AN441
Application note

Inductive load control with AC switches

Introduction

AC switches are now commonly used as static switches to drive inductive loads such as magnetic transformers, valves, induction motors, etc.

This application note describes the particular points to focus on when such loads are controlled by AC switches like Triac, ACS or ACST. For example, there is an explanation of just when a Triac has to be triggered to reduce the inrush current at turn on.

Typical examples are given for magnetrons used in microwave ovens, transformers for SELV halogen lamps, and universal motors used in vacuum cleaners.

1 Reasons for inrush current in inductive loads

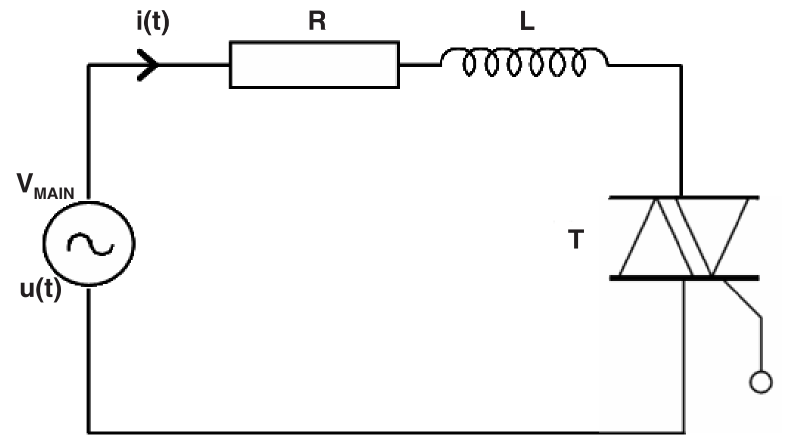
1.1 Inrush current due to inductive load behavior

Many inductive loads are controlled in full-wave mode. This is the case of valves, pumps, compressors, etc. For these loads, the inrush current greatly depends on turn-on delay at start-up.

We do not consider, in this section, the effect of magnetic circuit saturation that could also lead to inrush current increase. Refer to *Section 1.2* for this point.

A typical inductive load, controlled by an AC switch, can be simulated using a standard RL circuit (*Figure 1*).

Figure 1. Inductive load control with Triac



According to *Figure 1*, the AC load current i(t) is define by *Equation 1*.

Equation 1

$$u(t) = R \cdot i(t) + L\frac{di(t)}{dt}$$

Considering the circuit in sinusoidal full-wave mode, with turn on at zero mains voltage, the value of inrush current is:

Equation 2

$$i(t) = \frac{U_{RMS}\sqrt{2}}{(L \cdot \omega)^2 + R^2} \cdot \left(L \cdot \omega \cdot e^{-\frac{R}{L} \cdot t} - L \cdot \omega \cdot \cos(\omega \cdot t) + R \cdot \sin(\omega \cdot t) \right)$$

In case of a delay applied between zero voltage and Triac triggering in the first half-cycle (assuming following cycles are in full-wave mode), the value of inrush current is:

Equation 3

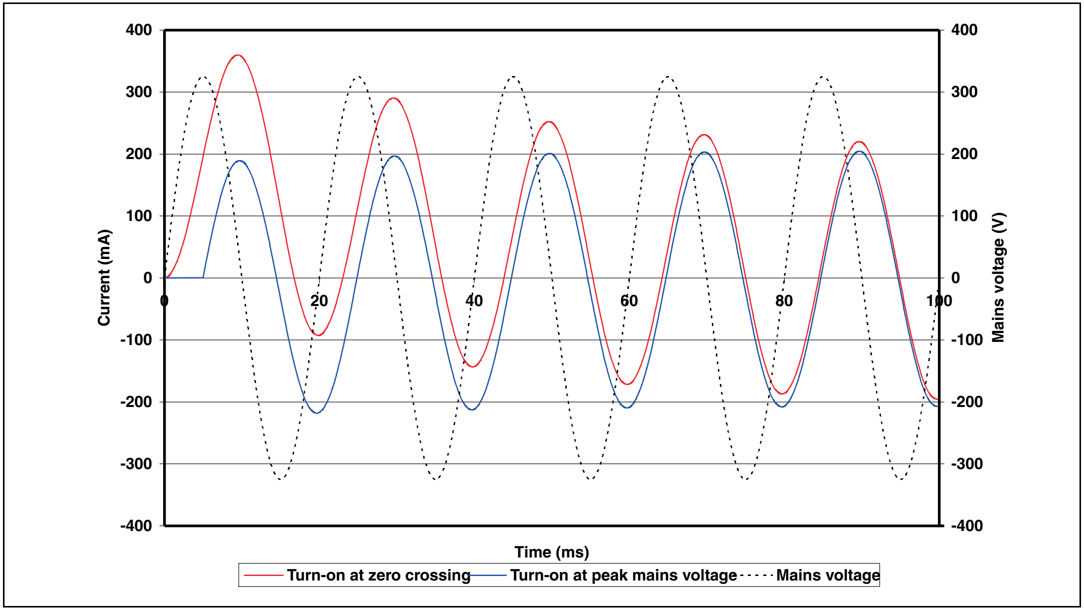
$$i(t, t_0) = \frac{U_{RMS}\sqrt{2}}{(L \cdot \omega)^2 + R^2} \cdot \left((L \cdot \omega \cdot \cos(\omega \cdot t_0) - R \cdot \sin(\omega \cdot t_0)) e^{-\frac{R}{L} \cdot t} - L \cdot \omega \cdot \cos(\omega \cdot (t + t_0)) + R \cdot \sin(\omega \cdot (t + t_0)) \right)$$

Where t_0 is the triggering delay at the first turn on

These two equations show that, when the inductive load is switched on in full-wave, the transient current depends on the Triac first turn-on delay with respect to the mains voltage zero point. *Figure 2* shows the load current curve for triggering at zero voltage and triggering at the peak mains voltage. This figure comes from PSPICE simulation for a 150 ohm and 5 H load switched on at a voltage of 230 V rms at 50 Hz.

Triggering at zero voltage brings the highest inrush current which can be up to twice the peak current reached in case of triggering at peak voltage.

Figure 2. Inrush current difference according to Triac first turn-on delay



Due to this high peak current, two problems may occur at AC switch level.

- High peak current may be higher than I_{TSM} value (maximum surge peak current). In this case the component can be damaged.
- AC switch temperature may exceed the maximum allowed junction temperature (this will not lead necessarily to device failure but electrical parameters are not anymore guaranteed if working temperature is above max allowed value).

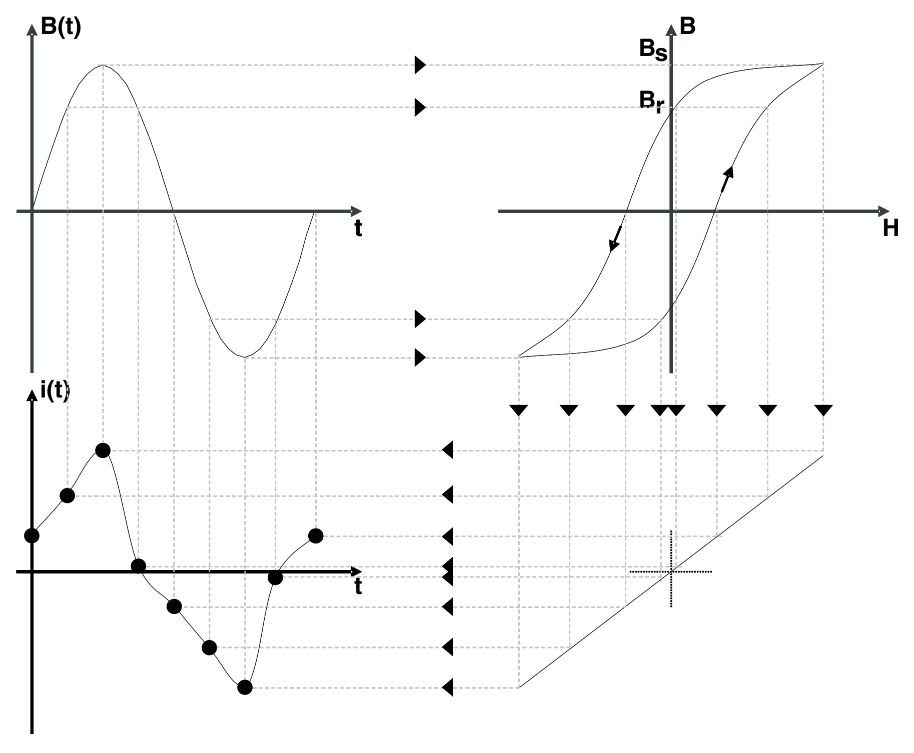
Inrush currents have also to be checked to fit electromagnetic compatibility standards. Actually, IEC 61000-3-3 standard make it mandatory to limit inrush currents of appliances connected to the power network to reduce the flickering effect on lighting.

