AN2991
Application note

Single-phase induction motor drive for refrigerator compressor application (formerly AN1354)

Introduction

Up to now, refrigerator compressors have been controlled by electromechanical switches (thermostat or even electronically controlled relays). This choice was driven by the high inrush current that can appear when the rotor is stalled. Furthermore, electromechanical relays were advantageous because they were less sensitive to line voltage disturbances. Today, new semiconductor devices feature overvoltage protection and high inrush current capability, allowing their use in cold appliances.

Electronic thermostats can now be implemented, allowing the appliance efficiency to be improved by more than 20 W, for 150 W compressors. This is possible because of the better temperature control and the PTC removal.

Hence, at a similar cost to electromechanical thermostats, this technical breakthrough can allow refrigerators or freezers to fulfill Class A, A+, or A++ consumption requirements, bringing the following advantages:

- Better reliability
  - Higher switching robustness in time of solid-state semiconductor switches compared with electromechanical solutions
  - Higher ACS and ACST overvoltage robustness compared with Triacs, which makes the metal-oxide varistor redundant
- Temperature regulation curve flexibility (automatic defrost, hysteresis threshold adaptation)
- Reduction of the temperature ripple (better food preservation, cooling elements downsizing)
- Possibility to add indication features for the end-user (inside temperature, open door warning)
- Spark-free operation and EMI reduction (switches can be turned on at zero voltage and are turned off at zero current)
- Over current protection of the motor winding

This application note presents the different topologies that can be used for induction motor control, and lists the electrical constraints that result from these different circuits. A comparison is also made between the different performances of electromechanical or electronic thermostats.

All numerical examples are based on the specifications for a 150 W compressor, which can be used in 350 L freezers.

1 Single-phase induction motor drive topologies

1.1 One or two Triac approach

Single-phase induction motors, used for compressor controls, have an auxiliary winding. This winding permits a higher torque to be applied at start-up. Two different ways can be implemented to control this auxiliary winding. The different topologies are given in *Figure 1* and *Figure 2*.

The most popular method is to add a positive temperature coefficient (PTC) resistor in series with this coil and the thermostat (see *Figure 1*). Then, each time the thermostat is closed, the current flows through the start winding and begins to heat the PTC. After a few hundreds of milliseconds, the PTC value rapidly increases from a few ohms to several tens of thousands of ohms. This results in reducing the start winding current to a few tens of mA. This winding can then be considered as open.

A second solution is to use a second Triac to control the auxiliary winding and replace the PTC function (see *Figure 2*). Then, at off state no power is consumed to keep the PTC hot, this results in improving the appliance efficiency (see *Section 3.2.1: PTC losses*).

A start capacitor is sometimes connected in series with this winding in location ① (see *Figure 1* and *Figure 2*). It is important to note, even for the same motor, that this capacitor can be placed or removed, without disturbing the motor operation.

When the capacitor is placed in location ② (split-phase capacitor), it always sinks a current, even when the PTC is hot or when the start Triac is off. This allows power factor improvement and power consumption reduction. The capacitor C will be added if the refrigerator or freezer does not reach the required efficiency level without it.

In the following study, we assume that C is always placed at location ②, if present.

Figure 1. One Triac topology

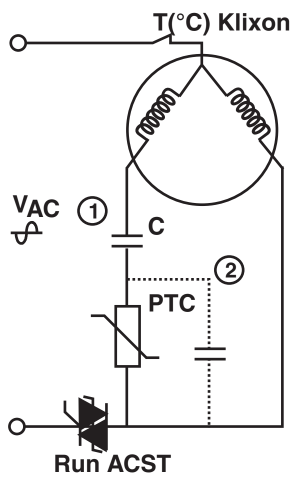
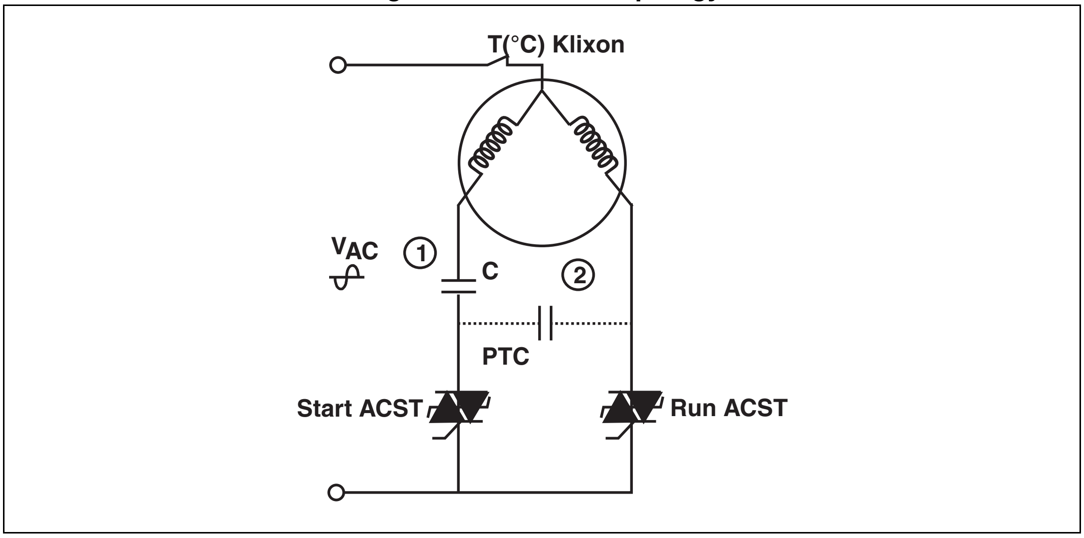


