Solutions for Current Protection

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PTC THERMISTORS FOR INRUSH CURRENT LIMITING

Improving Inrush Current Protection

Many applications today, including industrial machinery, power tools and other high current equipment, use limiting inrush current as a major design consideration to combat the problematic effects of inrush current. Inrush current occurs when a system powers on and experiences a spike in current. This current can be substantially higher than standard operating current. If not properly managed, it can reduce the effective operating life and impose damage to equipment. For example, inrush current could disable a cooling fan, eventually leading to total system failure.

Applications that are switched on and off quickly, such as welding equipment, present a particular concern for limiting inrush current. The limiting inrush current circuit must reset instantaneously during each power on to protect the system. This further complicates the management of inrush current.

Inrush Current Overview

During power on, a high inrush current can occur because the power supply's link capacitor functions to dampen ripples in the output current. This capacitor acts like a short, causing an inrush of current. The inrush lasts until the capacitor is charged. Length of the inrush current depends upon the power supply and link capacitor.

The low internal resistance of the power supply aggravates this issue. Any resistance in the power supply introduces inefficiencies through heat. To minimize resistance, engineers typically use an inductive load. While this improves the overall operating efficiency of the power supply, the lack of resistance enables the inrush current to pass through to the main system when the power supply switches on.

Temporarily introducing a high resistance between the power supply and system at power on limits inrush current. The resistance switches out when the initial current surge at power on reaches completion.

NTC-Based Limiting

For many systems, a negative temperature coefficient (NTC) thermistor can effectively limit inrush current. An NTC thermistor provides variable resistance based on its temperature. Placing an NTC thermistor between the power supply and system limits inrush current (see Fig. 1). At first, the initial temperature of the NTC thermistor is low, providing high resistance. When the system is powered on, it energizes the NTC thermistor, causing the temperature to rise, and thus lowering resistance. As resistance drops to a low value, the current passes through without adversely affecting normal operation or power efficiency.

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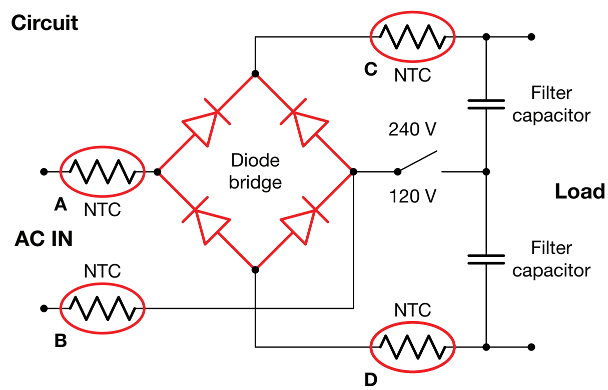

Fig. 1 - NTC-Based Limiting Circuit

Inrush current limiters are typically installed in either locations A and B or C and D and depending on applications sometimes only on location A or C.

To limit inrush current, an NTC thermistor is placed between the power supply and system (see Fig. 1). Upon power on, the NTC thermistor provides high resistance to limit inrush current. As the inrush current drops, the NTC thermistor self-heats and its resistance drops to a low enough value to pass current through.

For example, consider a system with 10 A continuous current and an inrush current of 100 A. Upon power up, an NTC MS32 100 15 thermistor has an initial resistance of 10 ohms. Instead of passing 100 A, the NTC MS32 100 15 only allows 35 A to pass through. Then, as the NTC MS32 100 15 self-heats, its resistance drops and lowers the current until the inrush current is over. The NTC MS32 100 15 still continues to heat, dropping resistance to as low as 0.05 ohm where it reaches a steady state and passes current through minimum loss in efficiency.

NTC-based limiting has several advantages compared to a surge limiting circuit that uses a fixed resistor and bypass circuit. An NTC-based circuit typically occupies half the board space of a fixed resistor. It also has a very simple selection criteria to design in the circuit. Because resistance drops as it self-heats, no bypass circuit is needed to disable the limiting circuit. Finally, an NTC-based circuit has a lower total cost compared to limiting based on a fixed resistor.

PTC-Based Limiting

NTC thermistors are the most commonly used limiter. They have a wide range of uses and applications. However, a few scenarios exist that require a positive temperature coefficient (PTC). If a system meets one of the exceptions listed below, a PTC thermistor is the best choice.