It should also be noted that reducing inrush current helps to increase the reliability of the load and other switches or breakers used in series with the load.

1.2 Magnetic core saturation due to remanent induction

In transient operation, the induction can follow a different path and reach the saturation value BS for which the magnetic field H increases very rapidly even for a low induction variation (see *Figure 3*). At saturation level the magnetic material permeability decreases drastically, down to air permeability. This leads to a lower inductance value. The load current is then mainly limited by the load resistance, and can increase substantially. Saturation then leads to a high increase of the coil current.

Figure 3. Magnetic field H versus induction B (continuous rating)



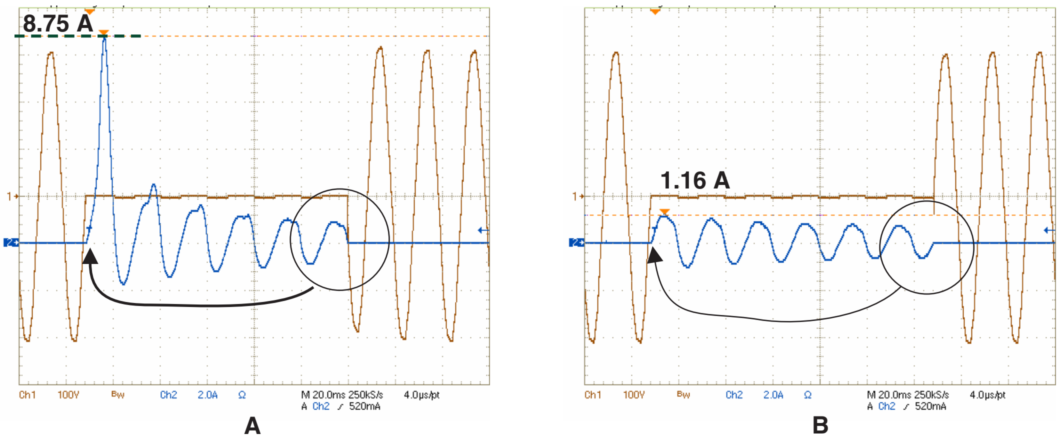
According to *Equation 2*, at start up at zero voltage the current is higher (longer time to integrate voltage and so higher induction reached in the 1st cycle) and so there is a higher risk of reaching magnetic core saturation.

Also a second phenomenon can increase risk of saturation. This phenomenon is due to remanent induction. The remanent induction (refer to B_r in *Figure 3.*), corresponds to the point where H equals 0. If a positive voltage is applied from a point where there is a positive remanent induction, the induction will start to increase from a higher initial value, so will reach saturation faster (refer to appendix 1 for further explanation on this phenomenon).

To avoid this phenomenon in circuits controlled by an AC switch, device switch on has to be implemented on the reverse polarity according to previous switch off. *Figure 4* shows two different test results carried out on a 200 VA 230 V to 12 V transformer. Curve A shows the current waveform, recorded after a previous identical current waveform. The particularity of this waveform is that the first half-cycle conduction is in the same polarity as the previous one. In this case the transformer reaches saturation very rapidly and the transformer behaves like a short circuit. The peak current is limited only by the series resistance of the transformer.

Curve B shows the same recording but here with the first half-cycle conduction in reverse polarity compared to the last one. These two curves clearly show that saturation is reached in case A due to previous conduction. Then load current can be approximately eight times higher than if care is taken to always trigger the device for an integer value of full-cycle periods.

