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Inrush Current Limitation

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Abstract

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This thesis work was carried out for Nexess, a French company specialized in asset tracking using RFID technology and smart cabinets. The project went through the process of designing an inrush current limiter prototype, in order to add this functionality to one of the company's products, the XL cabinet, which was developed by the company to make real time inventories of different kind of tools and assets.

The limiter device was intended to be implemented in the Nexess' XL hardware line and to have the ability to be adaptable into the existing hardware. Ultimately, the limiter will allow their customers to connect more equipment at the same time and more safely to the 230V sockets inside the equipment.

This thesis was divided into four parts. In the first part, the project focused on bibliographic research and described the different inrush current limiting topologies available on the market. The second part involved inrush current measurements and search for correlation between inrush current and the phase of the signal, this included the realization of a phase control circuit as well as the simulation of the circuit.

The third part concentrated on defining the limits of the system and testing the first prototype previously developed by Nexess.

The last part of this thesis work contained confidential informations which were exclusive to Nexess, thus for privacy reasons it was not allowed to publish all the content of this part. It was focused on the realisation of a new version of the inrush current limiter prototype. Simulations of the different circuits were done in Simetrix and LT Spice software, and the schematics and PCB layout were completed in Altium designer.

As result, this project was a success, and the company expects to introduce the inrush current limiter into Nexess' line of equipment after following qualifications.

Keywords: Inrush Current Limiter, Soft-start, Bypass Circuit, NTC

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List of Abbreviations

A: Amperes

AC: Alternative Current

Back emf: Back electro-motive force

BOM: Bill of Material

DC: Direct Current

DMM: Digital Multimeter

ESR: Equivalent Series Resistance

EMF: Electro Magnetic Field

Hz: Hertz

IC: Inrush Current

ICL: Inrush Current Limiter

In: Nominal Intensity

IOT: Internet of Things

kW: Kilo Watt

LED: Light Emitting Diode

MCU: Micro-Controller Unit

mA: Milli Amperes

ms: Milli Seconds

mV: Milli Volts

mW : Milli Watts

Mosfet: Metal oxide Semiconductor Field Effect Transistor

NO: Normally Open

NC: Normally Close

NTC: Negative Temperature Coefficient

PTC: Positive temperature Coefficient

Req: Equivalent Resistance

RMS: Root Mean Square

s : Seconds

SCR: Silicon controlled Rectifier or Thyristor

SMPS: Switch Mode Power Supply

SSR: Solid State Relay

TRIAC: Triode for Alternative Current

μ s: Micro Seconds

V: Volts

Vgs: Gate Source Voltage

$V_{gs(th)}$: Gate Source Threshold Voltage

V_{pp} : Peak to Peak Voltage

V_{ref} : Reference Voltage

W: Watt

1 Introduction

The purpose of this thesis study was to find a solution to limit the inrush current on power up of the XL cabinet (Appendix 1 shows a picture of this equipment).

The XL cabinet is one of the flagship products that Nexess has developed and commercialized along the years, it is based on UHF RFID technology and allows an automatic real time inventory of different type of tools and equipment. This cabinet also includes four inner sockets to ensure the charging of equipment (power tools, tablets, computers, etc.)

While the equipment is in charge, the radiated emissions from the chargers disturb the RFID measurements, so these sockets are cut via a relay during inventories. The only way would be to enclose the chargers in a shield, which is not acceptable from a user point of view. However, these cuts in the power supply to the sockets lead to inrush currents on power-up. The problem is that these inrush currents activate the circuit breaker (8A / 220V) inside the equipment and therefore limit the charging capacity of the products. Nexess had previously studied a solution to smooth inrush currents based on an NTC, but the project has not been finalized, however a first prototype was developed and was available.

The goal of this thesis is to propose one or more topologies as a solution, respecting the requirements for industrial equipment. Following this, a decision will be taken on whether to continue with the work already started or to develop a new solution.

2 Nexess

NEXESS is a French company founded in 2008 and located in Sophia Antipolis. They offer solutions for traceability and identification of tools by using RFID (Radio Frequency Identification) technology. With 20 years of expertise in energy industry, and more than 200 IOT (Internet of Things) solutions deployed on 80 sites, the company is leader of connected objects in the industry and offers RFID solutions for the supply chain, manufacturing, maintenance, and operations in areas such as Energy, Aeronautic, Oil and Gas and Aerospace industries.

Over the years, NEXESS has designed and developed a wide range of smart equipment solutions for the storage and inventory of different kind of material. Among their most important products, NEXESS has created a full range of smart RFID cabinets such as the XL cabinet, the XL cabinet Weight, the Roller cabinet X-Draw, the XS cabinet, etc. These cabinets help to make an automatic inventory of the tools / equipment and automate the geolocation, movement and management of connected objects present in the workspace. Thereby, this allows the companies to manage their material in a smarter, more efficient way, reducing costs, while increasing the work safety and productivity.

Alongside their range of smart RFID cabinets, NEXESS has also developed a smart RFID counter and an RFID portal, mobile devices, as well as applications such as NexCap MAT (Mobile Assets Tracking) which are used for equipment monitoring and management.

NEXESS has a staff of around 40 employees, who are working on three different sites in France: Sophia Antipolis, Toulouse, and Paris.

3 Inrush Current

Every time an electrical equipment is powered on (switch mode power supplies (SMPS), transformers, motors, inverters, chargers, etc.), this generates a high amplitude instantaneous current peak that usually lasts a few milliseconds before the current stabilizes at steady state and remain constant.

This peak is called inrush current and can potentially damage certain components in a circuit. For example, it can damage the DC link or smoothing capacitors or semiconductor devices which are in the current path when the circuit is energized. The amplitude of the inrush current can be equal to ten or twenty times (sometimes even more depending on the application) the amplitude of the steady state current when the equipment is in stable mode.

Although the magnitude of the inrush current is important, since it occurs only during a very short time (in the order of milliseconds or microseconds), it is not possible to notice it without the use of a measuring device.

Figure 1 illustrates the difference in amplitude between the steady state current and the inrush current. In this case the inrush current amplitude is approximately 12 times the amplitude of the steady state current. [1;2.]

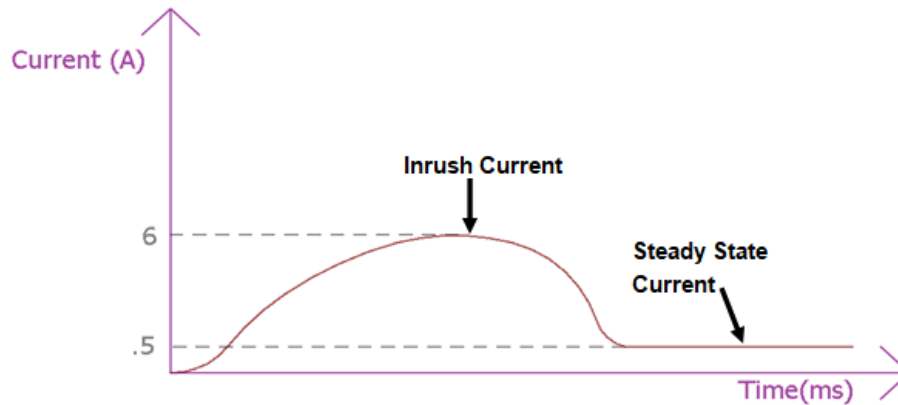


Figure 1. Inrush current vs steady state current amplitudes comparison [2].

Broadly speaking, in SMPS inrush current are mainly due to the charging of the filter or DC link capacitor, which act like a short circuit (low impedance) when the device is first powered on. When the AC line is turned on, the inrush current is only limited by the Equivalent Series resistance (ESR) of the connected circuit and the resistance of the mains wiring, which leads the generation of the current spike. [3.] For transformers and motors applications, IC is caused by the charging of inductors, at start-up, the back EMF is very weak, so there is not much resistance for the current to flow (apart from resistance of the windings), which causes a high inrush current into the inductor.

It should also be noticed that high IC can damage circuit components that are in its path in the circuit (e.g., stress capacitors and input bridge rectifiers, damage link capacitor, contacts in relays and switches, can destroy rectifiers, fuses, or semiconductor devices, etc., and is a common cause for circuit breaker failure and tripping. [1.] Thermal stress caused by the IC reduces the lifetime and is the cause of failure of solid-state switching devices [5].

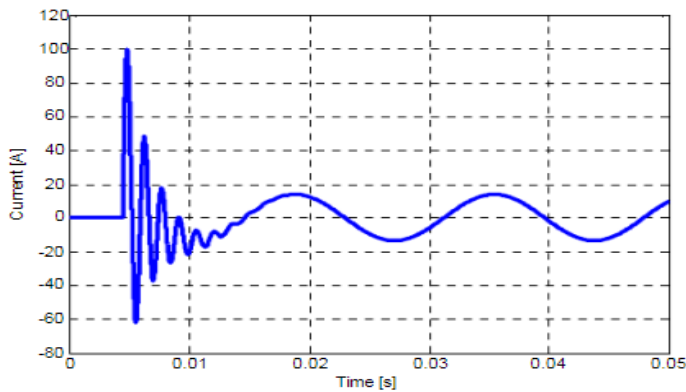


Figure 2. IC caused by a capacitive load [5]

Figure 2 shows an example of IC when a mainly capacitive load is connected to the grid, the amplitude of the IC is related to the capacitance of the load and to the moment when the load is connected to the grid voltage during start-up. For example, in the case of a capacitive load and an AC voltage, the IC magnitude is higher if the load is connected to the grid when the voltage is not at the zero-crossing point [5]. On the other hand, IC magnitude in iron core transformers is at its highest value at the zero-crossing point of the AC waveform [10].

Different Active or passive Inrush Current Limiting circuit solutions are available on the market. These solutions mainly use the principle of introducing a high impedance load into the circuit during the electrical device start-up.

3.1 Inrush Current Measurement (sense/shunt resistor, clamp)

The easiest way to measure inrush current is with a dedicated current clamp (connected or not to an oscilloscope depending on the clamp model), another way is to use a sense or shunt resistor and measure the voltage across it.

Figure 3 shows typical way of measuring inrush with a sense resistor, the oscilloscope is used in differential mode in this case (differential probe).

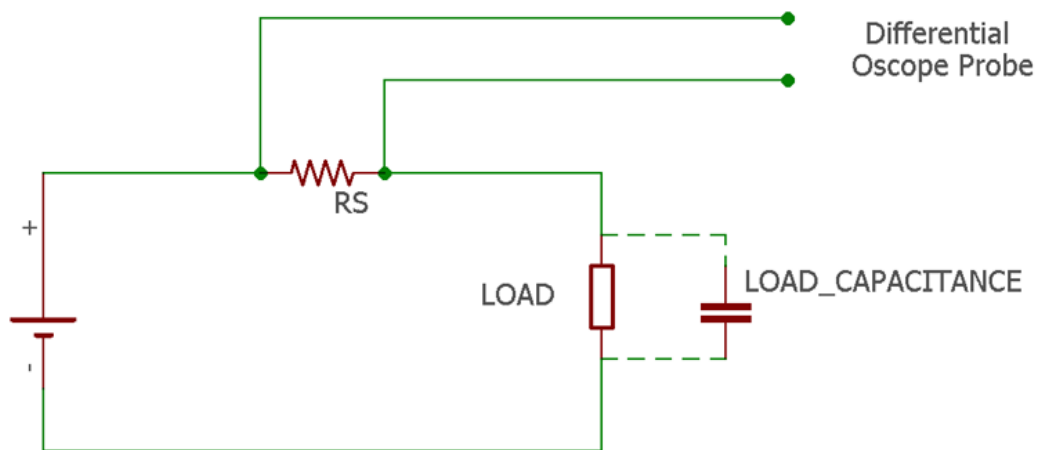


Figure 3. Inrush current measurement with shunt resistor [2]

4 Different Methods / Topologies for Limiting Inrush Currents

In this thesis, we will focus on ICL topologies to limit inrush current generated in AC mains. The circuit breaker inside the XL cabinet controls four 230 V AC power outlets, which are used to connect different kind of electrical appliances (tablets, chargers, etc.). Thus, we cannot act on the current limitation of the DC circuits of the connected equipment.

Nexess customers usually connect portable power equipment, such as drill chargers, tablets, etc. which can eventually include their own inrush current limiters circuits depending on the quality of their design.

However, it is worth noting that many ICL topologies made for DC circuit exist and are used in many electrical appliances.

4.1 Passive Inrush Current Limitation Methods

Passive ICL solutions are used for applications requiring low power rating and for simplicity of design, they are usually recommended for power ratings below around 500 W for power losses reasons [4].

4.1.1 Resistor Current limiting

The simplest way of limiting current in a circuit is simply to put a series resistor with the AC line. This approach was more common in the past, but it is still used for low-cost or small power supplies with low power ratings but it is not a good solution for higher power ratings. [4.] It is not a very efficient method as the resistor will dissipate power (which cause power losses) as it is always active in the circuit [6]. This approach can be seen in Figure 4.

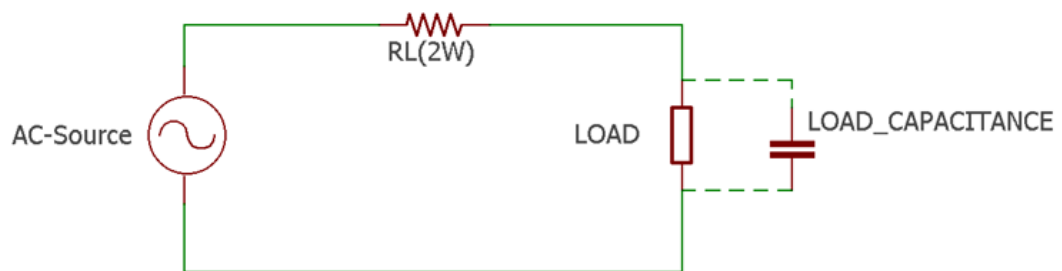


Figure 4. Inrush current limiting with a resistor [2].

Advantages and drawbacks are listed below.

Advantages:

- Cost effective compared to thermistors
- Very Simple circuit
- Current limitation is not dependent on the temperature
- Generates less heat than an NTC

Drawbacks:

- Power losses are important
- Only for low power rating supplies

4.1.2 NTC Current limiting

NTC current limiting is a standard approach for passive ICL, and is widely used in SMPS. It uses a thermistor such as an NTC (Negative temperature coefficient) in series with the AC mains, as shown in Figure 5.

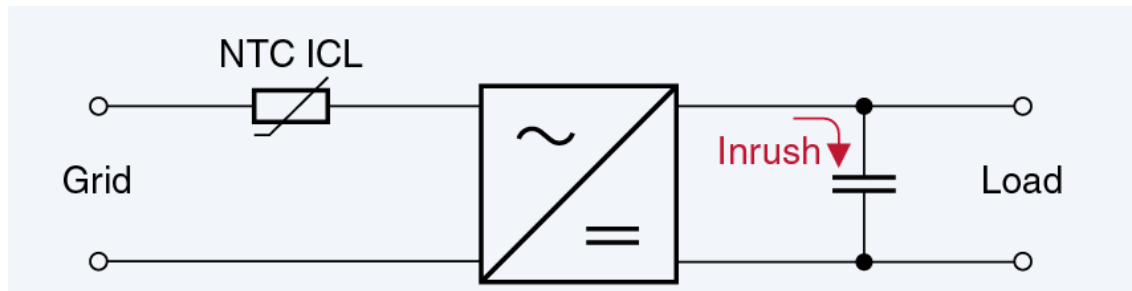


Figure 5. NTC ICL in series on the AC side of a power supply [4]

Inrush current limiting with an NTC is the most popular and standard passive method for limiting inrush current, it uses the intrinsic properties of the semiconductor material of the NTC.

When the NTC is at ambient low temperature, the resistance is high, which effectively limits the IC at start-up, but as soon as the current goes on steady state, the NTC temperature increases and its resistance drops significantly to a rather low value, allowing the current to flow without much limitation through the circuit after the inrush surge has occurred.

Thereby, NTC current limiting topology cannot be used in certain applications, where the ambient temperature is already high during the system start-up, since the NTC will not limit the initial IC.

One of the main drawbacks of this NTC topology is that the circuit do not have hot restart capabilities. In fact, during the process of limiting the IC, the NTC is energized and becomes quite hot, which reduces its resistance. Thus, if the circuit must be restarted after a short period of time on multiple occasion, the NTC does not have the time to cool down and will not limit effectively the IC at the next restart. [7.]

To remedy this problem, it is necessary to use a bypass or soft start circuit in parallel of the NTC, which allow to disconnect it shortly after the initial IC fades away (see active topologies to reduce IC).

Figure 6 shows different locations where it is possible to implement an NTC thermistor for Inrush Current Limitation. As an alternative, it is possible to install an NTC to (A and B) or (C and D) or only at location A or C. [8.] In our case, because we are dealing with an AC supply it is possible to implement an NTC at location (A and B) or only on location A.