Exceptions:

- Ambient temperature is greater than room temperature: If the ambient temperature is already high, the resistance of the NTC thermistor will be lower when the system is powered on. This lower resistance will reduce the limiting capabilities of the NTC thermistor and could put the system at risk.
- Ambient temperature is less than room temperature: If the ambient temperature is already low, the resistance of the NTC thermistor will be very high. The high resistance could limit all of the current and prevent the system from actually turning on, even after the initial inrush ends.
- Reset time needs to be near-zero: Certain types of equipment, such as welding gear or a plasma cutter, switch on and off frequently as part of their normal operation. This creates multiple instances of inrush current. NTC-based limiting operates on the nature of the NTC thermistor to self-heat and lower its resistance. However, when a system is quickly turned off and then on again, the NTC thermistor may not have completely cooled. It takes time for the NTC thermistor to release its heat and reset, dependent upon the size and mass of the NTC thermistor. If the NTC thermistor has not had sufficient time to cool, it will have a lower resistance when the system is turned on again, reducing its ability to handle the inrush current and protect the system.
- Short circuit: a short circuit drops the internal resistance of a system to near zero, quickly raising the current the system draws from the power supply. As the NTC thermistor limits this current, it quickly increases in temperature, thus lowering its resistance. This allows more of the current to flow through until it can damage the system. High current from a short can also destroy the NTC thermistor.

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PTC-Based Limiting Analysis

When the previous scenarios occur, a positive temperature coefficient (PTC) thermistor can provide effective inrush current protection. A PTC thermistor functions opposite to an NTC thermistor: as temperature rises, its resistance increases. Resistance begins to increase rapidly at Curie temperature (Tc). For example, Fig. 2 shows the behavior of a PTC MCL20500100 thermistor compared to an NTC thermistor. At Tc resistance increases rapidly. At low temperatures resistance stays constant.

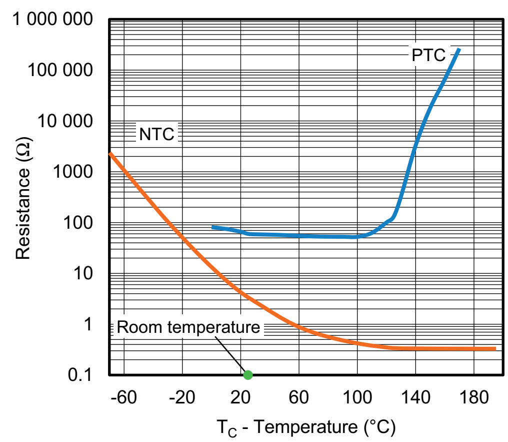

Fig. 2 - Resistance vs. Temperature

Resistance for an NTC thermistor drops as it self-heats while resistance increase for a PTC MCL20500100 thermistor. At a specific threshold, 120° C for the PTC MCL20500100, resistance increases sharply, enabling the PTC MCL20500100 to respond quickly to inrush current. Also note how the PTC MCL20500100 has a flat response at low temperatures, making it effective across the entire temperature spectrum.

PTC Thermistor Trade-Offs

There are a few tradeoffs when designing in a PTC-based limiting circuit. A PTC thermistor costs about 1.5 times more than an NTC thermistor. Additionally, PTC-based limiting requires an active circuit to bypass the PTC thermistor to prevent shutting the entire system down. As resistance increases, it limits the incoming current. This occurs even after the inrush current has dropped to normal levels.

A bypass circuit is active during power on for a set interval, typically 3 or 4 times the amount it takes for the inrush current to settle (see Fig. 3). Then, the bypass circuit shuts itself off and sends current back through the PTC thermistor to protect the system against shorts. If the bypass circuit were always triggered by a high current, the limiting circuit would not provide protection during a short. Overall, the increased responsiveness and advanced protection outweigh the added complexity and cost of a bypass circuit.

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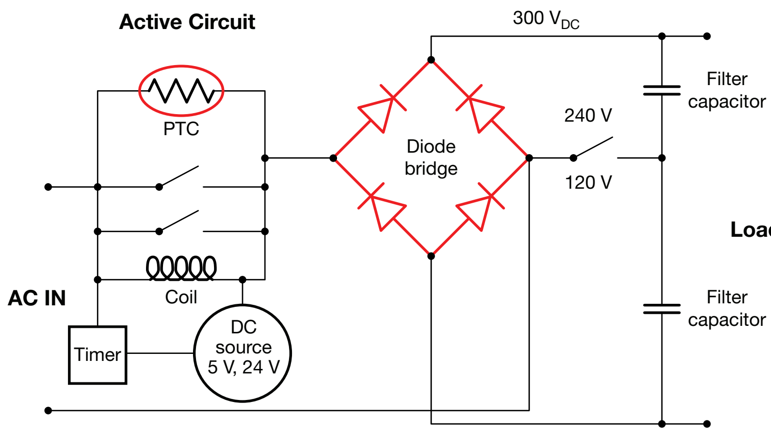

Fig. 3 - Complete PTC-Based Limiting Circuit, With Bypass Circuit

A PTC-based limiting circuit requires a bypass circuit to send current back through the PTC thermistor to protect the system against shorts. By setting the bypass to 3 or 4 times the amount it takes for the inrush current to settle, response time for the PTC-based limiter is extremely fast.

