilizers. The equipment regulates the mains voltage input by tap changing relays connected to transformer windings with a voltage range between 170 – 300 V. As the sensed line voltage increases, the relays tap-change to a lower winding, and vice versa, thus maintaining a relatively constant output voltage. A two-horsepower air-conditioner with perhaps other lighter loads will require at least a 5 KVA voltage stabilizer to be able to work conveniently. The cost of this size and rating of stabilizer is in most cases unaffordable and quite often these are not invulnerable to surge themselves.

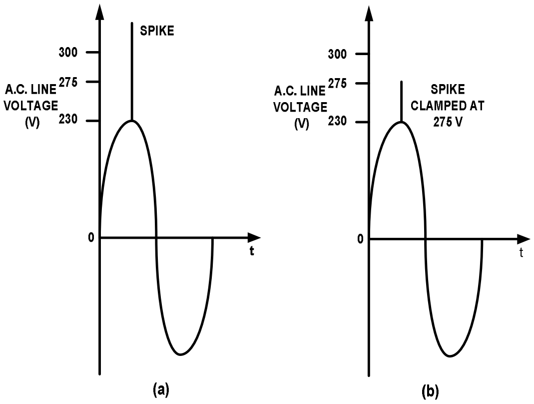

Fig. 1. Line voltages (a) spike (b) clamped spike

The voltage switch device presented is not able to supply continuous AC power to the load, as it disconnects the mains supply as soon as it detects an irregular voltage; all the same it monitors the ac line voltage continuously, thereby protecting the appliance from damage from the dangerous mains supply. It is also cheaper to produce and the components are readily available.

BRANDS

Numerous brands of similar concept of this type of device have since flooded the market and from study, most of them comprise of some variety of mains filter designs, high/low voltage detection and load switching arrangements. Popular imported brand names sold in commercial quantities are the Sollatek series of AVS 13 Voltshield, AVS 15/30 Micro, and AVS3P-0, the Lanborg S-1103, the Binatone IVP-115 and the Supermaster. The Akai DAVS-30A and the Novatek PH-02 Volt Control both have a.c. digital display. The Fridgeguard product consists of just an op amp comparator and a couple of transistors for delay and relay switching. Latest market developments reveal the use of PIC microcontrollers by some trademark names for a more efficient and compact product. Some products use triacs rather than contact relays. Some designs use small step down transformers (230 V primary to 0-24 V secondary) to power the whole circuit (Louis, 2002). This project features a transformerless power supply similar in principle to those used by the brand names mentioned above. It is a simple, locally designed prototype voltage switch that can be constructed by the electronics hobbyist. The design uses an op amp configured as a window detector and a dedicated monostable IC for time delay and control. It also incorporates a varistor anti-surge protector and a load switching section. From an academic perspective, it consists of different building blocks and circuit techniques that might be useful for a hobbyist in understanding basic electronic principles. From a budgetary viewpoint, the components are cheap and easily obtainable.

PRINCIPLE

Essentially, the simplest principle of operation is for the circuit to detect when the mains voltage applied to an equipment shoots above or below pre-settable threshold points, i.e. >250 V for ‘HIGH’ and <180 V for ‘LOW’. When these tolerance thresholds are crossed and the voltage goes outside of this window, the circuit triggers a monostable circuit which in turn switches off a relay, thus disconnecting power to the appliance. It then ‘waits’ or goes on ‘stand-by’ until the mains normalises, i.e. returns to between (180 + hysteresis) to (250 – hysteresis) before reconnecting mains power to the appliance. The hysteresis is a few volts above or below the cut-off voltages to avoid retriggering if switch-on voltage is close to threshold voltage. Sollatek (1996) preset their under-voltage disconnect at about 185 V and allow a 7 V hysteresis for it to switch back on (185+7 = 192 V), with a wait time of 15 seconds to 3 minutes, while their over-voltage disconnect is fixed at 260 V and a 7 V hysteresis. By adjusting a potentiometer, a start-up delay or wait time can be set from a few seconds to about five minutes. It has been observed that at times, in densely populated urban areas or industrial layouts, when the mains voltage is as low as 185 V and the switcher has disconnected at this threshold, inductive loads such as heavy motors used for grinding grains, or large mains transformers and even fluorescent lights switched on, usually cause a momentary drop in supply voltage from 185 V to about 175 V. As the voltage normalises, the voltage switcher, whose timer at some point would have timed out and on its way to switching on the relay to connect the appliance, will sense this undesirable brief drop and again immediately switch off. This behaviour resembling false triggering is undesirable for the equipment. This design incorporates a re-triggerable monostable as a form of delay to accommodate the short-lived voltage drop in mains supply. The circuit is not galvanically isolated from the mains. There is the possibility active live and neutral lines may be interchanged, so extreme caution is required when testing or troubleshooting and safety standards regarding mains electricity should be strictly adhered to.