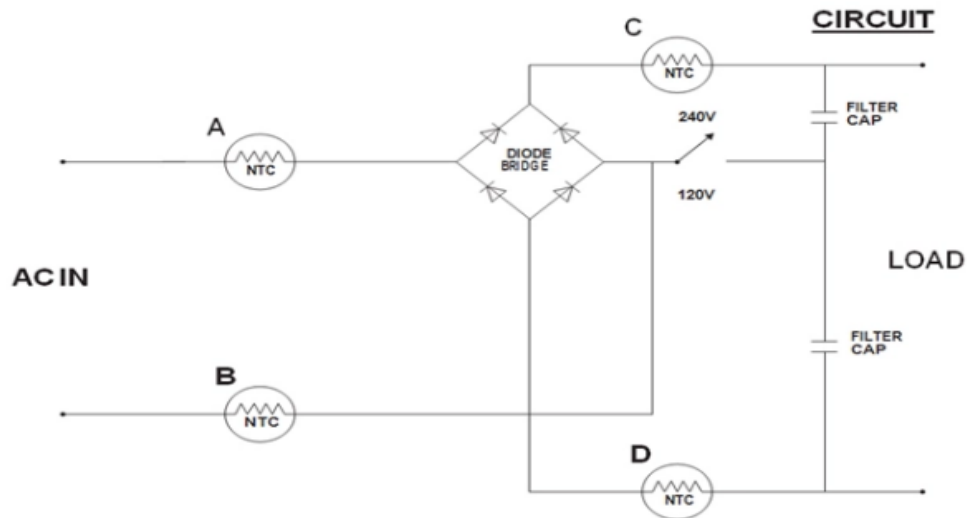


Figure 6. Different locations to implement an NTC thermistor [8]

Figure 7 shows an example of how the resistance of the NTC varies in function of the temperature.

The normal NTC resistance is calculated by using formula (1):

$$R_{NTC} = V_{peak} / I_{max}(IC) \quad (1)$$

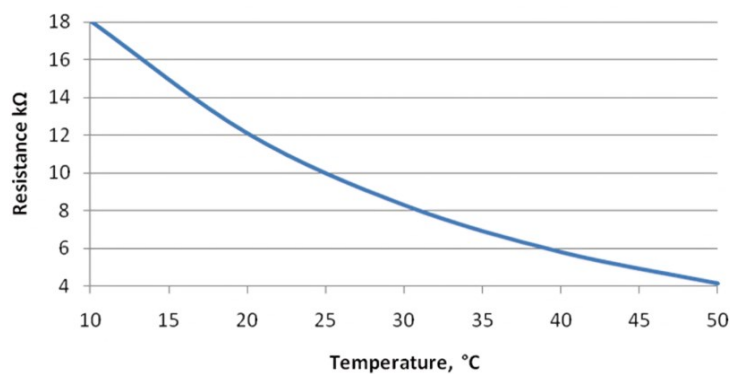


Figure 7. NTC resistance vs temperature graph [9]

Advantages and drawbacks of using an NTC are listed below.

Advantages:

- Easy to realize solution / Easy Circuit
- System cost compared to active topologies
- Can be used for higher power ratings (up to approximately 500 W)
- No bypass circuit is needed

- Occupies less space on a PCB compared to a resistor
- Lower cost compared to NTC active circuit
- Fast response time to IC

Drawbacks:

- Current limiting at start-up is affected by the ambient temperature
- Power losses but much less than with a resistor
- Long cool down time (not appropriate for hot restart of the circuit)
- Cannot be used if the ambient temperature is high or too low(0°C)
- Higher cost than a single Resistor ICL
- NTC do not protect from a continuous short circuit in the event of an electrical breakdown
- Heat generated by surrounding components affects the behaviour of the NTC
- Heat generated by the NTC can affect surrounding components / parts which are close to it (plastic parts, solder joints, etc.)

Figure 8 shows an example of IC in a motor with and without IC limitation.

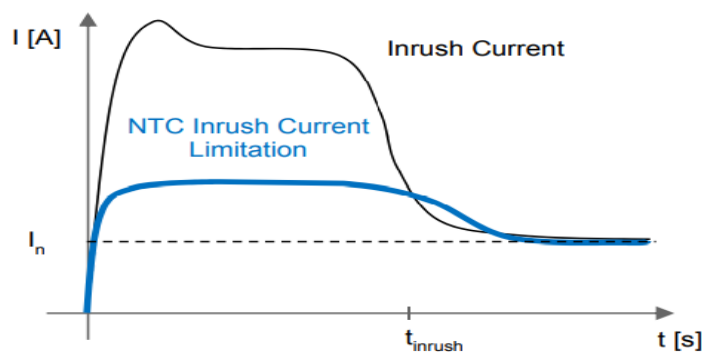


Figure 8. Inrush current of a motor with and without NTC limitation [5]

4.2 Active Inrush Current Limitation Methods

Active ICL solutions are used for applications requiring higher power ratings, or hot restart capabilities, circuit designs are more complex since they require the addition of a bypass or soft start circuit. They are usually recommended for power ratings above 500 W. The soft start circuit is used to bypass the current limiting

circuit soon after the IC has occurred and faded.[4.] The current limiting element can be either a resistor, an NTC, or a PTC.

Generally, the bypass circuit is a mechanical relay, but it can be replaced with SSR (solid state relay) or a Triac (which is made with two thyristors and is used to control AC). Generally, the bypass circuit includes a time delay circuit (control circuit) to switch off the relay or SSR after the IC has occurred and decayed enough.

4.2.1 NTC Current limiting + Bypass Circuit

Using an NTC in conjunction of a bypass circuit is a very popular method, in this configuration, a bypass circuit bypass the NTC after the initial spike of current has decayed. This is also an effective way to limit IC in a circuit but is more appropriate for higher power ratings. This method reduces the NTC power losses during steady state operation and is used for applications where the system is restarted multiple times (hot restart) on short time intervals. [5.]

Since the NTC is getting warmer during IC limiting operation, its resistance decreases which could potentially makes the NTC inefficient to limit IC after several frequent system restarts.

An NTC can take between one to several minutes to cool down enough to allow a hot restart, that is why the bypass circuit needs to be implemented, in order to limit the current, and then bypass the NTC, so that the temperature is not rising too much and allow a hot restart.

Usually, the NTC is bypassed after only a few milliseconds after the start-up, this allows the IC which is usually very short-lived to be absorbed before the NTC is bypassed.

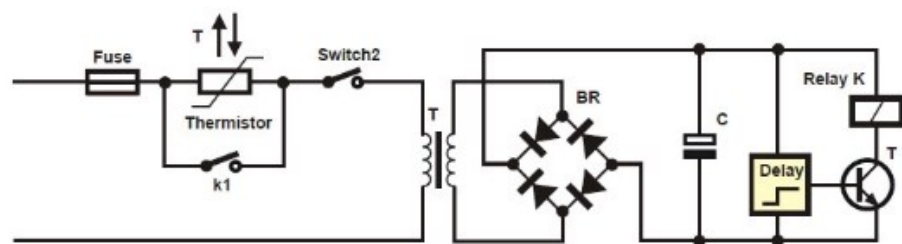


Figure 9. NTC with bypass circuit ICL and control circuit in a power supply [14]

In the circuit of Figure 9, an auxiliary transformer is used to supply the bridge rectifier and creates the DC supply voltage necessary to trigger the time-controlled relay, switch two is optional [14]. Similar circuit as in Figure 13 can also be used but by replacing the PTC by an NTC.

Another drawback of NTCs is that they add heat to the overall system (they can reach temperatures around 125°C). The parallel bypass circuit allows the NTC to cool down between multiple operations, but after many stops and restarts sequence close in time, it is possible that the NTC is too warm and does not limit the IC correctly at the next restart.

To remedy this, a temperature monitoring system can be added to the circuit, which prevents a restart of the system if the NTC is too hot (with a visual indication for example).

It should also be noted that it is possible to make a thermal separation between the NTC and other sensible components in the circuit (such as solid-state switching devices), which could otherwise may not work properly or get damaged because of the thermal stress caused by the NTC temperature, or simply to put the NTC away from solid state components to avoid component failures [5].

Advantages and drawbacks of using an NTC in conjunction with a bypass circuit are the following.

Advantages:

- Bypass circuit allows system hot restart
- Less power losses compared to fixed NTC method
- Take less space than a power resistor

Drawbacks:

- Cannot be used in high temperature environment
- Performance of NTC depends on heat generated by surrounding components
- NTC heat limit the number of possible hot restarts and the time interval between them

4.2.2 Resistance Current Limiting + Bypass Circuit

Resistance current limiting with a bypass circuit setup is also quite popular. The principle remains the same as with an NTC and bypass circuit method, but the power NTC has been replaced by a power resistor. As an alternative, the Triac or SSR can be replaced with an electromechanical relay, as shown in Figure 10. Please note that in that case an NTC is also used after the bridge rectifier to reduce the inrush current on the DC side of the SMPS.

The main drawback with this topology is that if the relay or triac fails to work properly, then the resistor stays in the circuit and will cause power losses. This can also lead to damage or destroy the resistor and be the cause of a fire [6]. The resistor needs to be chosen carefully, for example, wire wound resistors or high current surge resistors are usually a good choice. [16;21.] Also, the power resistor size is usually bigger and requires more space on a PCB than an NTC.

Wire wound resistors resistance do not fluctuate with temperature and can include a thermal protection inside their body. They are a good compromise to PTC or NTC and it is possible to make a more precise estimation of the IC than with a PTC. [17.]

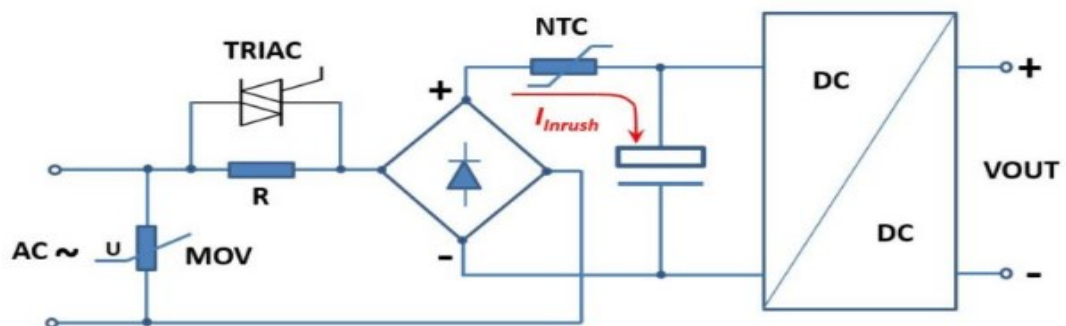


Figure 10. Fixed resistor with triac bypass circuit ICL in a SMPS [11]

Figure 11 shows another ICL topology using a high power resistor and a mechanical relay based bypass circuit. In this setup, the relay is triggered and short the resistor when the voltage cross a certain voltage threshold. [12.]

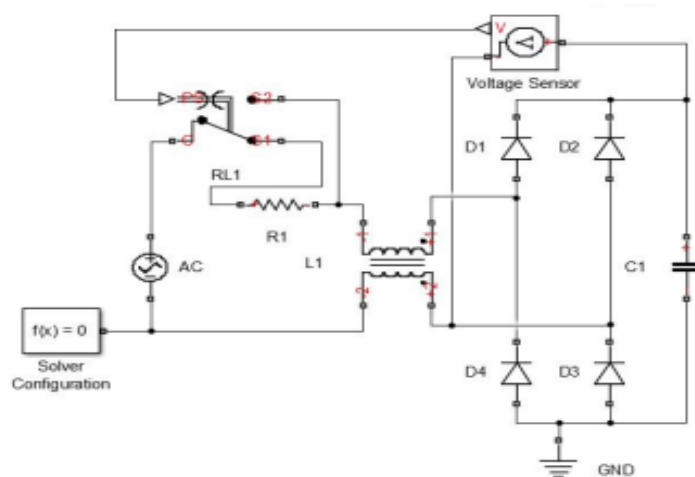


Figure 11. Fixed resistor ICL with voltage-controlled relay [12]

Advantages and drawbacks of using a resistance current limiting with a bypass are listed below.

Advantages:

- IC limitation not dependent on temperature
- Hot restart works better than with an NTC, since the resistance does not fluctuate depending on the temperature
- Tolerance can be adjusted more precisely to fit project specifications (5% tolerance for a resistor compared to 20% for an NTC)

Drawbacks:

- Can lead to power losses in case of relay failure
- Resistor takes more place than a thermistor
- Power losses and risk of fire in case of relays failure
- Wire wound resistors are more expensive

As shown in Figure 12, it is also possible to use parallel resistors in the bypass circuit to precisely get the desired resistance value.

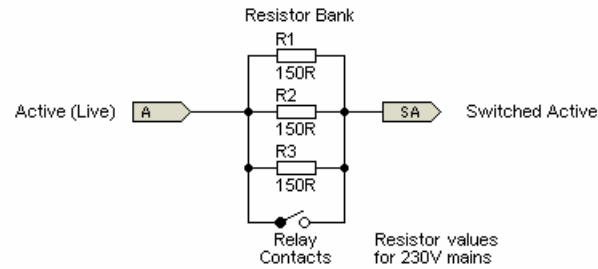


Figure 12. Example of bypass circuit with parallel resistors configuration [18]

4.2.3 PTC Current Limiting + Bypass Circuit

PTC also use the properties of a semiconductor material, but they work in the opposite way of the NTC. Their resistance is relatively low when the temperature is low, and the resistance increases dramatically as soon as the temperature reaches a certain point (known as the Curie temperature) [6].

PTCs are mainly used for overcurrent protection, but in some specific cases they can also be used for inrush current protection [6].

For example, if the room ambient temperature is high, the PTC resistance will also be high, thus it will be able to limit the inrush efficiently compared to an NTC. If the ambient temperature is too high, the resistance of an NTC drops to value close to zero Ohms and it reduces its ability to limit the IC during the start-up of a device. Hence a PTC is more appropriate.

In special cases, a PTC can be used as an ICL, but the user must verify that the default resistance of the PTC at ambient temperature is high enough to limit the IC on start-up, otherwise the PTC will not limit the initial IC (the response time of the PTC is too slow).

PTC are generally used at high ambient temperature, in circuits requiring frequent On / Off switching time since they do not have to cool down between each On / Off state in order to limit IC. [11.]

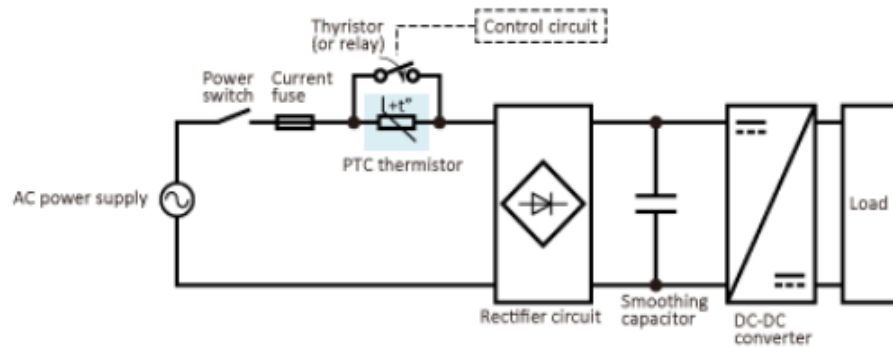


Figure 13. PTC based current limiting with bypass circuit in a SMPS [6].

In the Figure 13 circuit, the relay is initially open (or in a high ohmic state if thyristors or triac is used). When the power switch is closed, the PTC limits the IC with its default resistance and starts to heat up. After a short amount of time, the relay is closed which bypasses the PTC and allows the circuit to work under steady state condition (without power losses). As indicated on Figure 13, the mechanical relay can be replaced by an AC switch (Triac or SSR).

Since the resistance of a PTC is rising with the temperature, it is always used in conjunction with a bypass circuit.

Advantages and drawbacks of this topology are the following.

Advantages:

- Can limit IC in places where ambient temperature is high (65° C or more)
- Work better than NTC if the ambient temperature is very low (below 0°C)
- Overcurrent protection in case of relay failure (if the relay does not short the PTC)
- Near zero reset time when switched On / Off frequently

Drawbacks:

- More expensive than an NTC
- If the PTC default resistance at ambient temperature is too low, it will not limit the initial IC

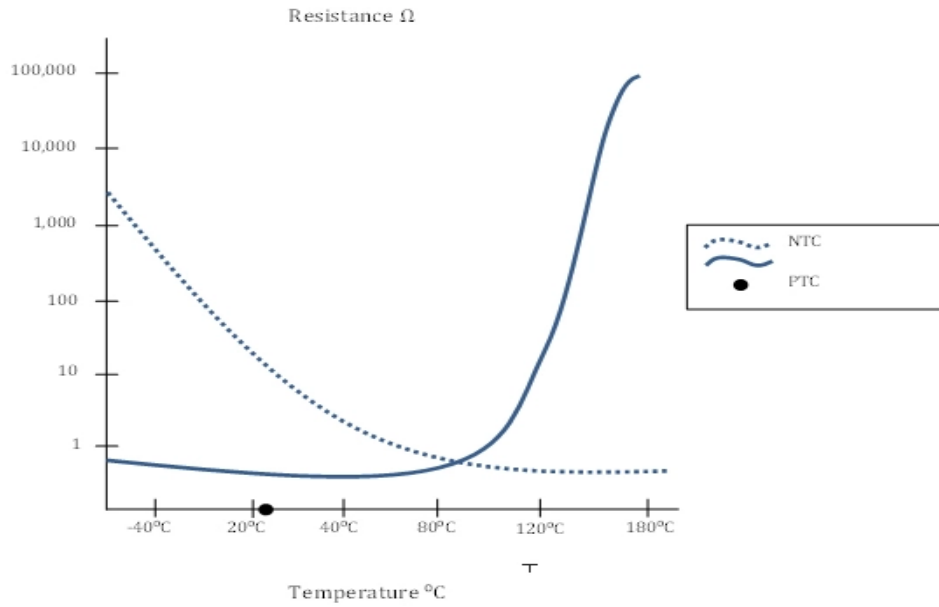


Figure 14. NTC vs PTC resistance vs temperature graph [8]

Figure 14 illustrates that the resistance of the PTC increases exponentially from around 80-100°C.