Conclusion

NTC thermistors limit inrush current by providing series resistance at the moment the device is powered on. They are also the most commonly used thermistor because they fit a wide range of equipment. Certain scenarios, however, may require PTC thermistors. These thermistors stop inrush current by providing high resistance in high temperatures. Examples include industrial equipment, power tools, and other fast switching systems (see Table 1). For these cases, PTC thermistors provide cost-effective protection and superior responsiveness. Other benefits include: near-zero reset time, ability to operate in extreme temperature conditions, and effectiveness when limiting high current from shorts.

NTC VS. PTC COMPARISON TABLE

PTC VS. NTC	SIZE	RESET TIME	EFFECTIVE OPERATING TEMPERATURE	PROTECTION AGAINST DEAD SHORTS
NTC	• Dependent on the amount of energy the device needs to absorb, based on size of link capacitor, KVA of transformer, and input voltage	• Ranges from a few seconds to several minutes, dependent on size • Effected by airflow that travels through leads, such as fan and heatsinking	• Operates between 0 °C and 65 °C without any derating • Temperatures below 0 °C increase resistance, possibly effecting operation • Temperatures above 65 °C lower resistance, possibly effecting operation	• Cannot handle shorts, such as charge time of the link capacitor for short durations • Short circuit current continues to increase beyond rating of NTC, causing failure
PTC	• Dependent on the amount of steady-state current required before switching to high state of resistance and voltage handling capability	• Activation suppresses inrush current with high resistance to occur instantaneously	• Operates efficiently at both, high and low, temperatures ranging from -40 °C to +90 °C • Effectively blocks inrush current and switches out of the circuit very quickly	• Reduced reset time protects against shorts • Resistance rapidly increases once heated and stops current until fault is removed

PTC-based inrush current limiting provides many advantages over fixed- or NTC-based limiting for applications such as fast switching and high current industrial equipment and power tools.

References

- Special thermistors limit inrush current: www.ametherm.com/inrush-current/inrush-current-limiters-pcim/
- How to stop inrush current: www.ametherm.com/inrush-current/how-to-stop-inrush-current/
- Ametherm thermistor datasheet: www.ametherm.com/datasheetspdf/MCL20500100A.pdf

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INVERTER INRUSH CURRENT PROTECTION, PROTECT AN INVERTER FROM INRUSH CURRENT

Inverters

Inverters are electrical systems that provide variable voltage (AC output) when connected to a DC input source. Inverters are available in two varieties: three phase and single phase. These inverters are also known as static frequency battery chargers or variable frequency drives.

Inrush Current in Inverters

A common failure of inverters is overloading the inverter due to inrush current. This is due to the fact that most inverters are designed with a minimum amount of resistance to increase their efficiency and minimize losses due to heat.

INVERTER COMPONENT	CAUSE OF FAILURE
Failure of electrolytic capacitors	Current and voltage stress
Welding of contactors	Inrush current
Failure of Bridge rectifiers	Inrush currents greater than the rating specified

Cause of Inrush Current Failure

An overload condition will occur even if you switch on three appliances–one by one–connected to an inverter.

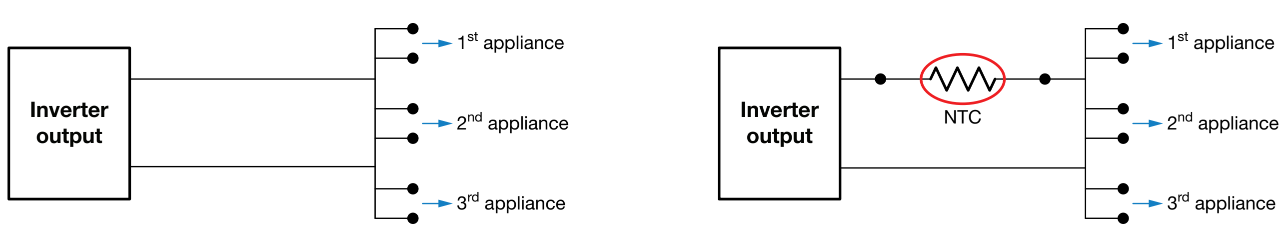
Consider the following:

- A 1000 W inverter (more specifically, a 1500 W inverter with 50 % total overload capacity)
- Three standard appliances, such as a refrigerator of 300 W, an LCD Television of 300 W, and a computer of 300 W. Total load for these appliances: 900 W
- A 1000 W inverter is fully capable of running the above three appliances
- The overload condition happens because of energy required for start-up. But, the start-up or inrush current for each appliance could be as high as 900 W or 3 times the rated power

The Inverter Overloads in the Following Scenario

- Step 1: if we switch on the first appliance, the load is 900 W which is less than the rated capacity of the inverter. Thus, no overload situation is encountered
- Step 2: if you switch the second appliance, the total wattage needed is as follows: First appliance 300 W + second appliance 900 W = 1200 W. No overload situation is encountered
- Step 3: if you switch the third appliance, the total wattage needed as follows:
- 1^{st} appliance 300 W + 2^{nd} appliance 300 W + 3^{rd} appliance 900 W = 1500 W

Notice that an overload condition is encountered as soon as the third appliance is switched on to the inverter, see (a) in the figure below:



(a) Without Using a Thermistor

(b) With Using a Thermistor

Fig. 4 - Inverter Inrush Overload Diagram

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Solution - Inrush Current Limiter

Use an inrush current limiting thermistor (see Fig. 4 (b)) to address the overload scenario of the sample problem:

- As per step 3 above, the inverter wattage needed including the overload condition > 1500 W
- Since max. output power allowed is 1000 W
- Allowed current: 8.0 A, 50 × 2 at 120 V
- Normal continuous current per appliance = 300 W/120 V = 2.50 A
- Due to inrush current = 2.50 A × 3 = 7.50 A
- Duration of inrush = one cycle = 1 × 1/50 s = 0.02 s
- Energy of the thermistor = 120 V × 7.50 A × 0.02 s = 18.0 J (the energy requirement, mentioned above, is needed to handle without self destruction)
- So, for three appliances that start up at the same time, we need 3.0 × 18.0 J = 54 J
- Minimum resistance: 120 V × 1.414/8.0 A = 21.21 Ω (this ensures that the current does not exceed 8.0 A)
- So if we assume ambient of 50 °C, min. resistance = 40 Ω, so we can reconnect

Ametherm Suggests Two Methods for Solving the Inrush Current Problem

Method (a)

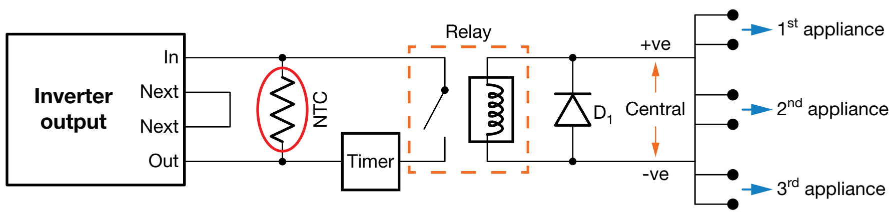

Fig. 5 - Inrush Current Inverter Schematic

In the above circuit (Fig. 5):

- NTC = SL22S0004 (50 Ω, 4.0 A, 75 J), UL (E204153), CSA (CA40663) is used to bypass the surge after one second
- Note that the NTC inrush current limiter does not interfere with the efficiency of the inverter since the relay is also protected from the inrush current by the thermistor. The thermistor will conduct through the relay with 99.2 % efficiency loss of current

Method (b)

As shown in Fig. 6, choose Vishay Ametherm P/N: MS3220008 × 2 to provide 40 Ω, 10 A, 500 J.

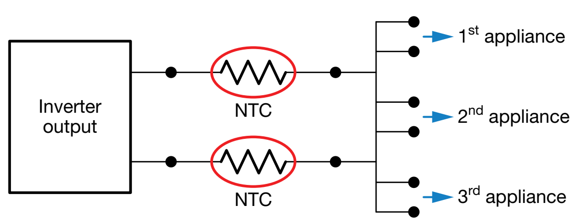

Fig. 6 - Inrush Current Inverter Schematic

- Efficiency C 8.0 A = I^2R = 14.1 W losses due to thermistor
- RC 8.0 A = 0.22
- Efficiency = 985.90/1000 W = 98.6 %

Conclusion: method (b) is more cost effective

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Inverter Circuits With Thermistors

Simple NTC thermistors are shown below in the following three circuits: Fig. 7, Fig. 8, and Fig. 9. These thermistors minimize the effect of inrush current on components, such as bridge or link capacitors.