Figure 4. Last turn-off polarity influence on the next turn on



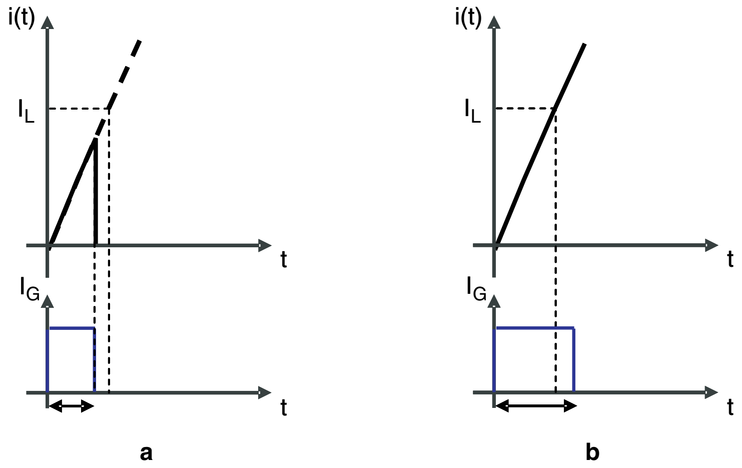
2 AC switch control with an inductive load

2.1 Latching current

The latching current I_L of a Triac is the minimum value of the load current (circulating through terminals A2 and A1), to keep the device conducting when the gate signal is removed. Diagram a in *Figure 5* shows a bad Triac turn on due to too short gate pulse width and Diagram b in *Figure 5* shows a good Triac turn on. The pulse width is sufficiently large so that the current i(t) reach the latching current. See Application note AN303 for more information.

For inductive loads, as the current rate of increase is limited by the inductance, care has to be taken to have a large enough gate pulse width to reach I_L (refer to *Section 2.2*).

Figure 5. Latching current of the AC switch



2.2 Gate control for full-wave operation

2.2.1 Gate current pulse width

Gate current pulse width must be set up to reach the required I_L value. To avoid a break in the current waveform at zero point, holding current also has to be taken into consideration (see Application note AN302 for a definition of I_H). Pulse width is given by *Equation 4*.

Equation 4

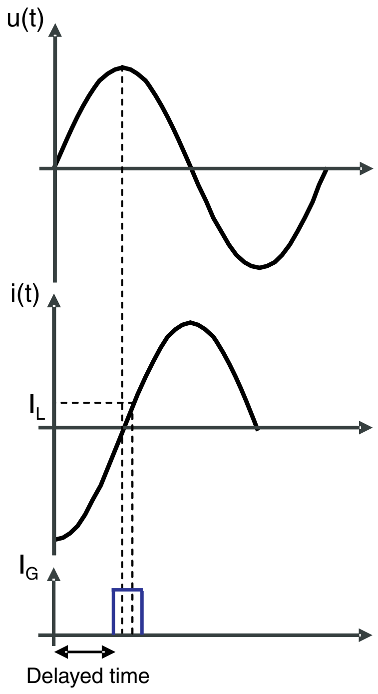
$$t_P > \frac{1}{\omega} \cdot \arcsin\left(\frac{I_{H\,MAX}}{Ipeak}\right) + \frac{1}{\omega} \cdot \arcsin\left(\frac{I_{L\,MAX}}{Ipeak}\right)$$

To reduce the pulse width duration, a more sensitive Triac could also be used.

2.2.2 Gate current synchronization with mains voltage

In case of inductive load, the current is lagging regarding to the mains voltage. This is why, in case of control by gate current pulse, the gate pulse has to be applied with a delay after each line zero voltage point which approximately equals the current-voltage phase shift (as shown on *Figure 6*)

Figure 6. Triac pulse width synchronization



In case the zero line voltage event is not sensed by the Triac control circuit or no timer is available to manage triggering times, one solution is to apply a DC gate current. In this case the average current consumption for the power supply will be higher. But today more and more switching mode power supplies (SMPS) are used offering a higher output current capability.

If a power supply with reduced output current capability is used (for example, the case with capacitive or resistive power supplies), a solution to reduce the gate current average value is to apply a high-frequency (several kilohertz) burst to the gate. This solution allows reduction of Triac off time that occurs after current has reached zero and before a new gate current pulse (coming with the high-frequency burst) is applied. This maximum off time will then approximately equal (at worst case) to one gate-burst period (see Application note AN308).

2.3 Inrush current limitation

To limit the inductive load inrush current, triggering at peak mains voltage could reduce the peak current as previously shown. Also, especially for transformers, it is better to ensure that the device is switched-on at a different polarity compared to last half-cycle conduction (refer to *Section 1.2*).