5 Types of Bypass Circuits

Bypass circuits can use a mechanical relay or SSR (Triac based) to short the resistor, NTC or PTC (Figure 15).

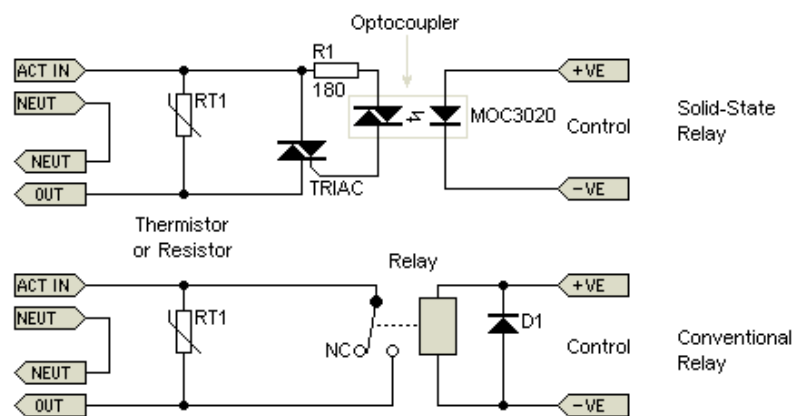


Figure 15. Thermistor or resistor bypass using mechanical relay or SSR [10]

Mechanical relays are usually a good choice since they are very robust, reliable and are easily found on the market for a relatively cheap price.

Otherwise, it is possible to use a SSR (or an opto-coupler and a triac) instead of a relay, advantage being that they have a longer life, because they do not have any mechanical parts, they can be switched on and off at a higher rate. However, they dissipate some power, so the power losses are around 1 or 2 Watts for each amp of continuous current. It should be noticed that inside a SSR there is a triac controlled by an opto-coupler. [10.]

N.B: SSR can easily be triggered directly by the output of an MCU.

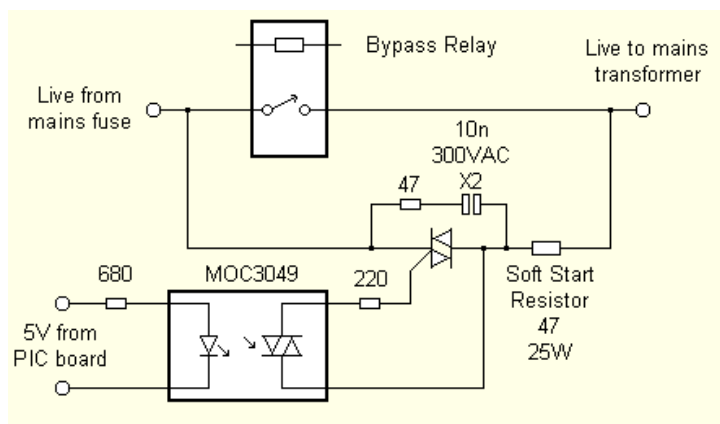


Figure 16. Example of bypass circuit using 2 relays [19]

Figure 16 shows another type of bypass circuit using 2 relays, a Triac based and a mechanical relay. The MOC3049 opto-coupler drives the gate of the triac which activates the limiting resistor (soft start resistor), when the IC has decayed the bypass relay is closed which shorts the bypass resistor and finally the triac is turned off.

The advantage of this bypass circuit is that the bypass resistor does not stay in the circuit if the bypass relay does not operate correctly, but requires the addition of a PIC micro-controller to control the MOC3049. [19.]

This design also avoids power losses, since the bypass / soft start resistor is put in the circuit by a SSR and bypassed after the IC by the mechanical relay.

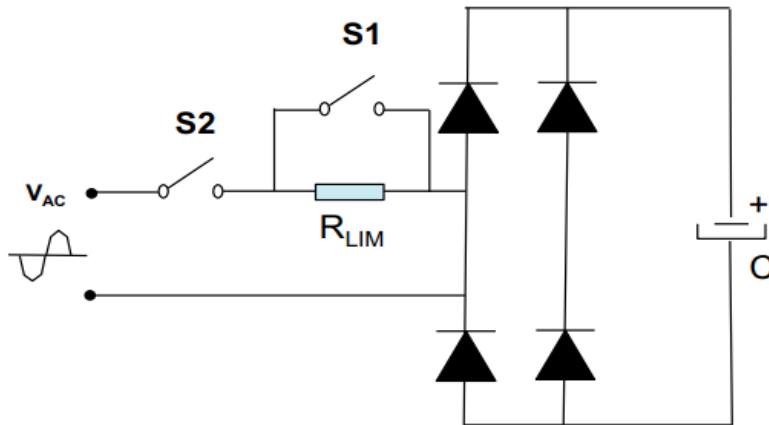


Figure 17. Bypass circuit using 2 relays to minimize standby losses [20]

As an alternative (Figure 17), a switch can also be added before the thermistor or resistor, to disconnect it completely from the bridge rectifier if the circuit is in standby mode (used in SMPS), to minimize standby losses [15].

Advantages and drawbacks of using a mechanical relay or SSR are listed below.

Mechanical relay:

Advantages:

- Cheap / Cost less than an SSR
- Easily found on the market
- Virtually no power loss
- Complete isolation between control circuit and the switch
- Power losses are negligible
- No heat sink is needed
- Not sensible to heat generated by surrounding components

Drawbacks:

- Shorter On/ Off cycles lifetime
- Take more place / more cumbersome
- Vibrations can damage the relay
- Risk of explosion in flammable environments

SSR relay:**Advantages:**

- Longer On/Off cycles lifetime (no moving parts)
- More sensitive than mechanical relay (less power needed to control it)
- Can switch On / Off faster than a mechanical relay
- Can easily be triggered by an MCU
- Ability to be switched at the waveform zero crossing point
- SSR are not suffering for arcing

Drawbacks:

- Higher cost
- Some power losses
- More heat is generated than with traditional relay
- More sensible to heat from surrounding components
- Heat sink is sometimes required / Voluminous
- Generate some RF interferences when switched On and Off (can be reduced by switching the SSR at zero crossing)

5.1 Time Controlled Bypass Circuit Using a Mechanical Relay

An example of time controlled circuit can be seen on Figure 18. The circuit is used to control a relay after some initial delay time. The delay time before the relay is closed, is defined by resistance R_1 , capacitor C_1 and also the Zener diode D_1 . [13.]

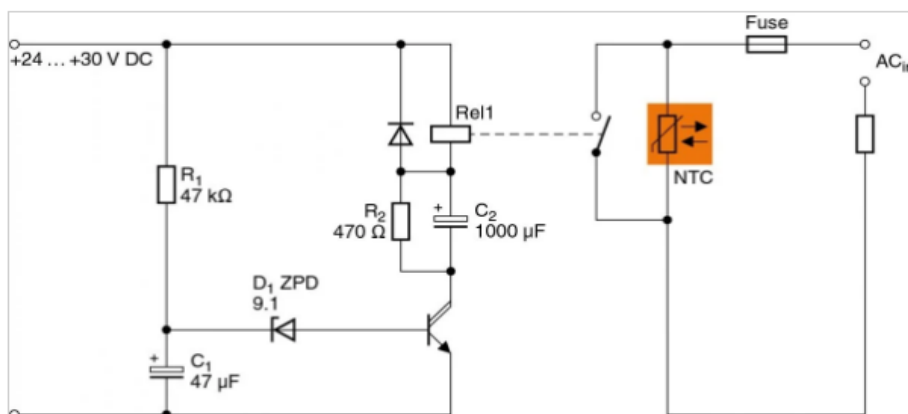


Figure 18. A time controlled bypass circuit to short an NTC [13]

This way, it is possible to activate a switch placed on the AC line with a DC time-controlled current, as shown in Figure 18.

Time controlled circuit can also be done with a chip such as the 555 timer but it is more complex and requires more components.

5.2 Reducing the IC by Switching the SSR at the Zero Crossing Point

If the load is mainly resistive, the IC current can be reduced by switching on the bypass circuit at the zero crossing of the AC waveform. This can be done with a zero crossing SSR.

N.B: If the load is a transformer, switching at 90° phase angle is the point where the IC is at minimum amplitude. It should be avoided to switch at the zero crossing point with transformers, as it is where the IC has it highest value [10].

Figure 19 shows how the IC amplitude varies when switching the SSR at the zero crossing point or at the waveform peak in a SMPS.

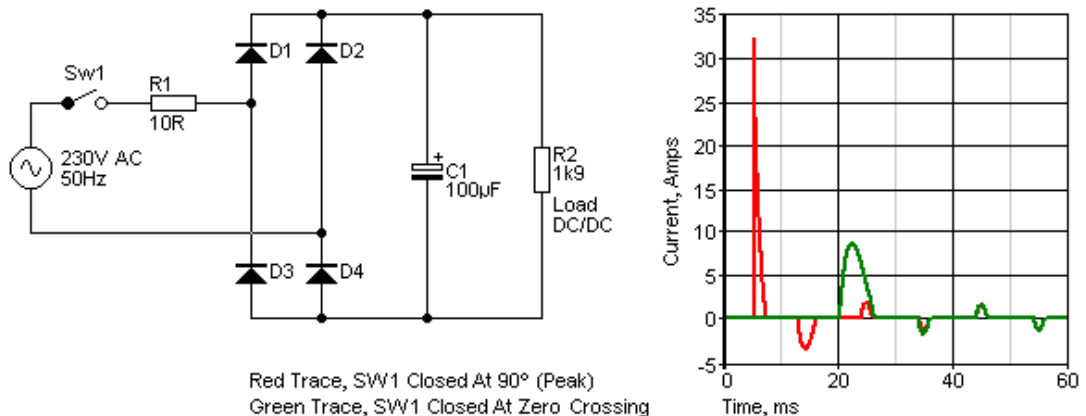


Figure 19. IC comparison between zero crossing and peak switching with a SMPS [10]

Figure 20 illustrates another bypass method. The MOC 3163 is a zero crossing opto-coupler. It will trigger the Q6030 Triac at the zero-crossing point of the AC waveform, then the relay RL2 is closed after a short delay bypassing the

thermistor. In that example, the MOC3163 opto coupler is activated by a signal coming from an MCU. [17.]

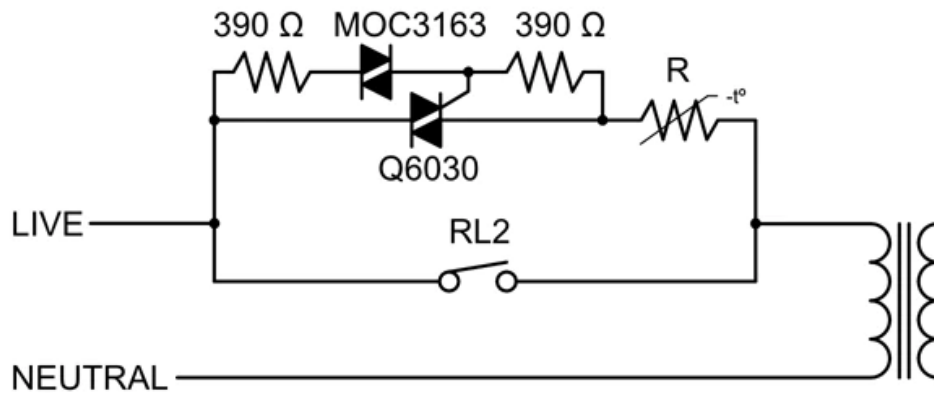


Figure 20. Example of a bypass circuit using zero crossing detection and a mechanical relay for a transformer load [17]

Generally, it is better to use a combination of SSR or Triac (Solid state AC switches) and relays in that kind of application. SSR are not ideal to use as main switches, because they lead to some power losses, so depending on the application, it is preferable to use them to switch on the thermistor or resistor on start-up at the zero crossing point. This configuration reduces the relay RL2 arcing. Since the relay is closed when the Triac is active, the thermistor is limiting the IC. Thus the relay contacts are closing when the current is already reduced, which reduces the arcing phenomenon. [17.]

It is worth noting that in this example, it should be better to not switch the thermistor / resistor at the zero crossing point of the AC waveform since the AC mains are connected with the primary of a transformer. This circuit is more relevant to reduce capacitive IC.

6 Phase Angle Controlled Triac Current Limiting

A more modern approach (that has been primarily used to reduce IC at the start-up of single-phase motors, or control LED intensity) is to control the gate of a Triac with a pulse signal often generated by an MCU. By varying the firing angle

of the Triac, it is possible to limit smoothly the IC on start-up, as shown in Figure 22 phased controlled circuit.

The firing angle can be defined as the angle between the instant an SCR is forward biased (zero crossing point in AC waveform), and the instant it is triggered [23]. Firing or delay angle is shown on Figure 21.

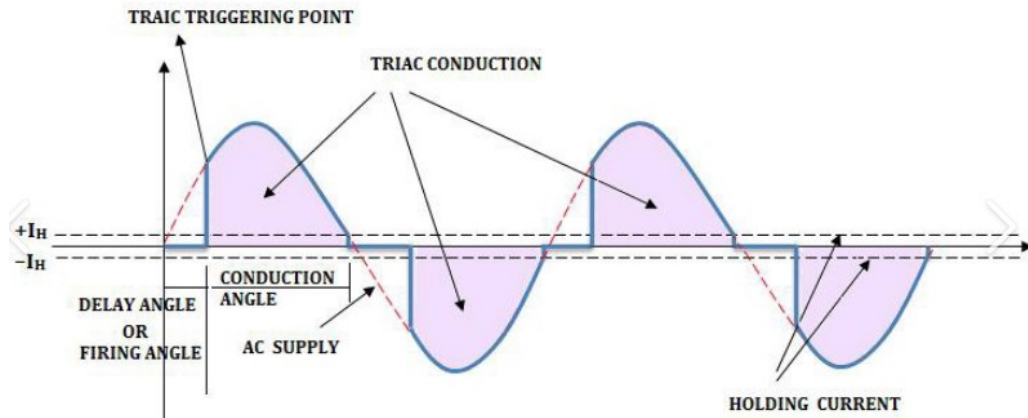


Figure 21. Triac firing angle and conduction angle [24]

The drawback of this setup is that because of the power losses caused by the Triac, it is used mainly for low power AC-DC converters applications [15].

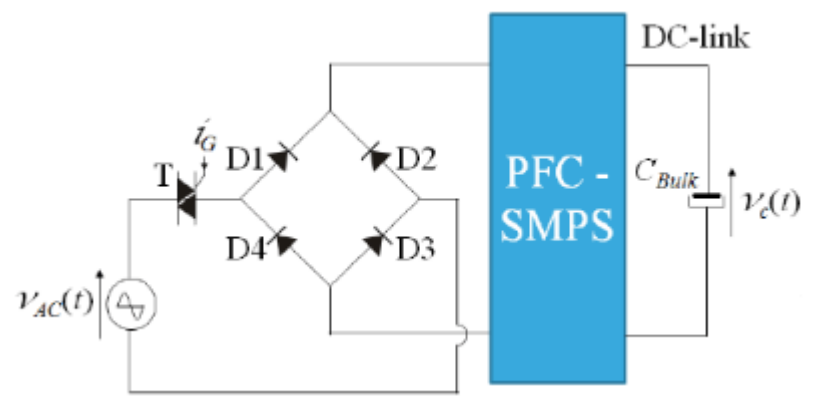


Figure 22. Phase controlled Triac ICL in a SMPS [15]

IC is limited by triggering the gate of the Triac at specific phase angles. This setup needs a zero crossing detector circuit in order to work correctly.

Figure 23 illustrates how the phase angle control works. During the first positive AC half cycle, after a short delay (α_1) from the zero crossing point, the Triac is triggered near the 180° phase angle and will stay in On state until the next zero

crossing point. This controls the AC flow through the Triac and allows only a very small portion of the voltage to pass through the Triac. Accordingly, V_{out} voltage rises slowly until reaching a plateau, which limits the charge of the DC link capacitor and limits the IC.

During the next AC half cycle (negative) the Triac is triggered with a shorter delay (α_2) from the last zero crossing, which allows a bigger portion of the voltage to flow through it and the capacitor to be further charged. Each AC half cycle, the delay is reduced and this process is repeated until the DC link capacitor is fully charged at maximum voltage and that the current has reached steady state. [22.] By varying the firing angle of the Triac, it is possible to control the average voltage received by the load and limit smoothly the IC, this method can also be implemented with inductive loads such as motors and transformers.

As an alternative, the Triac can be triggered with equal firing angles ($\alpha_1 = \alpha_2$) during the first positive and negative AC half cycle, and reduced after each next full AC cycle, until the current is stable.

The main drawback of this method is that the Triac is not activated at the zero crossing point, which generates RF noise interferences. A Triac needs to be switched at the zero crossing point to reduce interferences.