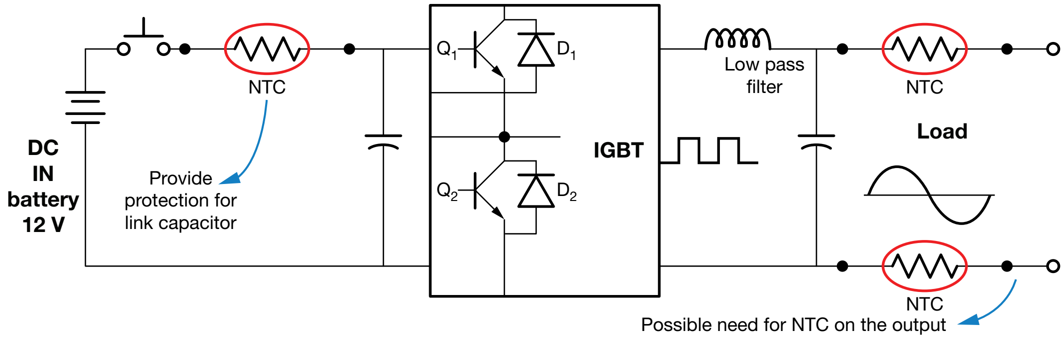

Fig. 7 - Schematic - Classic Inverter Circuits With NTC Inrush Current Limiters

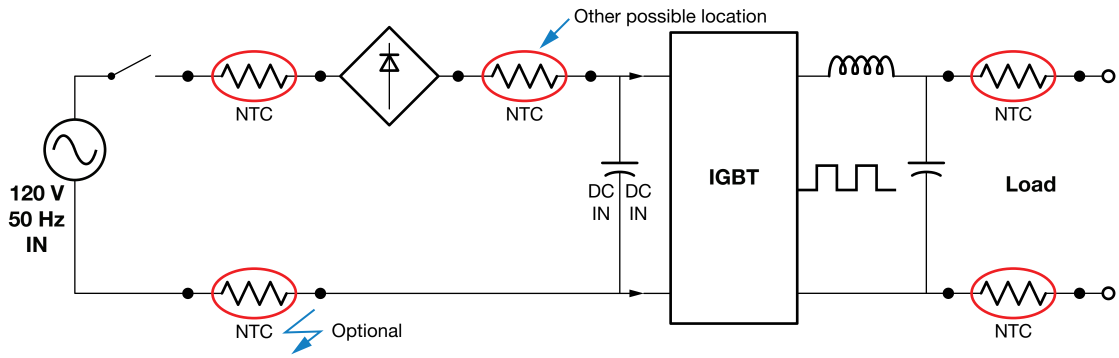

Fig. 8 - Schematic - Frequency Charger With Inrush Current Limiters

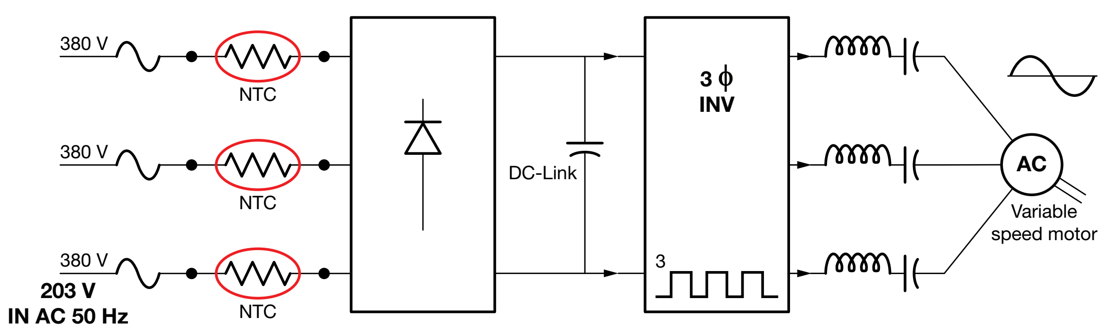

Fig. 9 - Schematic - Variable Frequency Drive

References

- Elliot Sound Products
- Sinetech Advanced Power Products
- Rockwell Automation Publication PFLEX_A700lk_EN_P Sept 2011
- US Patent 2003/0150369A1