But this triggering method will only be efficient in applications where the inrush current comes from inductive part of the load or from core saturation. This is mainly the case with transformers or valves. The inrush current period usually lasts less than 100 ms.

For other applications, the inrush current could also come from other phenomenon.

- Low-resistance value at start-up (cold filament of incandescent lamp)
- High starting torque (induction motors used in compressors)
- Low back EMF at zero speed, i.e. at start-up (universal motor or permanent-magnets induction motors used in pump applications)

For these applications, the inrush current can last up to 500 ms.

As the inrush current is not only due to the behavior of the inductive part of the load, the problem cannot be resolved just by triggering the Triac at peak voltage for the 1st half-cycle and then control it in full wave-mode. The solution consists of implementing a soft start by progressively increasing the conduction angle of the AC switch. This solution allows the maximum current at turn on to be limited to a value near to the steady state. This brings the following benefits:

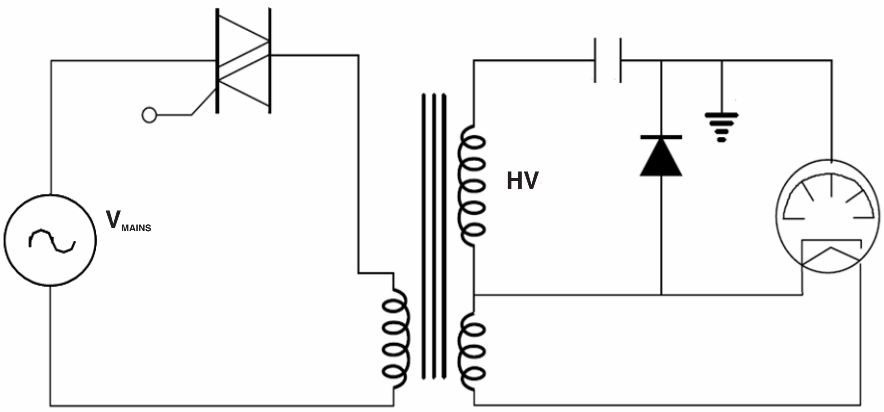
- Lower rate of rise of temperature for the device and so better device reliability
- Compliance with the IEC 61000-3-3
- Lower peak current and so better load reliability

3 Typical examples of inrush current reduction

3.1 Magnetron in microwave oven

The magnetron of a microwave oven is generally supplied by rectified high voltage obtained through a 50/60 Hz transformer. The power supplied to the oven is controlled by a Triac in series with the primary winding of the transformer (see *Figure 7*).

Figure 7. Typical circuit of a magnetron controlled by a Triac

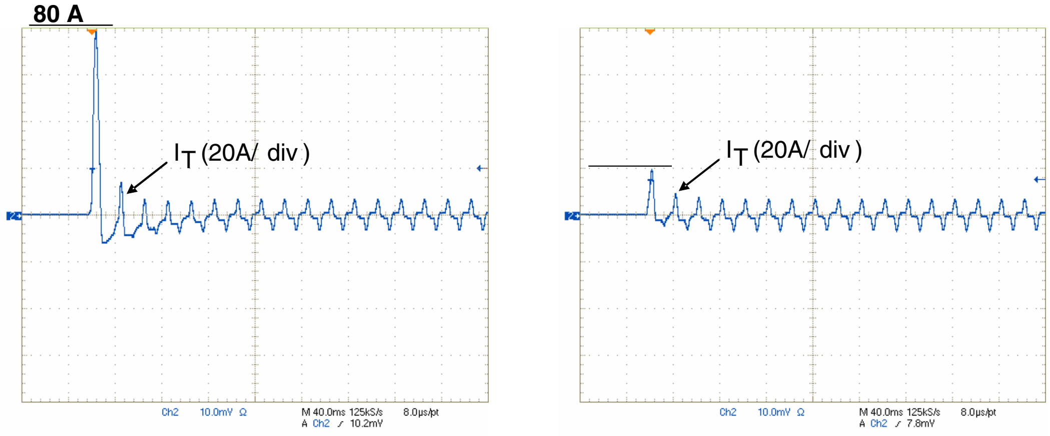


The power to be controlled is typically between 1 to 2 KW and the nominal rms current is in the range of 10 to 20 A according to the line voltage. The inrush current comes from the magnetizing current through the transformer at turn on.