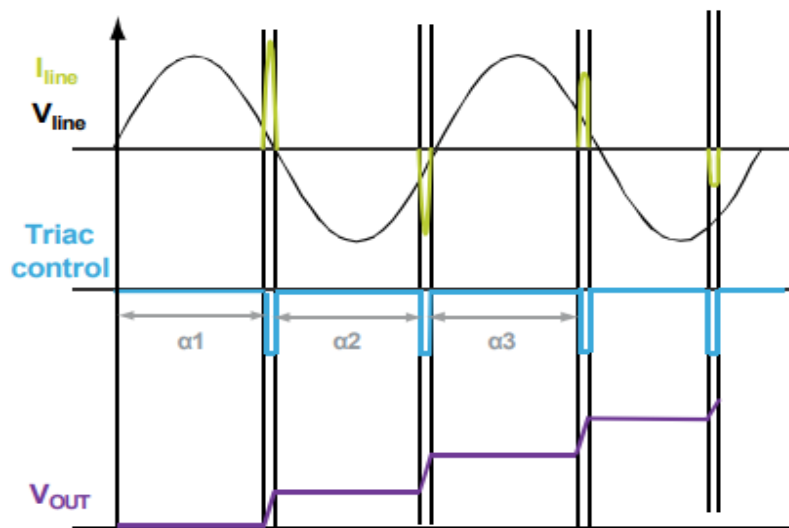


Figure 23. Example of phase shift control of the Triac [22]

Figure 24 illustrates how it is possible to control the power transmitted to the load and reduce the IC by triggering the gate of the Triac at different angles. The smaller the triggering / firing angle, and the greater the transmitted power.

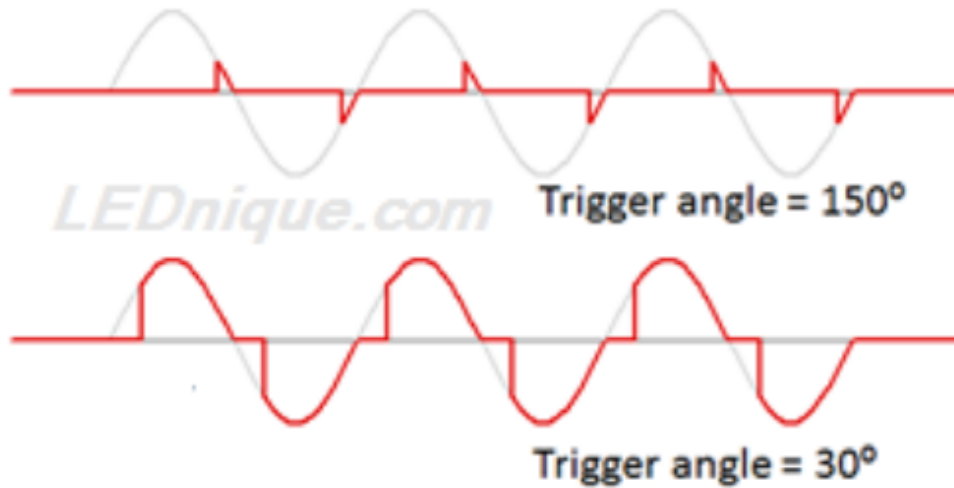


Figure 24. Example of Triac Firing Angle Control [27]

Furthermore, a mechanical relay can bypass the Triac once the IC has been limited by the soft start system, to avoid power losses, as shown in Figure 25 (Hybrid relay solution). [22].

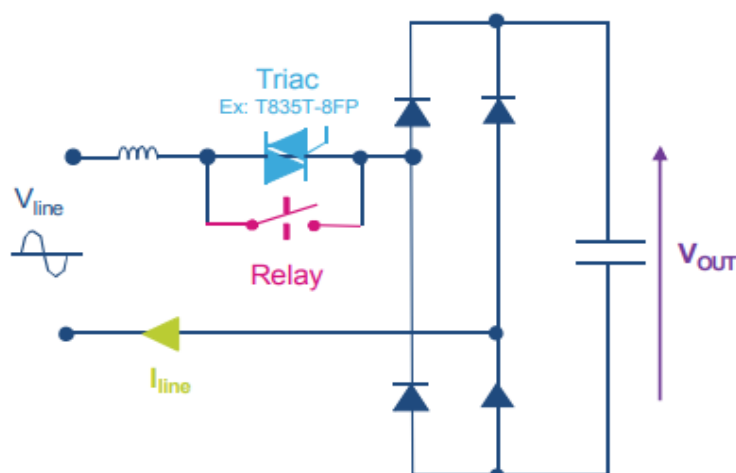


Figure 25. Phase controlled Triac with relay in parallel (hybrid relay configuration) [22]

This configuration is practical to avoid power losses induced by the Triac when the current has reached steady state. ST recommend also to put an inductor in series with the Triac .

6.1 Example of Zero Crossing Detection Circuit

Zero crossing circuits are generally using operational amplifiers or optocoupler. Figure 26 illustrates an example of zero crossing detection circuit, based on an optocoupler [25].

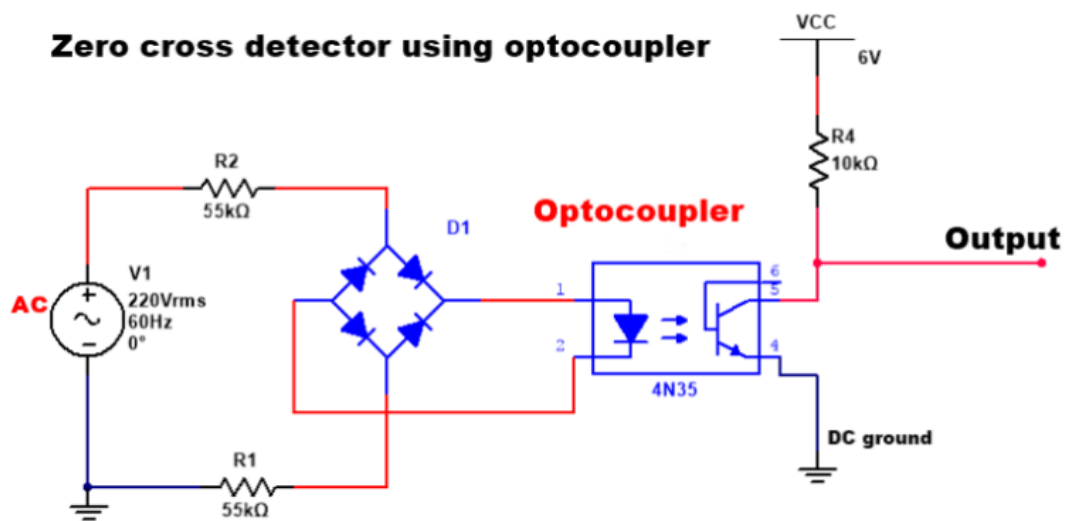


Figure 26. Zero crossing detection circuit [25]

Figure 27 shows the relation between the input and the output of the zero crossing detection circuit using an optocoupler.

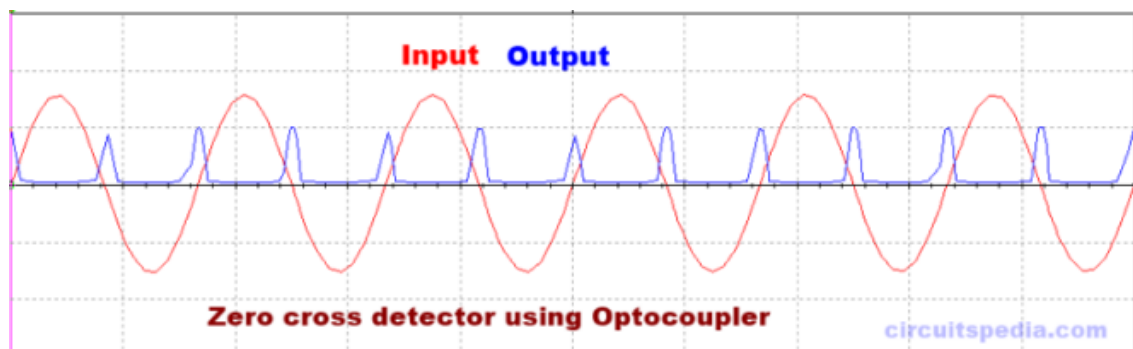


Figure 27. Zero crossing detector [25]

Table 1. Summary of the Different ICL Topologies

ICL Topologies	Advantages	Drawbacks
Passive		
Resistor	<ul style="list-style-type: none"> - Cost effective compared to thermistors and active topologies - Simple circuit - Current limitation is not dependent on the temperature - Generates less heat than an NTC 	<ul style="list-style-type: none"> - Power losses are important - Only for low power rating supplies
NTC	<ul style="list-style-type: none"> - Easy to realize solution / Simple circuit - Can be used for higher power ratings (up to approximately 500 W) - No bypass circuit is needed - Occupies less space on a PCB compared to a resistor - Lower cost compared to NTC active circuit 	<ul style="list-style-type: none"> - Current limiting at start-up is affected by the ambient temperature - Power losses but much less than with a resistor - Long cool down time (not appropriate for hot-restart of the circuit) - Can't be used if the ambient temperature is high or too low(0°C) - Higher cost than a single Resistor ICL - NTC do not protect from a continuous short circuit in the event of an electrical breakdown - Heat generated by surrounding components affects the behaviour of the NTC - Heat generated by the NTC can affect surrounding components

Active		
NTC + Bypass Circuit	<ul style="list-style-type: none"> - Bypass circuit allows system hot restart - Less power losses compared to fixed NTC method - Take less space than a power resistor 	<ul style="list-style-type: none"> - Cannot be used in high temperature environment - Performance of NTC depends on heat generated by surrounding components - NTC heat limit the number of possible hot restarts and the time interval between them
Resistor + Bypass Circuit	<ul style="list-style-type: none"> - IC limitation not dependent on temperature - Hot restart works better than with an NTC, since the resistance does not fluctuate depending on the temperature - Tolerance can be adjusted more precisely to fit project specifications (5% tolerance for a resistor compared to 20% for an NTC) 	<ul style="list-style-type: none"> - Can lead to power losses in case of relay failure - Resistor takes more place than a thermistor - Power losses and risk of fire in case of relays failure (fuse is necessary) - Wire wound resistors are more expensive than NTC or PTC
PTC + Bypass Circuit	<ul style="list-style-type: none"> - Can limit IC in places where ambient temperature is high (65° C or more) - Work better than NTC if the ambient temperature is very low (below 0°C) - Overcurrent protection in case of relay failure (if the relay does not short the PTC) - Near zero reset time when switched On/ Off frequently 	<ul style="list-style-type: none"> - More expensive than an NTC - If the PTC default resistance at ambient temperature is too low, it will not limit the initial IC
Phase Angle Control Circuit	<ul style="list-style-type: none"> - By controlling the average voltage, it is possible to limit smoothly the IC - This topology / circuit works for capacitive or inductive loads 	<ul style="list-style-type: none"> - Circuit is more complex to setup / requires more components and a programmed MCU - Some power losses are caused by the Triac - Triac generates RF interferences (more interferences when not switched at the zero crossing)

Finally, it was decided to use an NTC bypassed topology, which was also the solution that had been adopted by the company in a previous study. The main reason being that this topology is easier to implement compared to a Phase angle control circuit and does not require the addition of an MCU, which has to be programmed and requires a zero-crossing detection circuit.

It was chosen to use an active bypassed circuit topology because the total power that can deliver the XL cabinet is around 1850 W (the main breaker is 8A, thus $P=U \times I=230 \times 8 = 1840$ A).

The NTC takes less place and can be mounted on a PCB, compared to an equivalent power resistor, capable of absorbing the same IC during a few hundred milliseconds and that must be mounted externally on the chassis.

On the other side, by using the NTC, one loses the ability to perform many successive hot- restart of the system, but that was not the main requirement for this project.

7 Measurement of the Inrush Current in the XL Cabinet in Real Situation

First, it was decided to measure the IC caused by the connection of several portable power equipment that are normally used inside the XL cabinet. Nexess clients use the 230 V main sockets to charge portable electrical devices such as chargers, tablets, etc.

The idea was to have an idea of the magnitude and duration of the inrush current caused by these different devices when plugged in into the mains sockets and to find a device that can accurately simulate these chargers and tablets (for example, SMPS and resistor have been earlier proposed to approximate these chargers and tablets).

Inrush current measurement for each device was also done with different states of charge of each device and by triggering the system at different phase angles to compare the difference on the IC magnitude and duration.

7.1 Phase Controlled Circuit

In order to do this test under good conditions, a circuit to control the phase angle of the 230V mains voltage was built (shown in Figure 29). For each set of IC measurement, and for each device, the AC main voltage phase angle must be the same, in order to have a precise idea of the IC. In fact, since the IC amplitude is varying in function of the phase angle at which the circuit is triggered, it was necessary to have a setup which would allow us to make reproducible measurements.

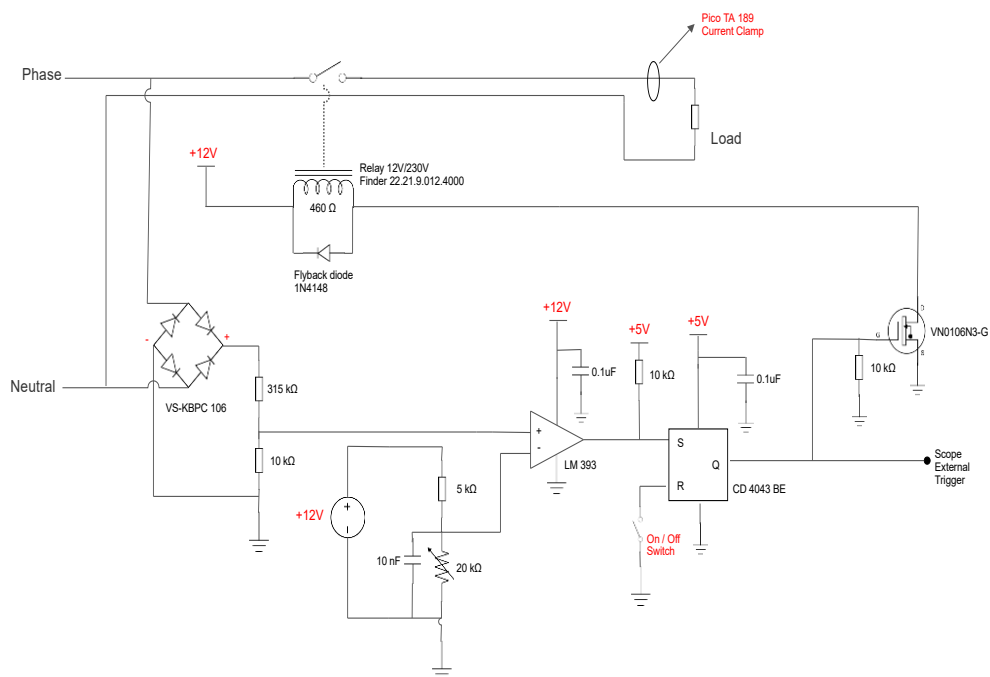


Figure 29. Circuit to control the phase angle at which the 230 V AC main is switched On

The phase angle circuit of Figure 29 works as follow:

The 230 V signal is split and rectified by a bridge rectifier (VS-KBPC 106), the rectified pulsating DC voltage which varies between 0 and 10 V is then compared by a comparator to a fixed DC reference voltage. This allows the user to select the phase angle at which the waveform will be triggered (by varying the 20k Ω potentiometer value, the voltage at V_{in-} change based on the voltage divider output). After the comparator, the signal is a square wave varying between 0 and 5 V, the width of the square wave depends on the value of the reference voltage.

The signal is then sent into an SR-latch flip flop, which sets the output to a high value at the first rising edge of the signal. The signal is then sent to the oscilloscope External trigger input and also to an npn Mosfet transistor which will activate a relay and allows the 230 V voltage to be triggered at the desired phase angle. To change the phase angle between measurements, the user turns the potentiometer to another value and resets the SR flip flop before making another measurement. The IC is measured using a clamp meter and the oscilloscope.

Since the relay takes a few milliseconds (15ms given to the datasheet) to activate, the phase angle control is not exact but can be compensated if necessary. In our case, it was not necessary to compensate the phase angle since we wanted to test the system with different phase angles under similar and reproducible conditions.

The period of the 230V /50 Hz voltage can be calculated as follows:

$$T = \frac{1}{f} = \frac{1}{50\text{Hz}} = 20 \text{ ms} \quad (2)$$

$f = \text{frequency (Hz)}$

$T = \text{Period (ms)}$

Thus, since one period corresponds to 360 degrees, 15 milliseconds correspond to a phase angle of 270 degrees and correspond to the offset that is added at each desired phase angles (corresponding to different positions of the potentiometer).

The next step was to suggest adequate components and values for the theoretical circuit by searching on supplier websites and datasheets (Bridge rectifier, resistor, op-amp, transistor, relay, etc...)

7.2 Phase Controlled Switching Circuit Simulation

Before building the phase angle control circuit in real life, it was simulated to verify that everything was working as expected. The simulation was done in Simetrix software.

Figure 30 shows the circuit schematic in Simetrix, the relay which triggers the AC main voltage is not represented in the circuit since it was not possible to find a spice model of the specified relay, and the SR latch flip flop has been replaced by a D flip flop, otherwise the simulation seemed to work as expected.