CIRCUIT DESCRIPTION

Figure 2 shows a block diagram of the circuit. The circuit comprises the following main sections: power supply (line filter/spike suppressor, step down capacitor, bridge rectifier and zener diode regulator), a window comparator, OR gates, a retriggerable monostable and a load switching section

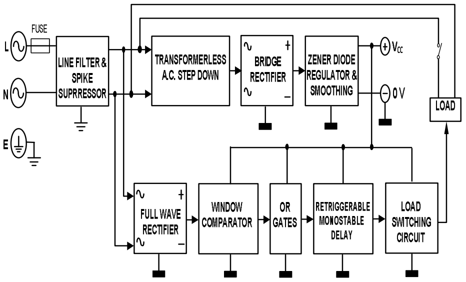

Fig. 2. Schematic block diagram of the circuit

POWER SUPPLY

Transient Attenuation

Capacitors C1, C2 and C3 constitute a Delta network to provide noise filtering as well as suppressing interference. The Metal Oxide Varistor, or MOV doubles as over-voltage clamp and surge protector. It also protects the drop down capacitor C4 from damage if the line voltage goes above its rated voltage. Varistors are frequently used as transient suppressors in surge protection devices to protect equipment from inductive load or capacitor bank switching (Littelfuse, 2013). Ordinarily, a MOV has a Maximum Continuous Operating Voltage (MCOV), however if the a.c. line voltage exceeds this maximum, the MOV then clamps the surge to a safe level, provided its maximum a.c. rms rating is not exceeded. The MOV typically exhibits a rectifying action (Beneden, 2003), forming a low ohmic path to absorb surge energy when it conducts. Its impedance, which is normally high, drops to a low value when a momentary spike goes above the clamp voltage. The surplus energy generated is released as heat, resulting in a blown fuse, F1. Clamp voltage ratings of about 20% higher than the 230 V a.c. are usually chosen and the preferred choice in this work was a 275 V a.c. rating.

Current and Impedance

The 230 V a.c. is dropped to about 20 V a.c. by the capacitive reactance of the capacitor C4 which also acts as a current limiter. By using a capacitor instead of a power resistor to drop the voltage, power dissipation is minimal. C4 is a 1.0 µF 'X2' type rated at 400 V for mains voltage applications such as interference suppression. The transformerless power supply is not isolated from the mains and can only supply small currents. The value of C4 therefore determines the amount of maximum supply current. R1 functions as an in-rush current limiter while R2 serves to discharge the capacitor so there is no hazardous residual charge present when mains power has been disconnected. Current supply to the semiconductor devices of the circuit is derived via C4 to the bridge rectifier, a WO1 rating. At 50Hz and using 1.0 µF, the impedance of C4 is:

$$X_C = \frac{1}{2\pi f C_4} = 3183.1\Omega \qquad (1)$$

Therefore, expected current supply to the rest of the circuit will be

$$I = \frac{V}{X_{C4}} = 72mA \qquad (2)$$

Regulation

Full wave rectification of the a.c. voltage is achieved via the bridge rectifier. Regulation is provided by the 1N5355B, 18 V, 5 W, Zener diode. 18 V is chosen in order to leave enough headroom so that when the low impedance relay is energised, the voltage drop to 10 V as a consequence is still adequate to supply sufficient current to the ICs. At 10 V supply, the ICs can still work well. A relay of higher resistance may be used but the contacts may be rated less than 30 A. C5 decouples the positive supply rail and provides the necessary filtering. R4, C7 and C8 provide further smoothing. R3 is chosen using

$$R_3 = \frac{V_{IN} - V_Z}{I_Z} \qquad (3)$$

Where V_{IN} = 20 V, V_Z = 18 V. If a maximum of 100 mA Zener diode current, I_Z is allowed, then, $R_3 = 20\ \Omega$. The closest available value is 22 Ω.