Due to the high inductance of this transformer this overcurrent can reach a peak value up to 4 to 20 times the steady state value.

The high peak current at turn on as shown in *Figure 8* can damage an 8 A Triac as it is close to I_{TSM} value (max surge peak current, 80 A for example for a BTA08 device).

Figure 8. Overcurrent at microwave oven switch on



Firing at zero mains voltage **Firing at peak mains voltage**

Triac turn on at peak mains voltage allows the reduction of the peak inrush current by 75% compared to a zero voltage switch on as shown in *Figure 8.*

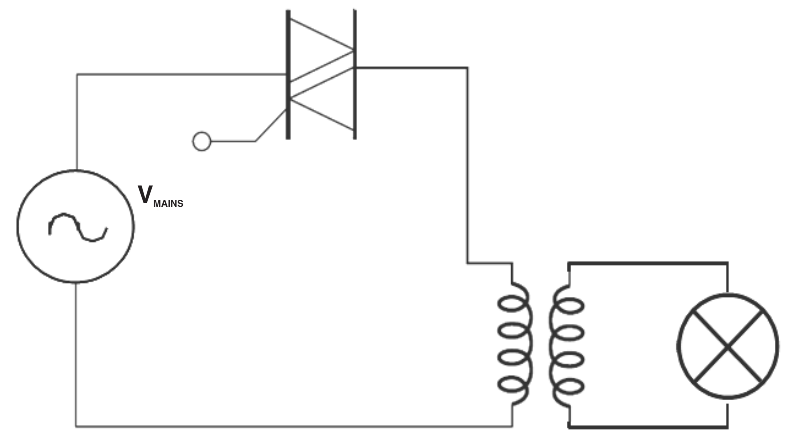
The reduction of first peak current allows:

- Use of a lower Triac range (lower $I_{T(RMS)}$ range),
- Safer margin for the Triac (I_{TSM}).

3.2 Transformer for lighting

A Triac could be used to dim SELV (safety extra low voltage) halogen lamps. In this case the lamps are connected at the secondary winding of a 220 V to 12 V step-down transformer. The Triac is then connected on this transformer in series with the primary winding (*Figure 9*). The power applied to the lamp is controlled by the variation of the conducting angle of the Triac and allows dimming the brightness of the lamp.

Figure 9. Typical schematic of a light dimmer for SELV halogen lamps



Like microwave oven transformers, transformers for lighting application present an overcurrent if they are switched on at zero voltage due to magnetizing current.

This inrush current is increased if the lamp filament is cold. Filament resistance decreases when the temperature decreases.

The high current due to the cold filament effect could cause transformer magnetic core saturation, which then drastically increases the primary winding inrush current.

To reduce the inrush current, an appropriate triggering needs to be used. *Table 1* shows different halogen lamp test results used with a transformer. The table shows that the maximum peak current is lower when the load is triggered at zero current.

Indeed the ratio between peak current at zero voltage and at peak voltage triggering is in the range of 2 to 4. It should also be noted that, in case of triggering at peak voltage, some transformers (transformer 1 and 2) have a peak inrush current close to 13 times the steady state peak current whereas others feature a ratio lower than 7 (transformer 3). This is linked to the low-saturation level of some low-quality transformers.

Table 1. Halogen lamp test through a transformer

	Turn-on moment	Output power (12 V halogen lamps)	Inrush current	
			I_{PEAK}	I_{RMS}
Transformer 1 150 - 300 VA	ZVS	275 W	17.52 A	1.26 A
	ZCS	275 W	8.65 A	1.26 A
Transformer 2 100 - 210 VA	ZVS	200 W	20.32 A	1.3 A
	ZCS	200 W	5.32 A	1.3 A
Transformer 3 200 VA	ZVS	200 W	7.48 A	1.12 A
	ZCS	200 W	2.83 A	1.12 A

3.3 Induction motor

Induction motors or universal motors are today widely used in home appliances for applications as such as vacuum cleaners, washing machines, blenders, and fridge compressors. The typical load power is in the range of 100 to 3000 W. These motors present a very high inrush current due to the inductive current in case of turn on at zero voltage.

This inrush current is also increased in the case of a universal motor as the back EMF is zero at zero speed. For zero speed the line current will then be limited only by motor winding inductance and resistance, but not by the back EMF that can reach 10 to 50% of line voltage. So applying the whole line voltage at motor start-up will cause a much higher current than applying the same voltage when the motor is running at full speed.