Figure 2. Two Triac topology

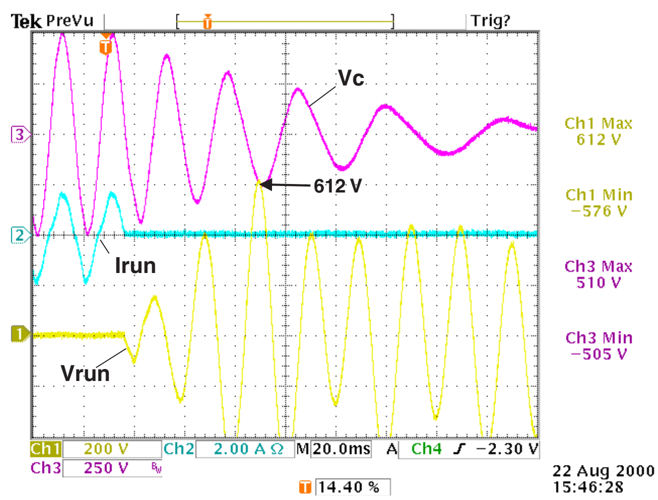


1.2 Semiconductor rating

1.2.1 Start capacitor voltage

The start capacitor and the auxiliary winding form a resonant R-L-C circuit. The capacitor voltage can thus be higher that the mains voltage. In practice the ratio between V_C and V_{AC} equals 1.1 to 1.5. The worst case appears at the run Triac turn-off, for both topologies. V_C is added to the mains voltage up to the capacitor complete discharge. This results in high voltages across the Triac (see *Figure 3*). Even for a 220-240 V application, 700 V semiconductors must then be chosen.

Figure 3. Voltage across Triac after turn off (612 V maximum)