WINDOW COMPARATOR

Diodes D1, D2, smoothing capacitors C9, C10 produce a separate ripple free supply for the under/over voltage section. This sampled voltage serves as the input of the window comparator. Referring to Figs. 3 and 4, the window comparator circuit comprises the LM393 dual op-amp IC containing two independent precision voltage comparators, a fixed reference, VREF, two 'pots' for HI and LO adjustments and two 1N4148 diodes constituting OR gates.

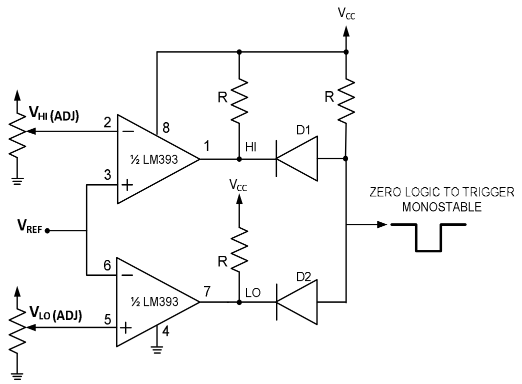

Fig. 3. Circuit diagram of the window comparator. (Source: Advanced Linear Devices, 2005)

The two outputs of the LM393 are open collector so resistances R in Fig. 3 or R13 and R14 in Fig. 4 serve as pull-up resistors for these outputs. VREF is derived from a 5 V, 400 mW zener diode. The comparator compares VHI, VLO input voltage signals to VREF and outputs logic HIGH level if the voltage is within the two thresholds or LOW if it is outside. When the input goes higher than the preset VHI, thus going outside the window, op-amp IC1a goes low, red LED1 lights. Similarly, when the input voltage goes lower than VLO, the op-amp IC1b also goes low and the second red LED2 lights. Either LED lighting implies zero logic required to trigger the monostable IC at its pin5. The 1N4148 diodes, D3, D4 are operated as OR gates and inserted to isolate the outputs of both op-amps from each other. At power on and assuming mains voltage is normal and within the window area, then both outputs of the LM393 remain in a HIGH logic state.

Hysteresis

Occasions do arise when both inputs of the comparator have almost equal voltages, especially when mains is normalising such that for example, VIN is close to VREF, the output will tend to oscillate and cause the relay to chatter. In order to prevent the chattering, a feedback resistor is connected between the output and the inverting input to form a hysteresis. The purpose is to shift the threshold down when the input is higher than the threshold and up when the input is below the threshold level (Horowitz and Hill, 1985). This then causes the comparator to change its output state smoothly without the chattering effect.

Retriggerable Monostatble

IC2, 4538B is a dual (A and B sections) precision retriggerable-resettable monostable mulivibrator but only one half section, A, was utilized independently. It is more reliable than the IC 555 or NAND gate monostable and not susceptible to false triggering. The monostable can be triggered or retriggered by either a rising or falling edge at pins 4 or 5 respectively. The two outputs pins 6 and 7 have complementary logic states Q_A and $\bar{Q}_A$ respectively (Phillips Semiconductors, 1995). A zero logic input at pin 5 triggers Q_A output high for time duration depending on the timing components R16, VR3 and C14, i.e. $T = (R16 + VR3) * C14$. The emitter of the PNP transistor, BC557 is connected to the RCTC pin2 of the A section of the monostable IC so that a fresh monostable pulse can be initiated before any ongoing pulse has been completed. RCTC pin connects the external timing components. The timing capacitor C14 is discharged each time the input pin 5 sees a low trigger pulse so that the output pulse can be made longer.