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TRANSFORMER INRUSH CURRENT PROTECTION

- A transformer draws inrush current that can exceed saturation current at power up
- The inrush current affects the magnetic property of the core
- This happens even if the transformer has no load with its secondary open
- The magnitude of the inrush current depends on the point on the AC wave the transformer is switched on
- If turn-on occurs when the AC voltage wave is at its peak value, there will be no inrush current drawn by the transformer. The magnitude of the current in this case will be at normal no load value
- If at turn-on, the AC wave is going through its zero value, then the current drawn will be very high and exceed the saturation current (see Fig. 10)

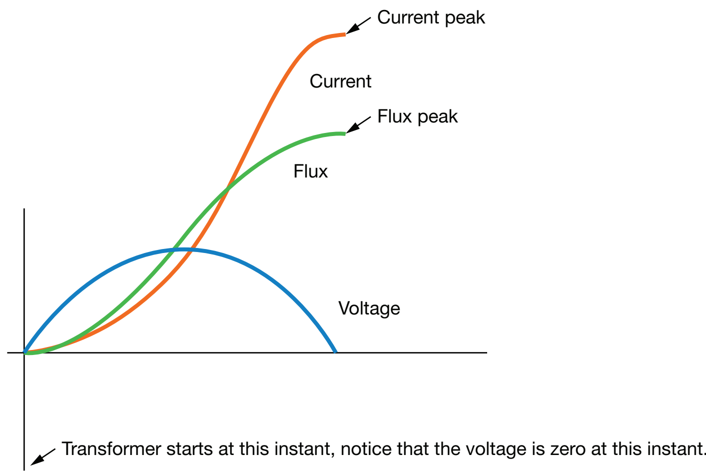

Fig. 10 - Transformer Wave - Inrush

In this scenario, the transformer has to be protected from inrush current.

Protection of the Transformer

This application note provides a convenient solution (see Fig. 11) to deal with the problem of inrush current exceeding saturation current in transformers.

The solution uses an NTC Thermistor in series with the primary.

This NTC Thermistor offers high resistance at the beginning of switching and limits the inrush current.

After a short time, the NTC Thermistor resistance decreases to a low value due to self heating and does not affect normal operation.

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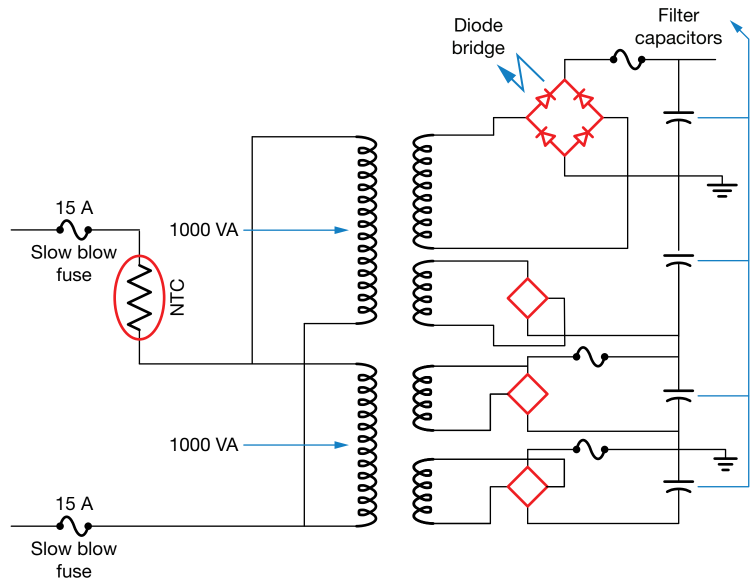

Fig. 11 - Transformer Inrush Schematic

Each transformer rating: 1000 VA, transformer step-down: 30 V

Total transformer rating: 2000 VA

Filter capacitors used: 30 V, 2300 μF

NTC Selection Criteria #1: Energy

Energy required for the NTC: Inductive reactance of the transformer

$$X_L = \frac{\text{Voltage}}{\text{Peak Current}} = \frac{120}{564} = 0.213\ \Omega$$

Note

- Peak inrush current occurs in one cycle = 564 A, as measured on the oscilloscope
- Input voltage = 120 V_{AC}
- Frequency = 60 Hz
- XL = 2pfK = 2 x 3.14 x 60 x L, so L = 565 μH

Energy rating for the NTC = $\frac{1}{2}(565 \times 10^{-6})(564)^2 = 90$ J

NTC Selection Criteria #2: Steady-State Current

Assume, Efficiency of transformer: 70 %, ambient temperature: 75 °C, minimum input voltage: 90 V

$$I_{steady} = \frac{\text{KVA of Transformer}}{(\text{Efficiency of Transformer}) \times (\text{Minimum Input Voltage})}$$

For this transformer, I_{steady} is calculated as $\frac{2.0\ \text{KVA}}{(0.70) \times (90\ \text{V})} = 31.75$ A

Normally thermistors are rated up to 65 °C for their operating current, and then a derating factor must be taken in to account.