A better solution is to implement a soft-start. This consists of progressively increasing the conducting angle of the AC switch.

Figure 10. Over current at Triac turn on for universal motor

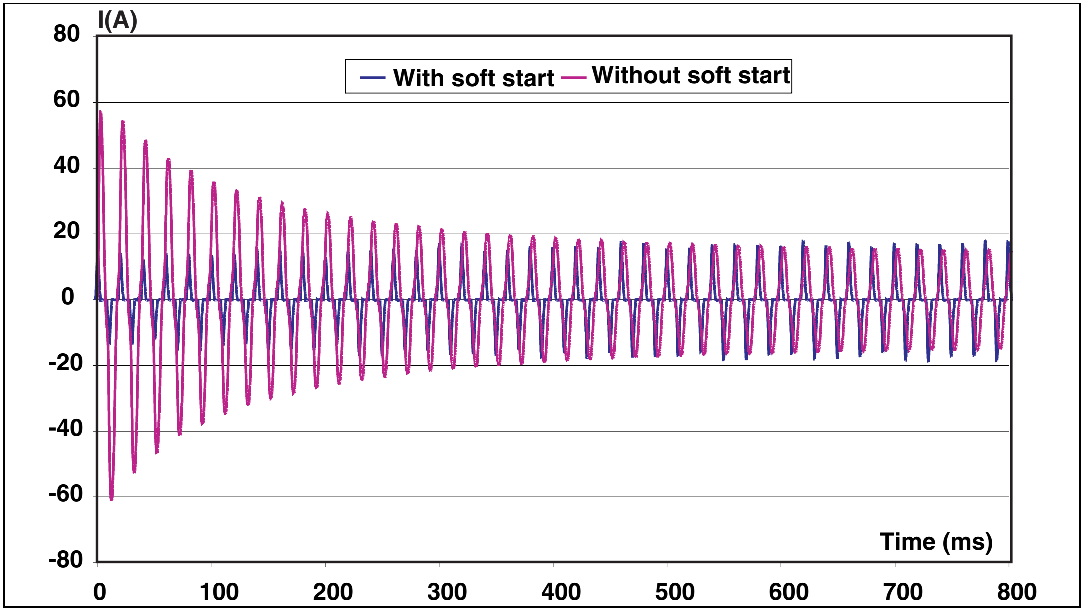
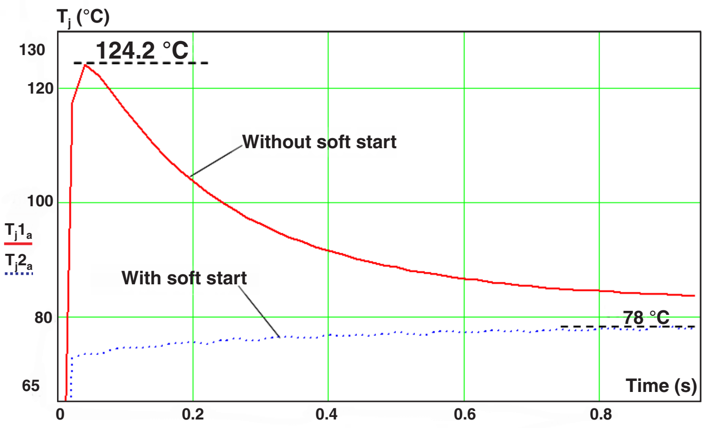


Figure 10 show an example of Triac switching on a 2200 W universal motor with or without soft start. The difference is very clear, the current reaches a peak current up to 60 A without soft start while it reaches 10 A with soft start. This current reduction has a direct impact in the AC switch maximum junction temperature as shown in *Figure 11* with a T1050H Triac.

The use of soft start at motor start-up allows:

- Lower junction temperature
  - Better temperature operation margin leading to increased lifetime for the AC switch
  - Use of lower AC switch range
- Lower peak load current
  - Lower load current stress, so appliance reliability increases

Figure 11. Junction temperature rise for Triac T1050H for universal motor



4 Conclusion

AC switches are widely used to drive inductive loads. With inductive loads, triggering synchronization with line voltage has a high impact on the inrush peak current and needs to be controlled to minimize the first peak current and reduce the maximum junction temperature.