(iii) Switch-on delay/standby flasher/relay switch

IC3a-d is a quad 2-input NAND Schmitt trigger IC and three of its gates are arranged to perform several roles in this circuit. At switch on and with mains voltage normal, then pin 5 of the monostable, IC2 (point A) receives a logic high input and at the same time it will be timing out. Its output at pin 6, Q_A, (point B) is high while its complement $\bar{Q}_A$ appears at pin 7 which is unused. This logic high from Q_A is used to initiate a standby ('wait') mode by switching on IC3b, a gated oscillator via its pin 5, providing a flashing standby mode when enabled. Yellow LED3 will begin flashing. Flashing rate is determined by the values of R18 and C15. At the same instance the output of gate IC3a (point C), is inverted to logic 0 so that the anode of D5 is LOW. Simultaneously also, from the initial power on, the supply voltage (Vcc) appearing across C16 begins to charge this capacitor via R20 at the input pins 12 & 13 of gate IC3c. Here, the voltage is decreasing from high to low and its output pin 11 (point D) is low at first. Both anodes of D5 and D6 (point E), are held low causing PNP transistor Q2 to conduct, switching Q3 on at point F. The collector of Q3 (point G) is then grounded so that Q4 is kept in the off state. Thus, the switching relay is held de-energised and the appliance remains disconnected from the mains. Green LED4 remains off. The function of gate IC3c and associated components is to keep the relay from triggering on as a result of spurious voltage when the device is first powered on. After several seconds determined by $t = C16 \, x \, R20$, output pin 11 of gate IC3c flips high but because pin 3 of IC3a is now low, Q4 by virtue of the states of Q2 and Q3 remains off and so is the relay. As soon as pin 2 of IC2 charges up via C14, the charging rate being determined by its value in combination with those of R16, VR3, Q_A output flips low to make gate IC3a output pin 3 change state to a logic high level. Both anodes of D14 and D16 are now held high. This logic level then switches off Q2 and Q3. Current now flows via R26 into Q4 base forward biasing it to switch it on. This in turn energises the relay.

If the comparator were now to detect inputs overshooting VHI, or sagging below VLO, its output will go low and trigger the monostable output into a high state at the same time initiating a standby mode, with LED3 flashing. Meanwhile, Q4 base is robbed of bias voltage and switched off via Q2 and Q3. The equipment remains disconnected until the comparator senses normal mains voltage determined by the presets VHI (ADJ) and VLO (ADJ).