Decision criteria: choose an NTC thermistor that can provide at least the steady-state current as calculated above:

Using the derating curve at 75 °C, use corresponding 90 % of max. rated steady-state current

= 0.90 × 36 A = 32.40 A

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You can use any of the NTC Thermistors that are rated up to 36.0 A to meet your steady-state current and energy requirements. See the charts for part numbers.

TYPICAL INRUSH CURRENT LIMITERS FOR SELECT TRANSFORMERS									
TRANSFORMER (kVA)	SINGLE PHASE INPUT VOLTAGE (V_{AC})	CONTINUOUS CURRENT (A)	INRUSH CURRENT (A)	IMPEDENCE		FREQ. (Hz)	ENERGY (J)	MIN. RESISTANCE (Ω)	RECOMMENDED PART
				X (Ω)	X_L (μH)				
0.5	120	4.16	104	1.63	4328	60	23.4	4.9	SL1210006
1.0	240	4.16	104	3.26	8642	60	46.7	9.78	SL2210008
2.0	240	8.33	208	1.63	4328	60	93.62	4.89	SL3210015
3.0	240	12.50	312	1.09	2881	60	140.6	3.26	AS325R020
5.0	480	10.42	260	2.60	6913	60	234	7.83	MS3210015
10.0	480	20.83	521	1.30	3457	60	469	3.92	2 x MS322R025 or 1 x MS355R025

INRUSH CURRENT LIMITERS FOR TRANSFORMER APPLICATIONS					
PART	UL	RESISTANCE	SSI MAX.	JOULES MAX.	VOLTAGE MAX.
SL1210006	Y	10.0	6	40	240
SL2210008	Y	10.0	8	90	240
SL3210015	Y	10.0	15	150	240
AS325R020	Y	5.0	20	300	240
MS3210015	Y	10.0	15	250	480
MS322R025	Y	2.0	25	300	480
MS355R025	N	5.0	25	600	480

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CAPACITOR INRUSH CURRENT

Reducing Inrush Current to Capacitors

Calculating the amount of current flowing to a capacitor, then protecting your load from this initial flow of current is important for any electronic device. The ability to reduce this inrush, caused at powerup, can typically be accomplished by the use of an NTC (negative temperature coefficient) thermistor inrush current limiter.

Cause of the Inrush Current

Filter capacitors are devices designed to reduce the effect of ripples when AC waveforms are converted to DC waveforms. In a typical power supply, the AC current flows through the diode bridge rectifier, converting the voltage to DC, then flows into the filter capacitor. At power on, an inrush of current occurs and while in its charging phase the filter capacitor acts like a dead short. This state continues until the filter capacitor is completely charged, leaving the potential of the inrush current to fully hit the load.

Inrush Current Protection

Safeguarding against the filter capacitor's charging period's initial current inrush flow is crucial for the performance of your device. Temporarily introducing high resistance between the input power and rectifier can increase the resistance of the powerup, leading to reduction of the inrush current. Using an inrush current limiter for this purpose helps because it can provide the initial resistance needed.

Placement of Inrush Current Limiter

The diagram below illustrates a typical set up of a circuit, with power entering at "AC IN" and the filter capacitors located at the "Filter capacitor".

To limit the onset inrush current, an NTC thermistor inrush current limiter is placed IN series with input power at "A", or "B", or optionally IN series after diode bridge at "C ", or "D". This allows the filter capacitor time to charge without the inrush current fully hitting the load.