Peak-voltage triggering or soft start solution allows inrush current reduction and the maximum junction temperature to be considerably reduced.

Appendix A B_{MAX} calculation for remanent induction

The winding is supplied by an alternating mains voltage “u(t)” given by *Equation 5*.

Equation 5

$$u(t) = U\sqrt{2}\cdot\sin(\omega\cdot t)$$

According to the laws of Lenz and Faraday, we have *Equation 6*, *Equation 7* and *Equation 8*.

Equation 6

$$u(t) = N\frac{d\Phi}{dt} = N\cdot S\frac{dB}{dt}$$

With:

- Φ = Flux
- B = Induction
- N = spires number (spires number of the primary for a transformer)
- S = section area for magnetic material

Then, induction versus time is:

Equation 7

$$B(t) = \frac{U\sqrt{2}}{N.S}\int \sin(\omega\cdot t)dt$$

Equation 8

$$B(t) = B_n\cdot\sin\left(\omega t - \frac{\pi}{2}\right) + B_0 \text{ with } B_n = \frac{U\sqrt{2}}{N\cdot S\cdot\omega}$$

We consider the case where the Triac is first triggered at mains zero voltage.

We can distinguish two cases:

Case 1

Winding is switched on whereas a remanent positive induction remains on magnetic core.

According to *Equation 8*, for t = 0, we have:

Equation 9

$$B(0) = -B_n + B_0 = B_r \rightarrow B_0 = B_n + B_r$$

So

Equation 10

$$\Rightarrow B(t) = B_n\cdot\sin\left(\omega t - \frac{\pi}{2}\right) + B_n + B_r$$

So the maximum induction will be: $B_{MAX} = 2\cdot B_n + B_r$

Case 2

Winding is switched on whereas a remanent negative induction remains on magnetic core.

According to *Equation 8*, for t = 0, we have then:

Equation 11

$$B(0) = -B_n + B_0 = -B_r \rightarrow B_0 = B_n - B_r$$

So

Equation 12

$$\Rightarrow B(t) = B_n \cdot \sin(\omega t - \frac{\pi}{2}) + B_n - B_r$$

So the maximum induction will be: $B_{MAX} = 2 \cdot B_n - B_r$

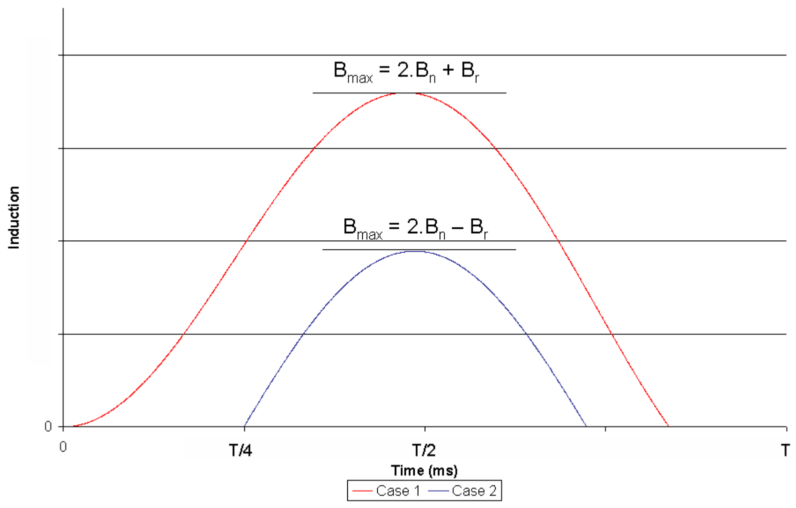
Figure 12 shows the maximum induction difference between two triggering methods according to previous remanent induction.

When the first half-cycle conduction is the same polarity as the previous one, the induction reaches a maximum which can be the double of the induction when triggering in reverse polarity compared to remanent induction.

In the first case saturation can be reached very rapidly and the load behaves like a short circuit. The peak current is limited only by the series resistance of the load.

Such phenomenon mainly occurs with transformers where the remanent induction can be very high.

Figure 12. Induction at beginning of conduction according to remanent induction



Revision history

Table 2. Document revision history

Date	Revision	Changes
May-1992	1	Initial release.
10-May-2004	2	Style sheet update. No content change
09-Mar-2010	3	All technical content revised and material from AN307 included.

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