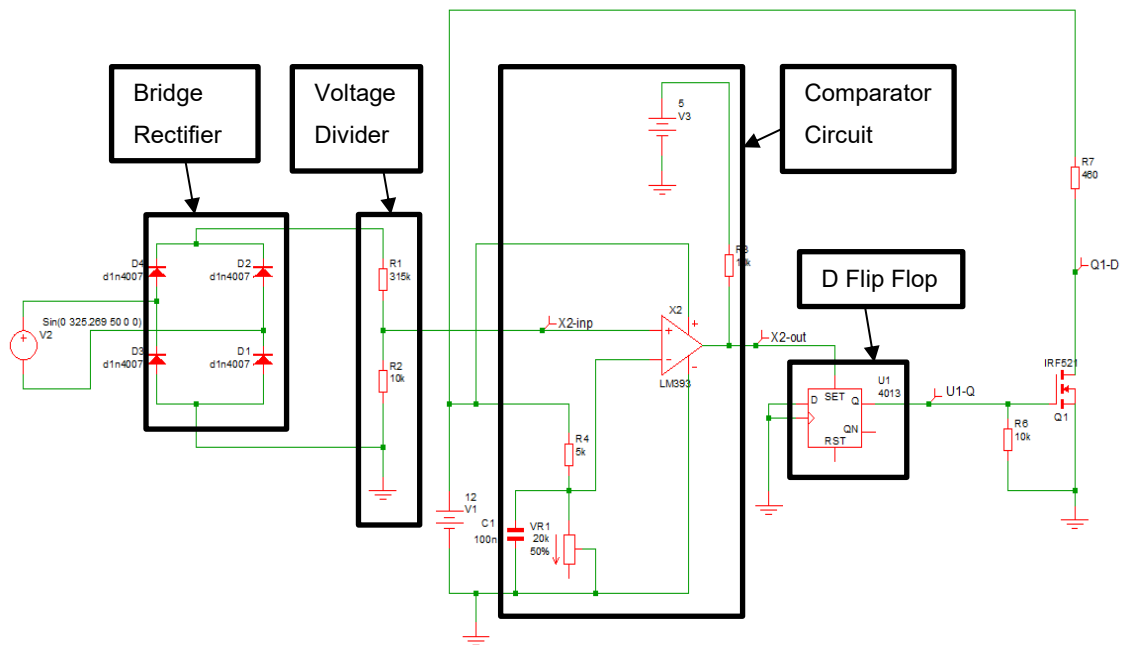


Figure 30. Electronic schematic of the phase angle control circuit

Expected voltages at the output of the bridge rectifier (green), comparator circuit (red), D flip flop (blue) and npn transistor collector (yellow) are shown in Figure 31.

The SR flip flop has been replaced by a D flip flop, but it has the same function as the SR latch in the circuit.

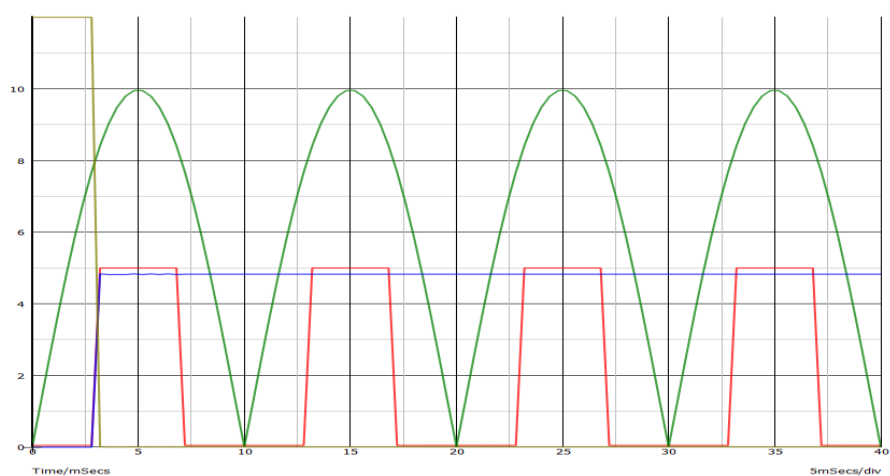


Figure 31. Output graphs

The green curve represents the DC pulsating voltage at the output of the voltage divider (varying between 0 and 10V), the red curve is the output of the comparator circuit which varies between 0 and 5V, the blue curve is the output of the SR latch circuit (made with a D flip flop), the yellow curve is the voltage at the npn mosfet drain.

N.B: It was also verified that the oscilloscope input channels were able to be connected directly if needed to the 230V AC main for voltage measurement. The probe can be directly to the 230V AC main voltage if a 10:1 probe is used, since the oscilloscope maximum input voltage for analog inputs is 300 V RMS. Finally, the voltage at the positive input of the comparator was measured to have a visual representation of the DC pulse to control the phase angle.

Lastly, another modification was made to the circuit, it was necessary to add an isolation transformer before the bridge rectifier in order to avoid the risk of damaging the oscilloscope input by a current circulating through the earth. A 230V / 15 V step down transformer was used, in order to maintain 10 V at the output of the bridge rectifier, it was necessary to change the 315 k Ω resistor value to 11 k Ω . The voltage at the secondary of the transformer is 15V RMS so it is equal to approximately 21V peak.

$$V_{peak} = V_{rms} \times \sqrt{2} = 15V \times \sqrt{2} \cong 21 V \quad (3)$$

The new value for R1 was calculated using equation (4).

$$V_{out} = \frac{R2}{R1+R2} \times V_{in} \Rightarrow R1 = \frac{R2 (V_{in}-V_{out})}{V_{out}} = 11 k\Omega \quad (4)$$

The schematic of the final setup with the added step-down transformer can be seen in Figure 32, it is worth noting the addition of a 5V voltage regulator in the circuit. The 12V is supplied by a portable DC power supply. The D flip-flop was finally wired differently than in the Simetrix simulation to have the expected Q output and reset functionality (see building of the phase-controlled circuit section). Also, a positive feedback loop and a feedback resistor were added to the comparator circuit in order to eliminate oscillations at the input of the comparator circuit (see Comparator with hysteresis section).

- The circuits operating at 12V and 5V DC (such as the 5V voltage regulator, comparator circuit, D Flip-flop and transistor) were built on breadboards and positioned outside of the box (see Figure 34). These circuits did not present a risk during the tests since the DC current was in the order of a few mA.

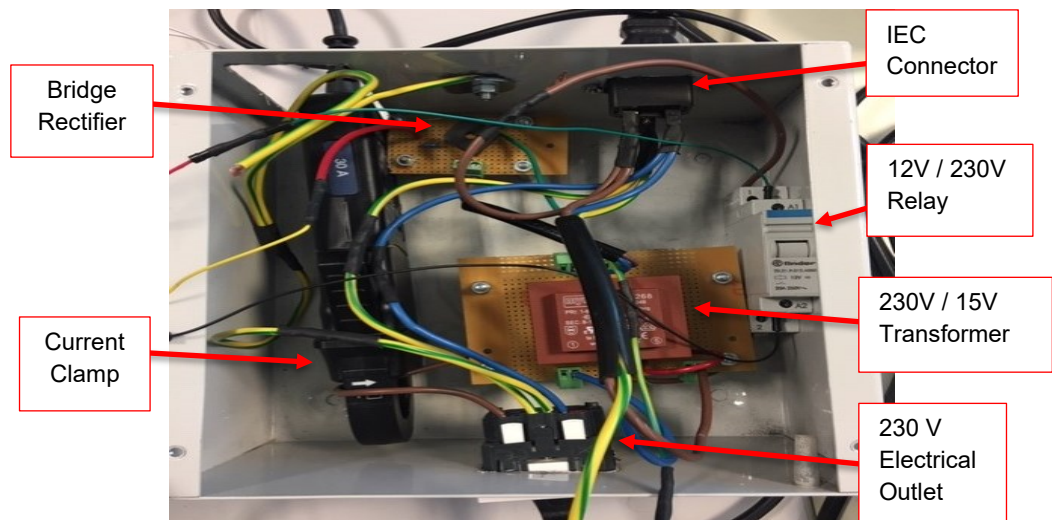


Figure 33. Instrumentation metal box isolating 230V circuits from the DC circuits

The circuit has been built gradually, circuit by circuits, by ensuring that each circuit were working in the same way as the simulation and theory predicted, but some little changes had to be made during the final setup of the circuit. For example, it was noticed that the voltage at the output of the transformer was close to 18 V instead of the expected 15V, thus the 11 k Ω resistor could be replaced by a 15 k Ω if more precision was intended. Also, the D Flip Flop had to be wired in a different way to be able to perform correctly a reset of the Flip Flop (see Figure 32).

A 65mA safety fuse had to be put on the primary of the transformer, which was bypassed after having measured the steady state current at the primary and made sure that the current was not too high (measured current was approximately 27mA). The first ordered fuse was a fast-acting fuse, and it was not appropriate for the task, it was later replaced by a time delay 65 mA fuse.

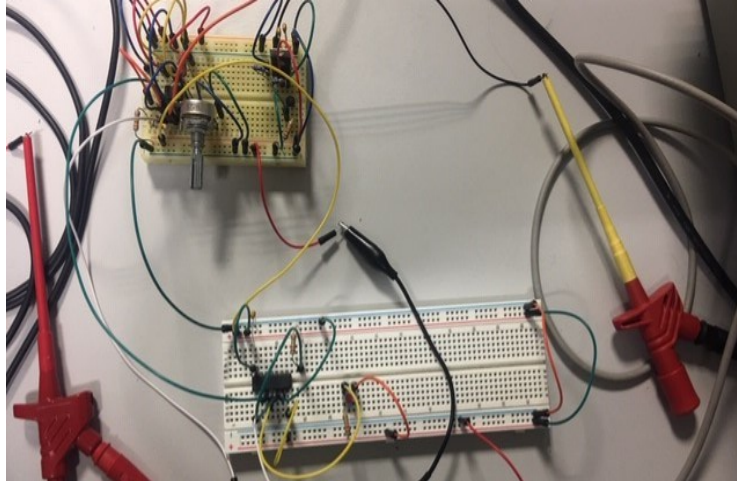


Figure 34. DC operating circuits on breadboards

7.4 Comparator with Hysteresis Circuit

Also, since oscillations were first experienced at the output of the comparator due to the presence of noise at the inputs, it was decided to use a Schmidt trigger configuration (also called comparator with hysteresis). A 680 k Ω resistor was added in the positive feedback loop of the comparator in order to have a sharper square waveform (sharper rising edges) at the output of the LM 393 P comparator. The resistor value was chosen to be at least 10 times the value of the input resistors, it was decided to start with a value of 150 k Ω , and then to manually adjust the value until the expected result.

Figure 35 and Figure 36 show the effect of the added resistor on the output waveform rising edges.

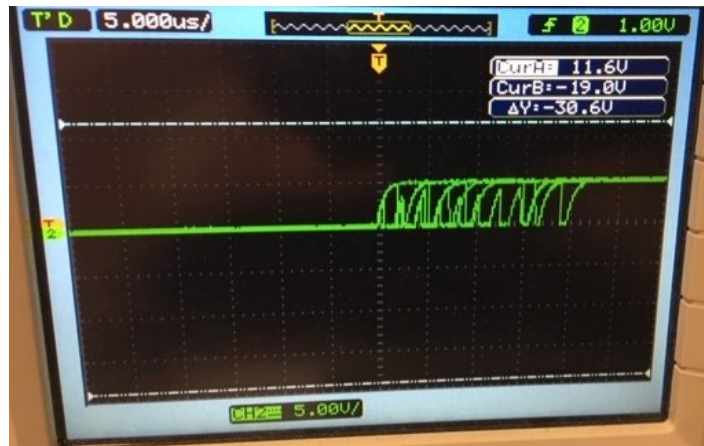


Figure 35. Oscillations at the rising edge of the square wave

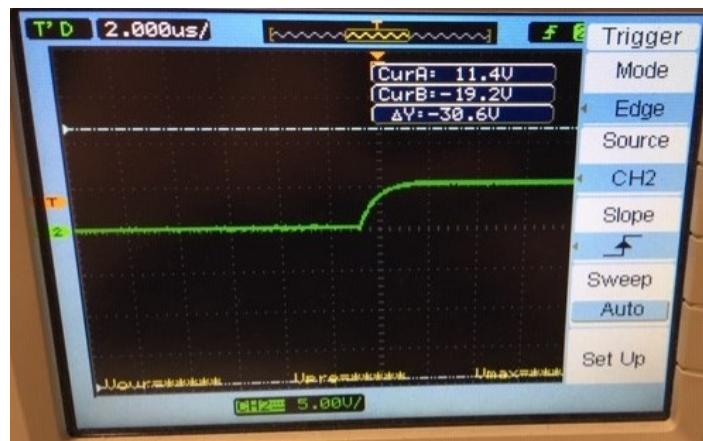


Figure 36. Square wave signal without oscillations

A picture of the whole setup can be seen on Figure 37.

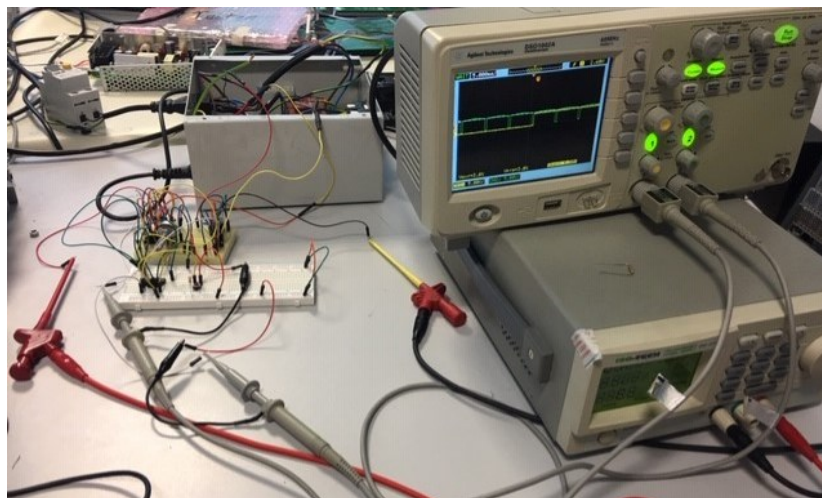


Figure 37. Phase Controlled Circuit Setup

Figure 38 shows a comparison between the square wave signal at the output of the comparator (LM393P) and the signal at the output of the D Flip Flop (CD 4013BE), indicating that the phase-controlled circuit was working as expected. By varying the resistance of the potentiometer, it was possible to control the width of the square wave (green signal) and thereby the phase angle at which the output Q of the D Flip flop (yellow signal) was triggered to 5V.

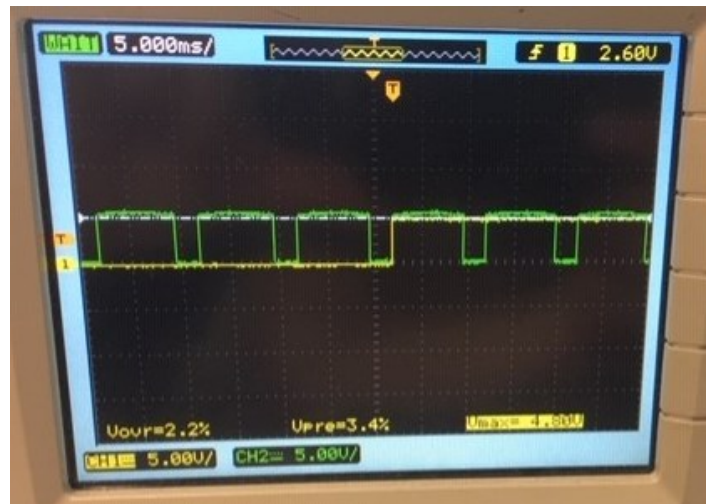


Figure 38. Comparison between comparator output and D flip flop output

Since the circuit seemed to be working correctly, it was possible to start measuring the inrush current on various electrical devices chargers.

7.5 Measuring IC of Different Electrical Devices Chargers

In order to have a good idea and representation of the IC amplitude and duration for each charger, IC was measured at three different phase angles, zero, forty five and ninety degrees and with different battery state of charge (fully charged, half-charged and completely empty). The steady state current (RMS and peak value) was also measured at the same time.

This testing process was implemented in order to evaluate later different solutions to simulate the chargers, tablets, etc. The reason why the different chargers need to be simulated is related to the number of chargers available at Nexess and to the total cost of the system to test the IC limitation. Since the company already

had several SMPS and resistors that they ordered for a previous study, it would be more interesting to use these instead of buying a significant number of each type of charger.

In a previous study, Nexess simulated the chargers by using SMPS and resistors, which seems to be a good solution. IC measurements with SMPS and resistors were also carried out to compare the IC generated by the SMPS to the one generated by the chargers of different tools. Five types of chargers were used for our tests, which cover a wide range of currents, to have a representative range of the chargers used by Nexess customers and to see if the SMPS and resistor solution can be used to simulate accurately a charger.

For the tests, a Makita 9 A DC18RC screwdriver charger, a 2.31 A Dell laptop charger, a 3.42 A Acer Laptop charger, a 2.58 A Tablet charger and a 4.34 A UHF RFID Gun Power Pax charger were used.

Makita Charger Characteristics:

Input:

100-240V AC 240 W

Output:

7.2-18V DC 9A

Table 2. IC Measurements with Makita Charger illustrates the IC measurements at different phase angles and battery states for a Makita DC18RC charger.