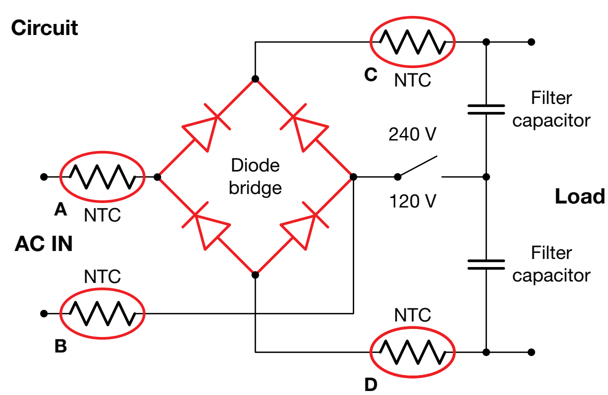

Fig. 12 - Circuit Example

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Inrush Current Limiter Proving Resistance

The placement of an inrush current limiter between the input power and load, demonstrated in the diagram, gives the inrush current limiter the ability to provide resistance. When energized, the inrush current limiter self-heats and causes its body temperature to rise. This then leads the inrush current limiter to lower its resistance. As the resistance drops to a low value, the current can pass through at a standard level, without adversely affecting the normal operation or power efficiency. By the time resistance reaches the circuit's steady-state condition, the filter capacitor will be fully charged and ready to deliver DC power to the load. At this time, the inrush current limiter will remain at this steady-state condition, allowing the current to flow through unaffected.

Inrush Current Limiter Selection

Choosing the right type of NTC thermistor inrush current limiter for your inrush current limiting needs can be vital when working with filter capacitors.

To select the right inrush current limiter there are a few measurements* you will need:

- Zero power resistance (R at 25 °C)
- Energy measured in Joules
- Steady-state current

There is one more variable you should keep in mind when choosing the right inrush current limiter, which is ambient temperature. The calculations / examples used in this article are based on the ambient temperature being between 0 °C and 65 °C. If your environment is outside this scope, you will want to refer to a derating chart to see how to modify your calculation to ensure the best productivity out your inrush current limiters.

Most of the time you can get these measurements from the specifications provided by the manufacturer.

To calculate yourself see below or skip to the next section

<u>Zero Power Resistance (Ω)</u>

Peak voltage/max. allowable inrush current

Where:

- Peak voltage = 1.414 V_{RMS}
- Max. allowable inrush current = fuse in power supply or breaker on AC line

Example:

(120 V_{RMS} × 1.1414)/20 A = 169.68 V_p/20 A = 8.4 W

<u>Energy Measured in Joules (J)</u>

0.5 × (capacitance) x (peak voltage)^2

Where:

- Capacitance = will come from the specifications provided by the manufacturer
- Peak voltage = 1.414 V_{RMS}

Example:

(0.5) × (.0047F) × (169.68)^2 = 67.6 J

<u>Steady-State Current (A)</u>

Will come from the specifications provided by the manufacturer

Can be formulated by:

Input power/output voltage (W/V = I)

Example:

Steady-state current given at 3 A

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Once you have the values for zero power resistance, energy measured in joules, and steady-state current, it's time to translate them into the specifications needed to choose your NTC thermistor inrush current limiter.

First, you will need to go to the inrush current limiter full line page to see a listing of NTC thermistor inrush current limiters Vishay Ametherm has available (chart explanation is shown below).

Part Number	UL	CSA	R @ 25 °C	SSI	Joules	D	T
SL32 0R230	UL		0.3	30.0	100	31.0	6.0
SL22 0R516	UL	CSA	0.5	16.0	160	22.0	6.0
SL32 0R530		CSA	0.5	30.0	150	31.0	5.0
SL32 0R536		CSA	0.5	36.0	150	31.0	5.0
MS32 0R540			0.5	40.0	250	31.0	7.0
MS35 0R550			0.5	50.0	500	37.0	9.0

Fig. 13 - Inrush Current Limiter Chart Example

- The first column is the part number
- The second column is whether it is UL listed
- The third column is whether it is CSA compliant
- The fourth is the zero power resistance number (reference from your calculations)
- The fifth is the steady-state current number (reference from your calculations)
- The sixth is the maximum amount of energy measured in joules number (reference from your calculations)

You always want to round up the numbers when using this chart.

Taking the numbers from the above examples - 8.4 Ω, 3 A, 6.65 J - round this up to 9 Ω, 3 A, 7 J

Reviewing the chart online, you will notice there are no R at 25 °C = "9" values, but there are R at 25 °C = "10", going up from "8.4" to "10" is fine when selecting an NTC thermistor inrush current limiter.

From here, looking at your value for steady-state current, you will want a value of 3 or more.

Finally, for the energy measured in joules you will want a value of 7 or more.

With these the values established, the ideal inrush current limiter is SL10 10003.

SL10 10003	UL	CSA	10.0	3.0	17	10.0	5.0

Fig. 14 - Inrush Current Limiter Chart Example