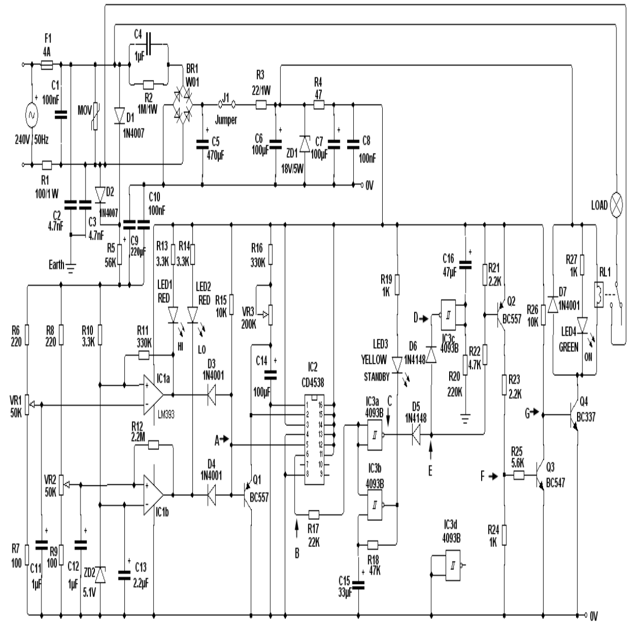

Fig. 4. Complete circuit schematic of the AVS

Table 1. Logic states

	CONDITIONS	A	B	C	D	E	F	G	OUTPUT
1	Switch On: 1 St 5 Sec.; C16 Charging Thru R20; Mains Normal	Hi	Hi	Lo	Lo	Lo	Hi	Lo	LED1 & LED2 Off; LED3 Flashing; LED4 & Relay Off; Appliance Disconnected
2	C16 Charged After 5 Sec.	Hi	Hi	Lo	Hi	Lo	Hi	Lo	Same As Above
3	Monostable Time Out	Hi	Lo	Hi	Hi	Hi	Lo	Hi	LED3 Flashing Stops; LED4 & Relay On; Appliance Connected
4	Mains Outside Window Threshold	Lo	Hi	Lo	Hi	Lo	Hi	Lo	Either LED1 or LED2 On;LED3 Flashing; LED4 & Relay Off ; Appliance Disconnected

A prototype of the project was constructed on a printed circuit board of size 8.5 cm x 9 cm, shown in the photo in Fig. 5.

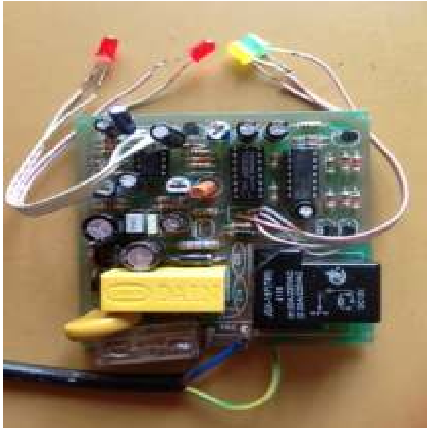

Fig. 5. Photo of the assembled AVS

SETTING UP

A variac is required for the setting up of the circuit. Set the circuit of the variac to 220V a.c. and switch it off from the mains. Next, connect the output of the variac to the mains input of the circuit. Before switching it on, remove the jumper link, J1. Now switch on the mains. Caution should be exercised here, as the circuit is not isolated from the mains. Measure the d.c. voltage at the positive end of the bridge rectifier. A reading of approximately 20 V should be read from a digital multimeter. Switch off the mains and allow C4 to discharge. Now link the jumper J1 and switch on the mains. LED2 should blink briefly as the voltage rises past the low voltage threshold. The dc voltage at the cathode of ZD1 should read 18 V. Wait until the green LED4 turns on and the relay clicks. Vary the output of the variac to 250 V and adjust VR1 slowly until LED1 illuminates and LED4 goes off. This will be the preset point for the over-voltage level. Now reduce the variac voltage to a point such that LED1 goes off. Allow the circuit to time out so that relay turns on and LED4 comes on. Now reduce the variac to 180 V and adjust VR2 slowly until LED2 illuminates. This will be the preset point for the under-voltage level. Lastly, vary the variac to a point between 190 V and 250 V, say 220 V. LED1 and LED2 should be off. LED3 will be flashing. After about 3minutes, depending on the setting of VR3, LED3 will cease flashing and LED4 will switch on at the same time the relay is switched on. During one of our tests, an over-voltage trip point was set at 250 V and a load connect point of 240 V, giving a hysteresis of 10 V. The under-voltage trip point was set at 187 V and a load connect point at 196 V, a hysteresis of 9 V. The relay is a JQX-15F 12 V DC with contacts are rated at 30 A, 220 V AC, adequate for heavy domestic appliances.

CONCLUSION

The circuit incorporates features such as cutting off the load on sensing under or over- voltage conditions of the mains supply to the load and delayed switching. The responses of circuit are slightly slow as a result of the timing of the make and break contacts of the mechanical relay and also because of the charge and discharge times of the capacitors. For faster switching, the circuit can be modified for a solid state relay, i.e., a power triac to replace the electro-mechanical relay. The triac would be driven by an optocoupler. Modifications will include RC snubber network across the triac to protect it from transients and to improve switching efficiency. Convenient standby periods can be obtained by varying VR3 to suit the needs of the load. For areas where the mains is very erratic, a 5-minute delay is ideal for compressor-based appliances. A follow up design will utilize a single PIC microcontroller to implement the functions of the comparator, monostable, standby and load switching sections.

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