Table 2. IC Measurements with Makita Charger

Battery Status	Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (A)	Delay Q->IC (ms)	IC Duration (ms)	Reset Time (s)
Charged	0	9.8	0.08	0.057	19	9	15
Charged	45	10.6	0.08	0.057	19	6	15
Charged	90	25	0.08	0.057	19	5	15
Charged	0	11	0.08	0.057	19	7	5
Charged	45	14	0.08	0.057	19	6	5
Charged	90	25	0.08	0.057	19	5	5
Half-Charged	0	12	1.68 / 3.76	0.56/1.16	19	7	15
Half-Charged	45	14.6	1.68 / 3.76	0.56/1.16	19	7	15
Half-Charged	90	30	1.68 / 3.76	0.56/1.16	19	4	15
Half-Charged	0	12	1.68 / 3.76	0.56/1.16	19	7	5
Half-Charged	45	14.1	1.68 / 3.76	0.56/1.16	19	7	5
Half-Charged	90	31	1.68 / 3.76	0.56/1.16	19	4	5

Empty	0	12.8	4.32 / 3.52	1.52/1.04	18.5	7	15
Empty	45	23.2	4.32 / 3.52	1.52/1.04	19	7	15
Empty	90	32.8	4.32 / 3.52	1.52/1.04	19	5	15
Empty	0	12	4.32 / 3.52	1.52/1.04	19.5	7	5
Empty	45	23	4.32 / 3.52	1.52/1.04	19	7	5
Empty	90	34	4.32 / 3.52	1.52/1.04	19	5	5
Faulty Battery	0	5.6	0.07	0.05	18.5	8.4	15
Faulty Battery	45	6.6	0.07	0.05	19	6	15
Faulty Battery	90	10	0.07	0.05	18.5	5	15
Faulty Battery	0	3.4	0.07	0.05	19.5	8	5
Faulty Battery	45	3.92	0.07	0.05	19	6	5
Faulty Battery	90	9.8	0.07	0.05	19	5	5

With the faulty battery, it was first noticed that the IC amplitude was higher when we reset the system more than approximately fifteen seconds between each measurement (which could possibly be due to the fact that the capacitors inside the charger have time to discharge in approximately fifteen seconds). After fifteen seconds off, the charger makes a noise and displays a red indicator on the next start. If we don't wait that amount of time, the charger restart without making any sound or displaying a red indicator.

However, with a charged, half-charged or empty battery, the difference was not significant.

For the IC measurements, a DSO1002A oscilloscope from Agilent technologies was used, Figure 39 illustrates the IC measurement on the oscilloscope screen for an empty battery, at a phase angle of zero degree. The Pico TA 189 current clamp (Output: 100mV/A) was used to measure the IC at the various phase angles.

The green waveform represents the rectified signal at the input of the comparator, the yellow waveform is the measured IC, and the T mark indicates the moment when the signal is triggered (or phase angle). Oscilloscope is in normal mode and External trigger is used to trigger on the rising edge of the Q output of the D flip flop.

Since the delay between the output Q of the D flip flop and the IC was approximately 20 ms instead of 15 ms indicated in the relay datasheet [28], it was considered that the phase shift between the instant the relay was triggered and when the relay was closed was approximately equal to 360 degrees which does

not change much the phase at which the signal was triggered with the potentiometer.

Figure 39 illustrates the IC amplitude on start-up for an empty battery, it was equal to approximately -1.28 V, which corresponds to 12.8 A (PICO TA 189 has an output of 100mV by Ampere).

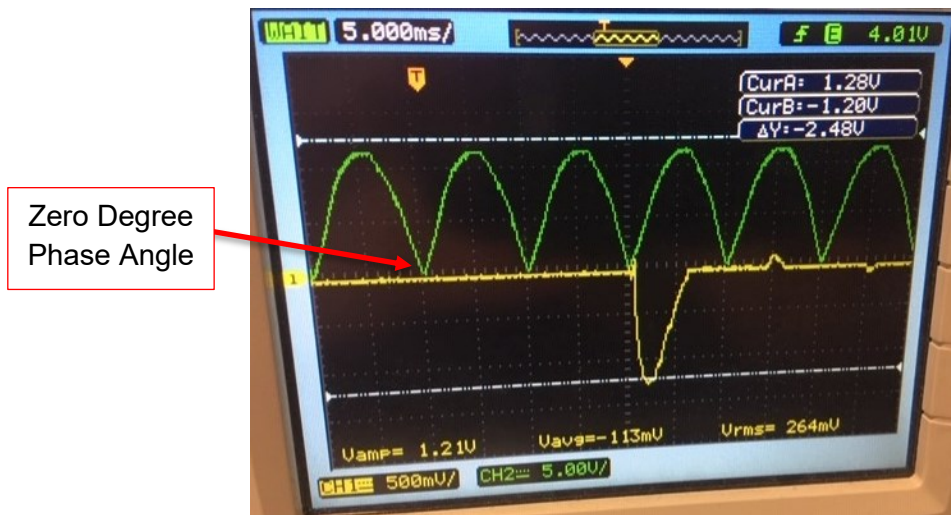


Figure 39. IC on start-up for an empty battery at a phase angle of 0 degree

Figure 40 shows the steady state current (Peak and RMS) (yellow waveform) with an empty battery.



Figure 40. Steady state current (peak and RMS) high value for an empty battery

The Makita DC18RC is a smart charger, which means that it optimizes the current according to the state of the battery, temperature, etc. by using an algorithm. During the charging process, the steady state current (peak and RMS) fluctuates, therefore it is difficult to measure it precisely.

For instance, when the battery is empty, the RMS steady state current stays at 1.52A during a moment but makes excursions for a few seconds at 1.04A every now and then. From time to time, the RMS / Peak current also jumps to lower values like 1 A RMS / 0.5 A RMS / 0.3 A RMS / etc. Thereby it is difficult to make a precise estimation of the current

This can be seen in the Figure 41. For the steady state current measurement, Normal mode was used on the oscilloscope with the trigger source set to Channel 1 (where the current clamp was connected), one can also notice that the steady state current (yellow waveform) was not a sinusoid.

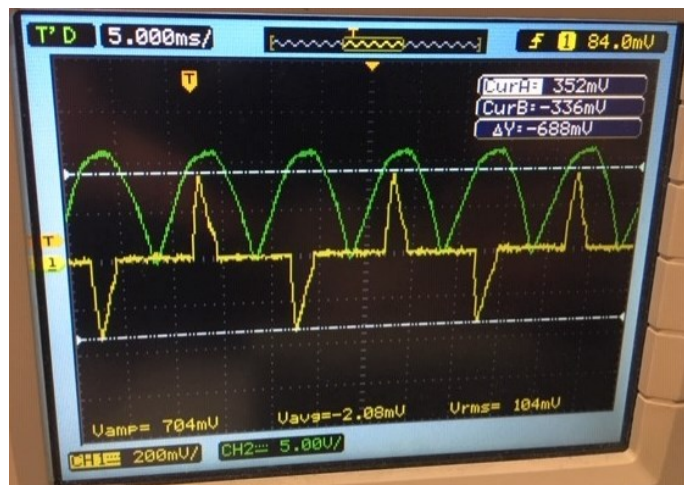


Figure 41 – Steady state current low value for an empty battery

For the Makita DC18RC charger and after these measurements, it was noticed that the IC was at its lowest amplitude when the charger was switched on at a phase angle close to zero degree. The IC was at its higher amplitude when the circuit was switched on at the 90-degree phase angle. The reset time between each measurement did not seem to have a huge impact on the measured IC amplitude. Moreover, the IC amplitude at all phase angles was higher when the battery was completely discharged.

It should also be noted that the TA 189 current clamp was able to measure 30 A maximum given to its datasheet [29], in some measurements the IC has reached 34 A, which is above the limit of that current clamp. However, the signal did not seem distorted, so maybe there is some headroom before the current clamp distorts the signal (in later measurements, see section 8 (Figure 47), it was noticed that the signal clipped clearly at approximately 34 A).

Given to these measurements, the Makita charger appeared to be a mainly resistive load.

Table 3 illustrates the IC measurements at different phase angles and battery states for a Dell Laptop charger.

Dell Laptop Characteristics:

Input:

100-240V AC 1.3A 50-60Hz

Output:

19.5V DC 2.31A 45W

Table 3. IC Measurements with Dell laptop charger

Battery Status	Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (mA)	Delay Q->IC (ms)	IC Duration (ms)	Reset Time (s)
Charged	0	7.6	0.88	150	20	6	5
Charged	45	26.4	0.88	150	19	5	5
Charged	90	32.8	0.88	150	19	5	5
50% Charged	0	9.6	1.44	315	20	7	5
50% Charged	45	27.2	1.44	315	19.5	6	5
50% Charged	90	32.8	1.44	315	19.5	4	5
Empty	0	9.6	2.24	450	19	8.5	5
Empty	45	26.4	2.24	450	19	6	5
Empty	90	39.2	2.24	450	19	4	5

Figure 42 shows the IC generated by a fully charged Dell charger switched on at a phase angle of around 90 degrees. The IC amplitude is equal to -3.28 V, which corresponds to 32.8 A since the current clamp output is 100 mV by Ampere.

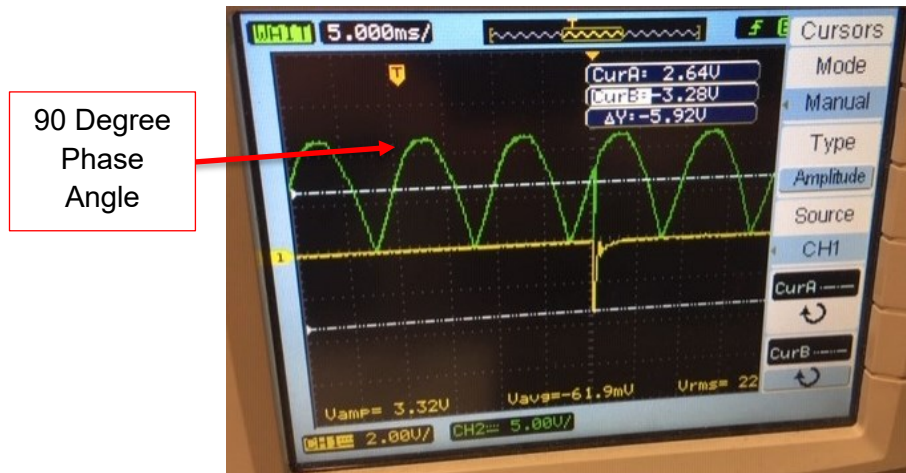


Figure 42. Dell charger 100 % charged / phase angle 90 degrees

Table 4 illustrates the IC measurements at different phase angles and battery states for a 3.42 A Acer Laptop charger.

Acer Laptop Characteristics:

Input:

100-240V AC 1.6 A 50-60Hz

Output:

19V DC 3.42A

Table 4. IC Measurements with Acer laptop charger

Battery Status	Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (mA)	Delay Q->IC (ms)	IC Duration (ms)	Reset Time (s)
Charged	0	11	0.72	130	20	7	5
Charged	45	28	0.72	130	20	6	5
Charged	90	34	0.72	130	19	4	5
50% Charged	0	11.2	1.48	340	20	7	5
50% Charged	45	31	1.48	340	20	5	5
50% Charged	90	33	1.48	340	20	4	5
Empty	0	11.2	1.6	375	18.5	7	5
Empty	45	17.2	1.6	375	19	7	5
Empty	90	37.6	1.6	375	19	3	5

N.B: Variations in the measurements of the IC at the 45-degree phase angle with an empty laptop compared to other battery states are possibly due to the position of the potentiometer, since the positions are adjusted visually and

manually it is not very precise, it is possible that the phase angle was not exactly at 45 degrees (but at 40 degrees for instance). However, it could be observed that the IC amplitude increased in relation with the phase angle.

Table 5 illustrates the IC measurements at different phase angles and battery states for a Tablet charger.

Tablet Charger Characteristics:

Input:

100-240V AC 1 A 50-60Hz

Output:

12V DC 2.58A / 5V DC 1A

Table 5. IC Measurements with tablet charger

Battery Status	Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (mA)	Delay Q->IC (ms)	IC Duration (ms)	Reset Time (s)
Charged	0	7.2	0.460	100	19	7	5
Charged	45	10.4	0.460	100	19	6.5	5
Charged	90	33.6	0.460	100	19	4	5
50% Charged	0	6.6	1.64	330	19.5	8.5	5
50% Charged	45	11.8	1.64	330	19	6	5
50% Charged	90	36.8	1.64	330	19	3.5	5
Empty	0	8	1.72	330	19.5	7	5
Empty	45	15.2	1.72	330	19.5	6	5
Empty	90	37.6	1.72	330	19	4	5

With the laptops and tablet chargers, there were also peak and RMS current fluctuations, but much lighter than with the Makita charger, for example, at 50 % charged, I steady Peak current was 1.64 A, but fluctuated briefly sometimes to 1.5 A, therefore it was possible to have a precise idea of the steady state current.

Table 6 illustrates the IC measurements at different phase angles and battery states for an UHF RFID Gun reader.

UHF RFID Power Pax Charger Characteristics:

Input:

100-240V AC 50-60Hz 1.4A Max

Output:

15V DC 4.34A 65.1W

Table 6. IC Measurements with power pax charger

Battery Status	Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (mA)	Delay Q->IC (ms)	IC Duration (ms)	Reset Time (s)
Charged	0	3.44	0.29	60	20	6	5
Charged	45	12.4	0.29	60	19.5	6	5
Charged	90	12.8	0.29	60	19.5	4.5	5
50% Charged	0	12.8	0.88	160	20	7	5
50% Charged	45	10.8	0.88	160	19.5	6	5
50% Charged	90	28	0.88	160	19.5	4	5
Empty (<25%)	0	12.8	1.52	320	20	7	5
Empty (<25%)	45	16.4	1.52	320	20	5	5
Empty (<25%)	90	29.2	1.52	320	20	5	5

Figure 43 illustrates the IC generated by a power Pax charger switched on at a phase angle of around 45 degrees.

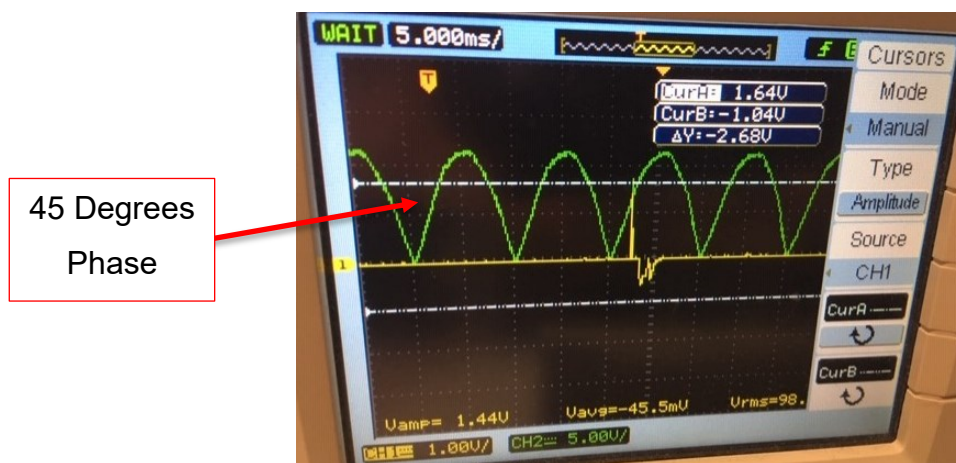


Figure 43. Power pax charger (empty) / phase angle 45 degrees

Measurements Conclusion:

From these measurements, it was observed that for each charger, the IC amplitude increased when the phase angle was increased, the lowest amplitude of the IC was found at a phase angle of zero degree, which could indicate that the chargers loads were mainly resistive. The highest IC in each case was when

the phase angle reached 90 degrees. Furthermore, the IC amplitude increased in relation to the state of charge of each battery, that effect was accentuated for 45- and 90-degrees phase angles compared to zero-degree phase angle.

Also, the IC duration decreased by a few milliseconds when the phase angle was increased. The IC duration was longer when the phase angle was zero-degree. Moreover, it was noticed that the IC waveform and amplitude was changing from measurements to measurements, the current peak could be positive or negative and a variation of 15 to 35 % could be observed between several measurements at the same phase angles. Therefore, inrush current values that were most frequently found were kept in the above tables.

7.6 Measuring IC of Meanwell SMPS

Meanwell SMPS measurements were also performed, to compare the inrush current to that generated by the various chargers.

First, the measurement of one SMPS with two 12 Ω resistors in parallel as the load was realized. A Meanwell 230V-24V SMPS was used. This setup equals a DC power of 96W. Measurements Results are shown in Table 7.

Table 7. IC of a SMPS (Meanwell RS-150) with a power of 96 W

Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (mA)	Delay Q->IC (ms)	IC Duration (ms)
0	24.8	2.8	890	18	10
45	15.2	2.8	890	18	7
90	26.4	2.8	890	18	6

The steady state current waveform and amplitude are shown in Fig. 44.

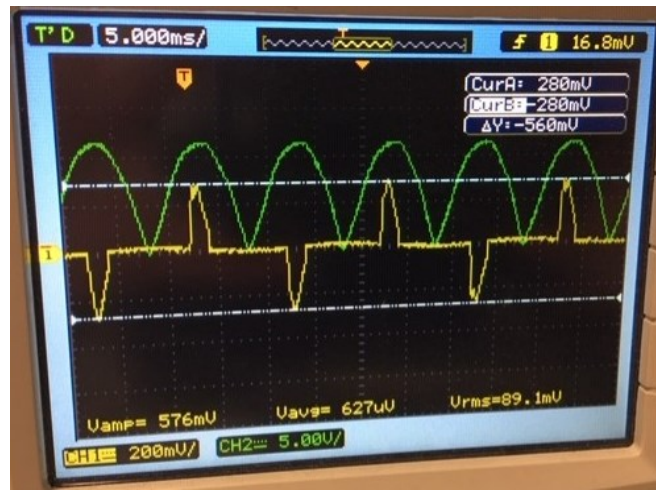


Fig. 44 – Meanwell SMPS (2x12 Ω resistors) Steady State Current

From that table we can calculate the AC power, which equal:

$$P = V \times I = 230 \text{ V} \times 890 \text{ mA} \cong 205 \text{ W} \quad (5)$$

This calculation is not exact, since the Meanwell power supply have an efficiency of 86% according to the datasheet (see Appendix 2), it should have an AC power of approximately 112 W [30]. This power difference could be due to the fact that the voltage and the current were not in phase on the AC side of the Meanwell power supply.

The same measurement was realized, but with one 12 Ω resistor as the load. DC Power=48 W. Results are shown in Table 8.

Table 8 – IC of a SMPS (Meanwell RS-150-24) with a power of 48 W

Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (mA)	Delay Q->IC (ms)	IC Duration (ms)
0	16	1.44	480	18	9
45	15.2	1.44	480	18	7.5
90	17.6	1.44	480	18	6

7.7 Measuring IC of Two Meanwell SMPS

Then, IC and steady state current of two Meanwell SMPS (each with two 12 Ω resistors in parallel) connected to the same power strip were measured, results are shown in Table 9.

Table 9 – IC of two SMPS (Meanwell RS-150-24) with a power of 2 x 96 W = 192 W

Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (A)	Delay Q->IC (ms)	IC Duration (ms)
0	30.4	4.4	1.66	18	9
45	27.2	4.4	1.66	18	7
90	35.2	4.4	1.66	18	6

7.8 Measuring IC of two Makita Chargers with Empty Batteries

Next, the IC and steady state current of two Makita chargers plugged into the same power strip were measured (see Table 10).

Table 10. IC measurements with two Makita DC18RC chargers

Battery Status	Phase angle (°)	IC (A)	I Steady Peak (A)	I Steady RMS (A)	Delay Q->IC (ms)	IC Duration (ms)
Empty	0	31.2	7.8/7.6/7.2/..	2.96/2.46/2.08/..	18	10
Empty	45	20.3	7.8/7.6/7.2/..	2.96/2.46/2.08/..	18	6.5
Empty	90	25.6	7.8/7.6/7.2/..	2.96/2.46/2.08/..	18	6

I steady Peak and RMS fluctuated between 7.8, 7.6 A and 7.2 A Peak or 2.94, 2.46 A and 2.08 A RMS. From time to time, the RMS / Peak current also jumped to lower values like 1 A RMS / 0.8 A RMS / 0.3 A RMS /etc. Thus, it was difficult to know the exact value of the current.

To double check our results, the measurements of the RMS current were also done with a multi meter (Fluke 115). In the same way, the RMS current fluctuated between multiple values (2.09A, 3.1A, 0.98A, 2.5A,0.53A,etc..).Thus, it was not possible to know the real value of the current drawn by the Makita chargers.

At zero degree, the IC of 2 SMPS with 12 Ω resistors or the IC of two Makita DC18RC are very close in amplitude and duration, and the zero degree phase angle position was the one on which the IC amplitude was at its maximum value.

From these measurements, it was observed that when multiple chargers or SMPS were used at the same time, it was not possible to predict anymore at which phase angle the IC will have its lower value. Previously, the lowest IC value was found at a phase angle of zero degree, but now the lowest value is found around 45-degrees. This is due to phase cancellation and summation between the different chargers; thus it is really difficult to predict the results. Thereby, there is no more advantage of switching the phase angle at zero degree when multiple chargers are used in conjunction.

Furthermore, it was not possible to link the RMS current consumption and the IC amplitude and duration.

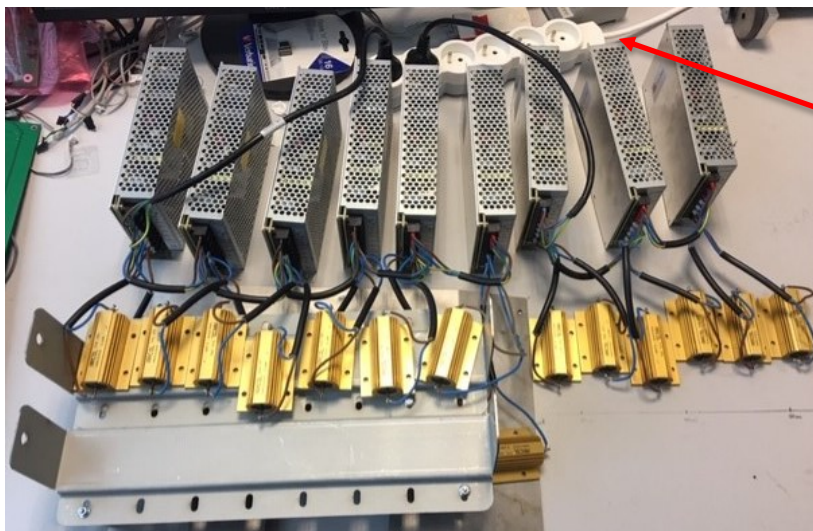
By looking at the tables above, it was noticed that the worst ICs were measured for the Makita charger, thus it would be possible to use this charger to determine the limits of the system (point where the main breaker would trip) and to measure the RMS steady state current. Since we did not have enough Makita chargers and given that the IC current footprint (amplitude and duration) was looking similar when we measured Makita charger and Meanwell SMPS, it was chosen to use SMPS (Meanwell RS-150-24) as a load reference to find out at what point the 8A circuit breaker would trip (the IC amplitude for the Meanwell SMPS was even higher at 45- and 90-degrees phase angles). Furthermore, as said earlier, it was not possible to know precisely the value of the steady state current of the Makita charger, since it fluctuated continuously.

8 Defining the Limit to Trip the Main 8A Breaker

Meanwell SMPS were used to define the IC limit to trip the main 8A breaker, and to define the maximum number of Meanwell SMPS that can be connected in series to the power strip at the output of the phase-controlled circuit. In the XL cabinet, the sockets are protected by an 8A circuit breaker (ABB S202M C8).

We carried out several tests, starting from three Meanwell SMPS plugged in at the output of the previous phase-controlled system, measuring the RMS steady state current with a DMM, and observing how many SMPS were needed to trip the main 8A breaker.

Figure 45 shows a setup with nine SMPS connected to the power strip at the output of the phase control circuit, current measurement with DMM and the addition of the 8A breaker are shown in Figure 46.



Power strip,
connected at
the output of the
phase control
circuit

Figure 45. Nine SMPS (Meanwell RS-150-24) setup

The 8A Main breaker (ABB CSS S202M) was also added to the circuit. To establish the probability of tripping the circuit breaker, measurements were taken 10 times for each configuration of power supplies, and by turning the current on and off every 10 seconds.

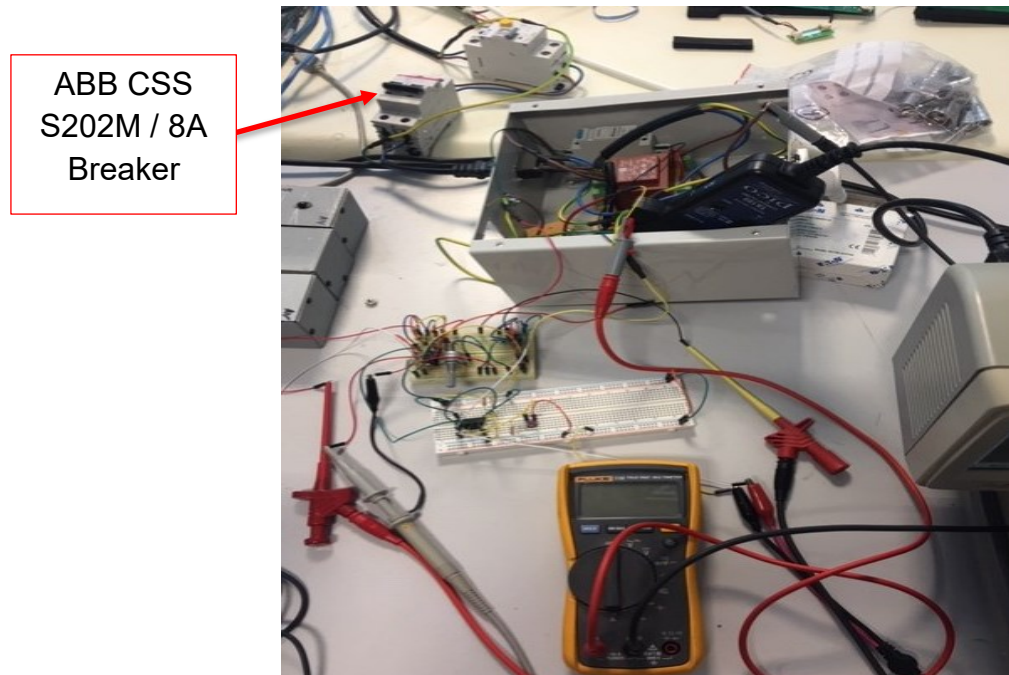


Figure 46. RMS steady state current measurement with DMM and 8A breaker

Measurements results are presented in Table 11.

Table 11. RMS current measurements and probability of tripping

Number Meanwell SMPS	Phase Angle (Degrees)	I steady (RMS) (A)	Probability of Tripping the Breaker (%)
3	0	2.43	0
3	45	2.43	0
3	90	2.43	0
4	0	3.2	0
4	45	3.2	0
4	90	3.2	0
5	0	3.97	0
5	45	3.97	0
5	90	3.97	0
6	0	4.8	0
6	45	4.8	0
6	90	4.8	0
7	0	5.6	0
7	45	5.6	0
7	90	5.6	30
8	0	6.28	50
8	45	6.28	70
8	90	6.28	60
9	0	6.95	70
9	45	6.95	100

9	90	6.95	50
10	0	7.8	80
10	45	7.8	60
10	90	7.8	50

From the measurements, it was found that the main breaker was tripping regularly with a probability between 50 to 70 % depending on the phase angle, when 8 Meanwell SMPS with two 12 Ω resistor in parallel were used ($8 \times 96 \text{ W} = 768 \text{ W}$). In that case, the steady state current (RMS) was equal to 6.28 A, for each added SMPS, the steady state current increased by approximately 0.8 A.

With 6 Meanwell SMSP or less connected, the probability of tripping reduced to zero percent. All in all, we connected up to 10 Meanwell SMPS in the circuit, but in that case the tripping probability increased between 60 to 80 % depending on the phase angle. It has also been observed that the probability of tripping the main breaker could not be linked to the phase angle, in some cases, the probability was lower at a phase angle of zero degree, and in other cases it was higher.

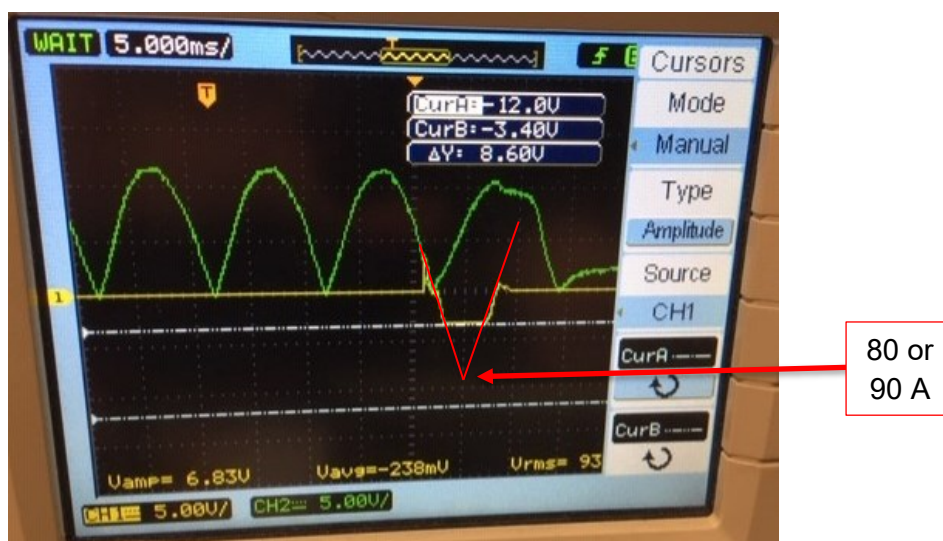


Figure 47. IC clipping with 8 Meanwell SMPS / phase angle 0 degree

It was tried to measure the IC in each case, but the signal was clearly clipping on the oscilloscope (see Figure 47) around 34 A, so it was only possible to make a rough approximation by extrapolation. For example, the IC for 8 Meanwell SMPS could be estimated around 80 or 90 A.

9 Testing the ICL Prototype and Setting the Limits of the System

As stated earlier, Nexess had previously worked on an ICL circuit prototype based on an NTC but the project has not been finalized, thus a prototype was available. It was decided to test this ICL prototype circuit with the Meanwell SMPS to see at which point the main 8A breaker was tripping.

Since Nexess prototype was based on an NTC and mechanical relays, it corresponded to the solution we were looking for. Conventional mechanical relays were a better choice compared to SSR because they were cheaper and in our previous tests, it was observed that it was not possible to establish a phase relationship with the magnitude of the inrush current when several power supplies were connected together, thus there was no need to switch the power at the zero-crossing point.

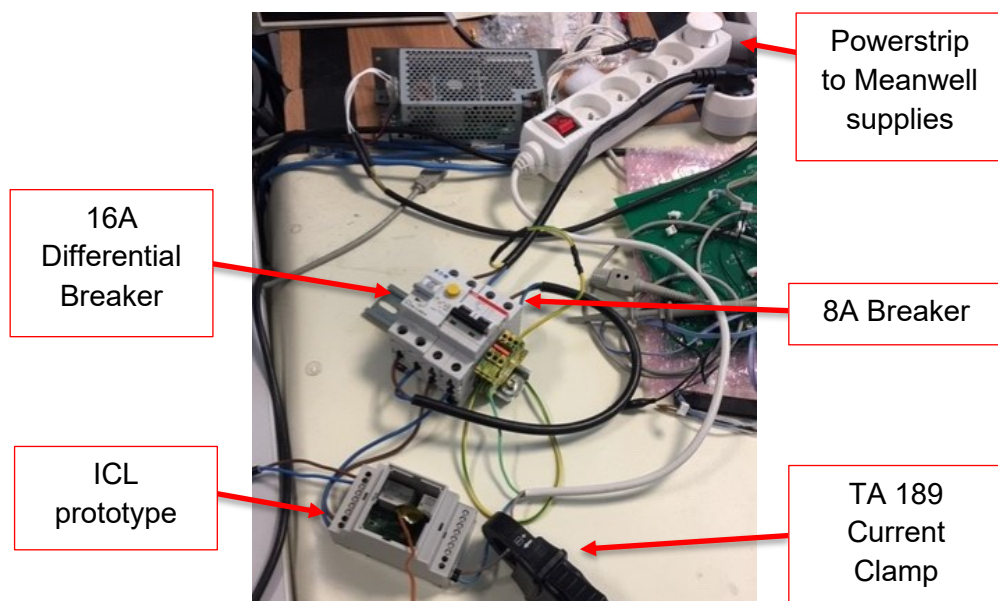


Figure 48. Measurements with ICL Prototype

The ICL prototype had been mounted in a drawer that had been set aside. Figure 48 shows our setup with the ICL prototype installed.

In the same way as before, we tested the circuit with six Meanwell SMPS (I steady (RMS) $\cong 4.8 A$) and incrementing by one SMPS each time to see at which point

the main breaker was tripping, when the ICL limiter was into the circuit. Each time, the NTC temperature was also measured with a Fluke 51 thermometer and the IC.

With ten Meanwell SMPS, the 8A breaker was still not tripping, the probability over ten trials of tripping the 8A breaker was still of zero percent, that confirmed that the ICL prototype was working well, and even better than we expected. Moreover, the temperature never exceeded 45 degrees during our tests, which meant that the NTC resistance was not varying due to temperature (the datasheet specified that the NTC resistance decreases above 65 degrees, see Appendix 3 [31]).

IC measurement for 10 Meanwell SMPS ($10 \times 96W = 960W$) can be seen in Figure 49, it was noticed that the IC duration was longer when the ICL prototype was used and that there was a second peak after a few ms. In the figure below, the IC peak was around 33.6 A, and the duration was approximately 128 ms (second peak included). It could also be noted that the current clamp limit was reached with this setup.

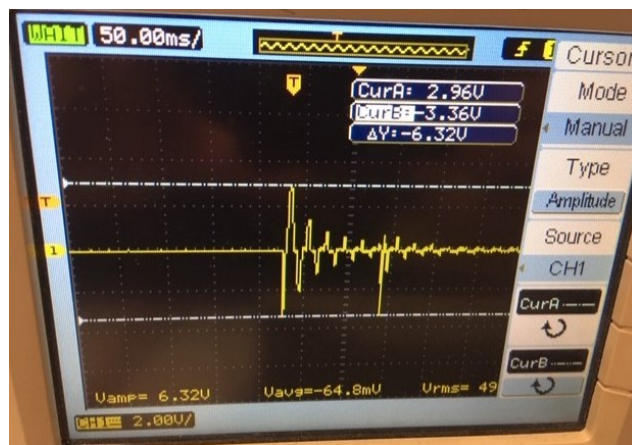


Figure 49. IC Measurement for 10 SMPS with ICL prototype

The fact that the IC was longer could be explained because the IC was limited by the ICL, so it took more time to charge the capacitors inside each SMPS.

It was noticed that even with 13 Meanwell (with two 12Ω resistors plugged on each one), the 8A breaker was still not tripping when the circuit was active during approximately 10 seconds (I steady state (RMS) $\cong 10$ A).

Looking at the 8A breaker C characteristic curve (see. Appendix 4), it was noticed that even at $1.5 \times I_n$ (12A), the breaker was supposed to trip between 20 seconds and 15 minutes, thus the behaviour described above was correct.

Since we had a steady state current of around 10A with our previous setup, the 8A breaker was supposed to trip between 1 min and more than 60 minutes ($1.3 \times I_n \cong 10A$). Because the resistors ($12 \Omega / 100W$) became too hot during the tests, it was necessary to put them on metal supports to dissipate the heat (as in the setup without the current limiter), but it was too risky to leave them on too long, due to the risk of explosion.

Furthermore, only 27 resistors were at our disposal, so it was not possible to increase the steady state voltage without buying new resistors and SMPS.

Therefore, it was decided to verify that the 8A breaker (C curve) was correct by setting up a Schneider 2A breaker (C curve) that we had at our disposal and to verify that the breaker was tripping at the datasheet specified range of time.

Six Meanwell SMPS were used (in conjunction with three 12Ω resistors in parallel). With this setup I steady state (RMS) $\cong 7A$ (corresponds to $3.5 \times I_n$). Given the Type C curve (see. Appendix 4) we verified that the 2A breaker was tripping at the right time. A tripping time of 15 s was measured (tripping range was between 1.6 s and 35 s), which was correct.

From these tests, it was verified that the ICL prototype was working correctly and able to limit the current even above the 8A breaker nominal current. The 8A breaker C curve was working as expected, but it is not recommended to go higher the breaker nominal steady state current (RMS) of 8A. That sets the limits of the system with the ICL prototype.

Looking at the ICL prototype, some improvements could have been made, for example, replace the transistors (as the gate source voltage of the transistors was too high), reverse the relays contacts (NO/NF), add fly-back diodes to the relays and from a PCB layout point of view, separate a little more the 230V tracks from each other and from the other tracks and components.

On the prototype, some tracks had been cut on both side of the PCB, to correctly reverse the relays contacts (NO/ NF), and wires had been added to the bottom

side of the PCB to correct the initial routing. Before plugging the ICL prototype to test it, it was necessary to widen the spaces of the cut made in the tracks to avoid any risk of short circuit when first powered up. ICL prototype PCB (top and bottom view) could not be presented in this document, as well as the schematics of the initial prototype developed by Nexess, for privacy reasons.

10 Conclusion

A new ICL prototype was finally developed, but it was not allowed to publish the entirety of this section because it contained confidential informations such as schematics, circuit simulations and pictures of the PCB layout, etc. Some modifications to the original circuit and simulations in LT spice were done, and the PCB layout was done in Altium designer. An additional temperature detection circuit and a current monitoring circuit were also added to the new ICL prototype.

At the end, the PCB layout was carried out, and the usual manufacturing files (gerbers, NC drill files and BOM) were generated. The next steps would be to order the assembled PCBs and to do some testing of the new ICL prototype, to check that it conforms to our expectations. Reaching the end of the time allotted to complete this thesis work, the assembled PCBs will be ordered and tested in the coming weeks by the company and will have to pass qualification tests before it could be implemented in Nexess equipment. Depending on the results, some adjustments may be achieved, or new features may be added.

All in all, this inrush current limiter project was a success, it gives us a detailed overview of all the steps that are necessary when developing a prototype and is a good example of a development project from start to finish.

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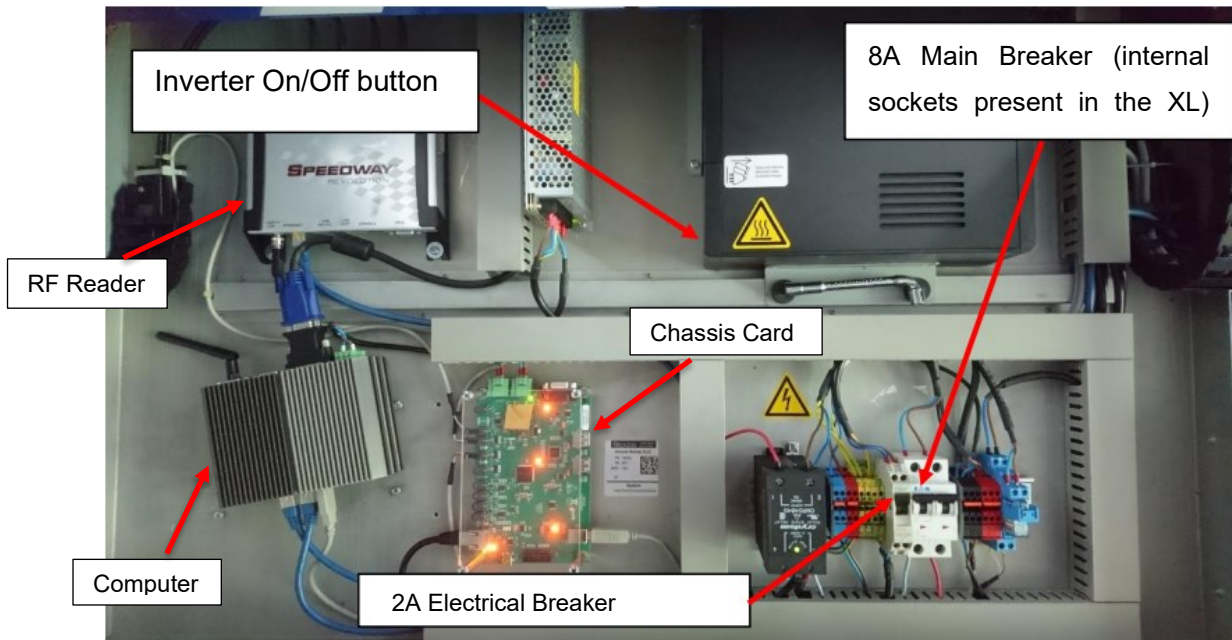
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Picture of the XL Cabinet and Front Drawer:

Front Drawer:



XL Cabinet:



RS-150-24 Datasheet



150W Single Output Switching Power Supply

RS-150 series



■ Features :

- Protections: Short circuit / Overload / Over voltage
- Cooling by free air convection
- LED indicator for power on
- 100% full load burn-in test
- All using 105°C long life electrolytic capacitors
- Withstand 300VAC surge input for 5 second
- High operating temperature up to 70°C
- Withstand 5G vibration test
- High efficiency, long life and high reliability
- 3 years warranty



SPECIFICATION

MODEL	RS-150-3.3	RS-150-5	RS-150-12	RS-150-15	RS-150-24	RS-150-48	
OUTPUT	DC VOLTAGE	3.3V	5V	12V	15V	24V	48V
	RATED CURRENT	30A	26A	12.5A	10A	6.5A	3.3A
	CURRENT RANGE	0 ~ 30A	0 ~ 26A	0 ~ 12.5A	0 ~ 10A	0 ~ 6.5A	0 ~ 3.3A
	RATED POWER	99W	130W	150W	150W	156W	158.4W
	RIPPLE & NOISE (max.) Note.2	80mVp-p	80mVp-p	120mVp-p	120mVp-p	120mVp-p	200mVp-p
	VOLTAGE ADJ. RANGE	3.2V ~ 3.5V	4.75 ~ 5.5V	11.4 ~ 13.2V	14.25 ~ 16.5V	22.8 ~ 26.4V	45.6 ~ 52.8V
	VOLTAGE TOLERANCE Note.3	±3.0%	±2.0%	±1.0%	±1.0%	±1.0%	±1.0%
	LINE REGULATION Note.4	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%	±0.5%
	LOAD REGULATION Note.5	±2.0%	±1.0%	±0.5%	±0.5%	±0.5%	±0.5%
	SETUP, RISE TIME	800ms, 20ms/230VAC 1200ms, 30ms/115VAC at full load					
HOLD UP TIME (Typ.)	28ms/230VAC 20ms/115VAC at full load						
INPUT	VOLTAGE RANGE	88 ~ 132VAC / 176 ~ 264VAC selected by switch			248 ~ 373VDC(Withstand 300VAC surge for 5sec. Without damage)		
	FREQUENCY RANGE	47 ~ 63Hz					
	EFFICIENCY(Typ.)	74%	78%	83%	84%	86%	87%
	AC CURRENT (Typ.)	3A/115VAC 2A/230VAC					
	INRUSH CURRENT (Typ.)	COLD START 40A/230VAC					
LEAKAGE CURRENT	<2mA / 240VAC						
PROTECTION	OVERLOAD Note.8	110 ~ 150% rated output power Protection type : Hiccup mode, recovers automatically after fault condition is removed					
	OVER VOLTAGE	3.8 ~ 4.45V	5.75 ~ 6.75V	13.8 ~ 16.2V	17.25 ~ 20.25V	27.6 ~ 32.4V	55.2 ~ 64.8V
ENVIRONMENT	WORKING TEMP.	-25 ~ +70°C (Refer to "Derating Curve")					
	WORKING HUMIDITY	20 ~ 90% RH non-condensing					
	STORAGE TEMP., HUMIDITY	-40 ~ +85°C, 10 ~ 95% RH					
	TEMP. COEFFICIENT	±0.03%/°C (0 ~ 50°C)					
	VIBRATION	10 ~ 500Hz, 5G 10min./1cycle, period for 60min. each along X, Y, Z axes					
SAFETY & EMC (Note 6)	SAFETY STANDARDS	UL60950-1, TUV EN60950-1 approved					
	WITHSTAND VOLTAGE	I/P-O/P:3KVAC I/P-FG:2KVAC O/P-FG:0.5KVAC					
	ISOLATION RESISTANCE	I/P-O/P, I/P-FG, O/P-FG:100M Ohms / 500VDC / 25°C/ 70% RH					
	EMC EMISSION	Compliance to EN55032 (CISPR32) Class B, EN61000-3-2,-3					
EMC IMMUNITY	Compliance to EN61000-4-2,3,4,5,6,8,11, EN61000-6-2 (EN50082-2), heavy industry level, criteria A						
OTHERS	MTBF	244Khrs min. MIL-HDBK-217F (25°C)					
	DIMENSION	199*98*38mm (L*W*H)					
	PACKING	0.7Kg; 20pcs/15Kg/0.8CUFT					
NOTE	<p>1. All parameters NOT specially mentioned are measured at 230VAC input, rated load and 25°C of ambient temperature.</p> <p>2. Ripple & noise are measured at 20MHz of bandwidth by using a 12" twisted pair-wire terminated with a 0.1uf & 47uf parallel capacitor.</p> <p>3. Tolerance : includes set up tolerance, line regulation and load regulation.</p> <p>4. Line regulation is measured from low line to high line at rated load.</p> <p>5. Load regulation is measured from 0% to 100% rated load.</p> <p>6. The power supply is considered a component which will be installed into a final equipment. All the EMC tests are been executed by mounting the unit on a 360mm*360mm metal plate with 1mm of thickness. The final equipment must be re-confirmed that it still meets EMC directives. For guidance on how to perform these EMC tests, please refer to "EMI testing of component power supplies." (as available on http://www.meanwell.com)</p> <p>7. Length of set up time is measured at cold first start. Turning ON/OFF the power supply very quickly may lead to increase of the set up time.</p> <p>8. Extra consideration should be taken when selecting output wiring for 3.3V and 5V models. This is to prevent the protection modes for overload and short circuit from becoming constant power.</p>						

Ametherm MS32 20010 Datasheet

Data Sheet
MS32 20010

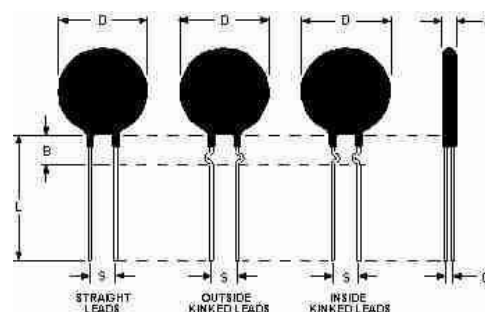
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ISO9001:2008 Certified

Mechanical Specifications (mm)

D:	31.0	± max
T:	10.0	± max
Lead Diameter	1.0	± nom
S:	7.8	± nom
L:	38.0	± nom
Coating Lead Run Down (straight Leads)	4.0	± max
B:	7.80	± nom
C:	6.70	± nom



Electrical Specifications

Resistance:	20.0 Ω	± 25 %
Max Steady State Current upto 65°C:	10.00	A
Max Rec. Energy Rating:	250	J
Actual Failure Instantaneous Energy:	500	J
Maximum Capacitance @ 120 VAC:	17,000	μf
Maximum Capacitance @ 240 VAC:	4,341	μf
Maximum Capacitance @ 440 VAC:	1,003	μf
Maximum Capacitance @ 680 VAC:	500	μf
Resistance @ 100% Max Current:	0.00	Ω
Resistance @ 50% Max Current:	0.64	Ω
Body Temperature at 100% Max Current:	224.00	°C
Dissipation Constant:	45.4	mw/°C
Thermal Time Constant:	194	Sec.
Material Type (for Beta and Curve):	I	

Comparison of tripping characteristics “C” and “K”

“K” solves the conflict of service continuity in the event of peak currents and rapid disconnection in the event of a short-circuit.

In circuits where inrush currents or starting current peaks can occur due to motors, chargers, welding transformers, etc., tripping characteristic “K” has proven to be successful for more than 70 years.

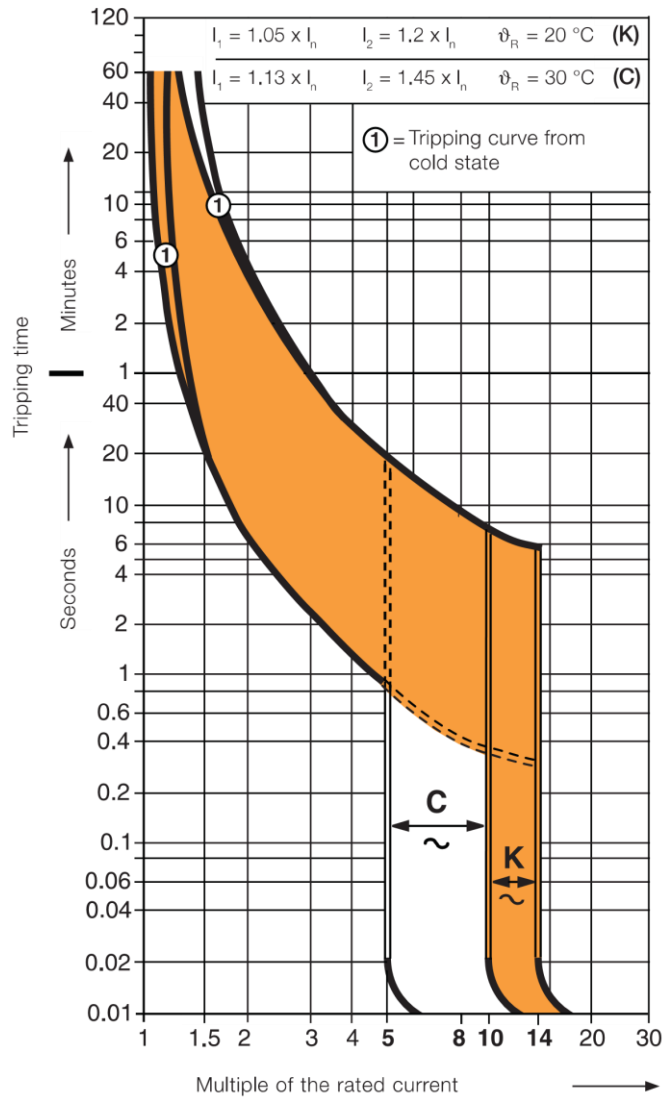
Current peaks of up to $10 \cdot I_n$ do not lead to unintentional disconnection. Tripping characteristic “C” only withstands current peaks of up to $5 \cdot I_n$.

Note

With direct current, the tripping values of the electromagnetic releases are increased by a factor of 1.5.

Protection against overload

As stated before it is obvious that tripping characteristic “K” provides better protection during operation and is easier to choose.



Temperature of PVC-insulated cables at overload

Load	Cable temperature*
$1.0 \times I_n$	70 °C
$1.2 \times I_n$	86 °C
$1.45 \times I_n$	116 °C

Service life of PVC-insulated cables using the Arrhenius equation

Cable temperature	Service life
70 °C	20.0 years
90 °C	2.5 years
100 °C	1.0 year

* 90 % of the temperature value is reached from operating temperature after 5 minutes.