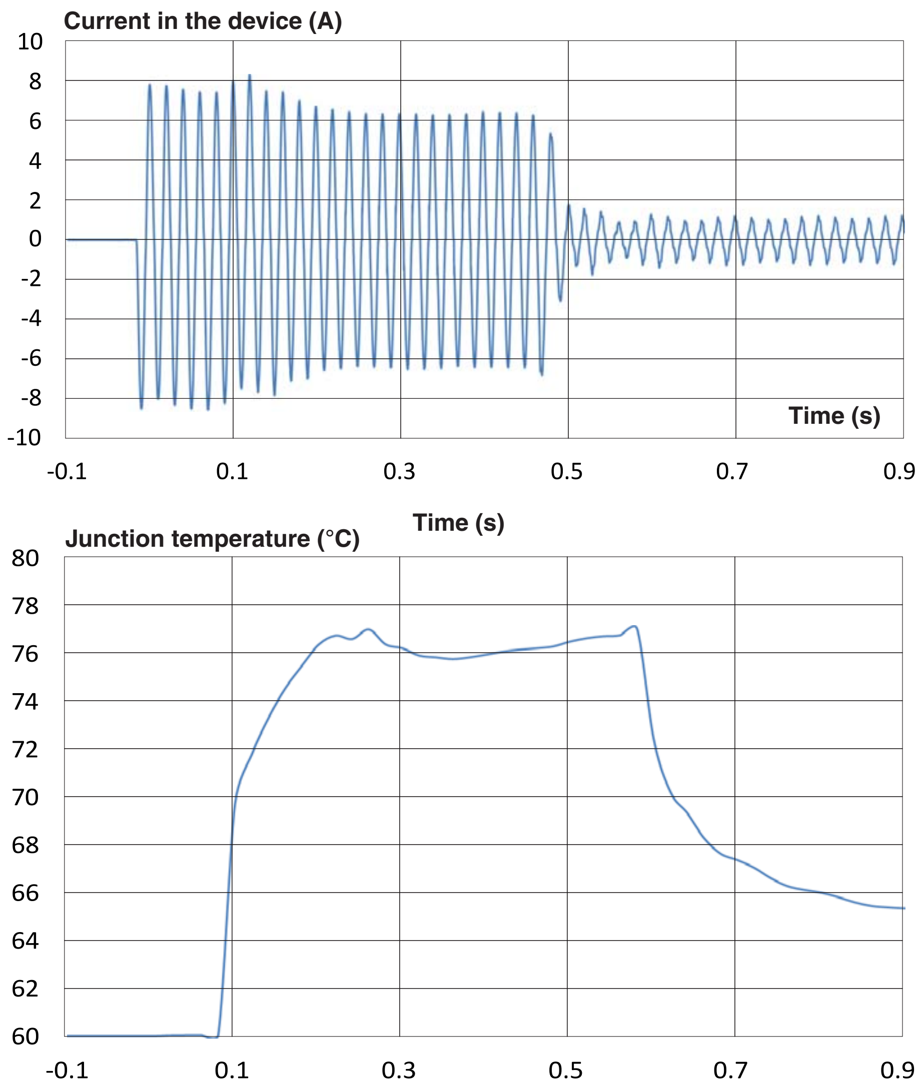


1.2.2 Current rating

Refrigerator or freezer compressors mostly feature input power in the range of 100-300 W. The steady state current is then in the range of 0.5 to 3 A rms for a 220-240 V mains voltage.

The highest current appears at start-up and can reach up to 4 times the steady state current. Thermal calculations can demonstrate that, as these events last a short time, 6 A devices can be used without any heat sink. For example, *Figure 4* gives the junction temperature increase of an ACST610-8T without any heat sink, due to the inrush current which is measured through the start winding of a 150 W compressor. It shows that T_j only reaches 77 °C, when coming from a 60 °C ambient temperature, and remains below the maximum allowed temperature (125 °C).

Figure 4. Inrush current in start winding (150 W compressor)

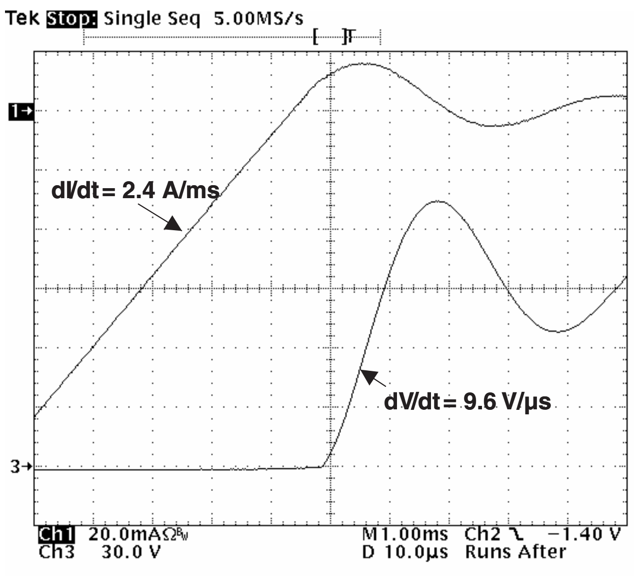


When dealing with the current rating for AC semiconductor switches, the rate of decrease of the current must also be checked. This constraint will depend on the chosen circuit topology.

The worst case of turn-off stress appears with a compressor without any start capacitor. In this case, the rise in voltage will not be slowed by the motor capacitor. The higher stress occurs for the “START” winding (where the impedance is lower than the “RUN” winding one) and when the rotor is stalled. These two conditions yield a higher current and therefore, a higher rate of decrease for the ACST current.

Then, for a stalled 150 W compressor, supplied with a 264 V rms voltage, the dI/dtc and dV/dtc equal respectively 2.4 A/ms and 9.6 V/µs through the start ACST (see *Figure 5*, measured with THERM01EVAL board). This is far below the maximum ratings for ACST610 devices, which is 3.5 A/ms with a 15 V/µs rate.

Figure 5. Turn-off constraint for the worst case scenario

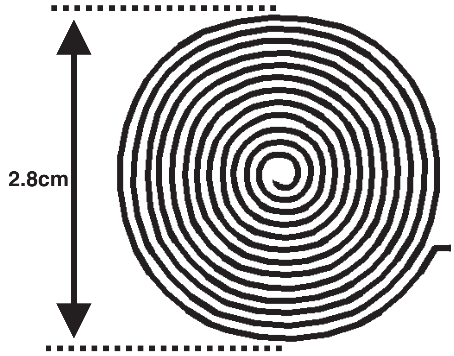


1.3 Protective inductor

With the two Triac topology, a spurious discharge of the start capacitor can occur when the start Triac is accidentally turned on. To reduce the dI/dt stress through the silicon switch, a small protective inductor can be added in series with this Triac.

In order to optimize the solution cost, this inductor can be implemented on the printed circuit board (PCB). For example, an inductor with 12 turns of 0.51 mm width track (see *Figure 6*), made on a 35 µm FR4 PCB, produces a 5 µH inductor and a 1.6 Ω resistor.

Figure 6. 5 µH PCB inductor



An inductor as described in *Figure 6*, allows the dI/dt rate to be limited (in case of a spurious firing of the start ACST when the run ACST is already on) below 60 A/µs (start capacitor is charged up to 510 V). The semiconductor device operation is then well secured.

2 Stalled rotor management

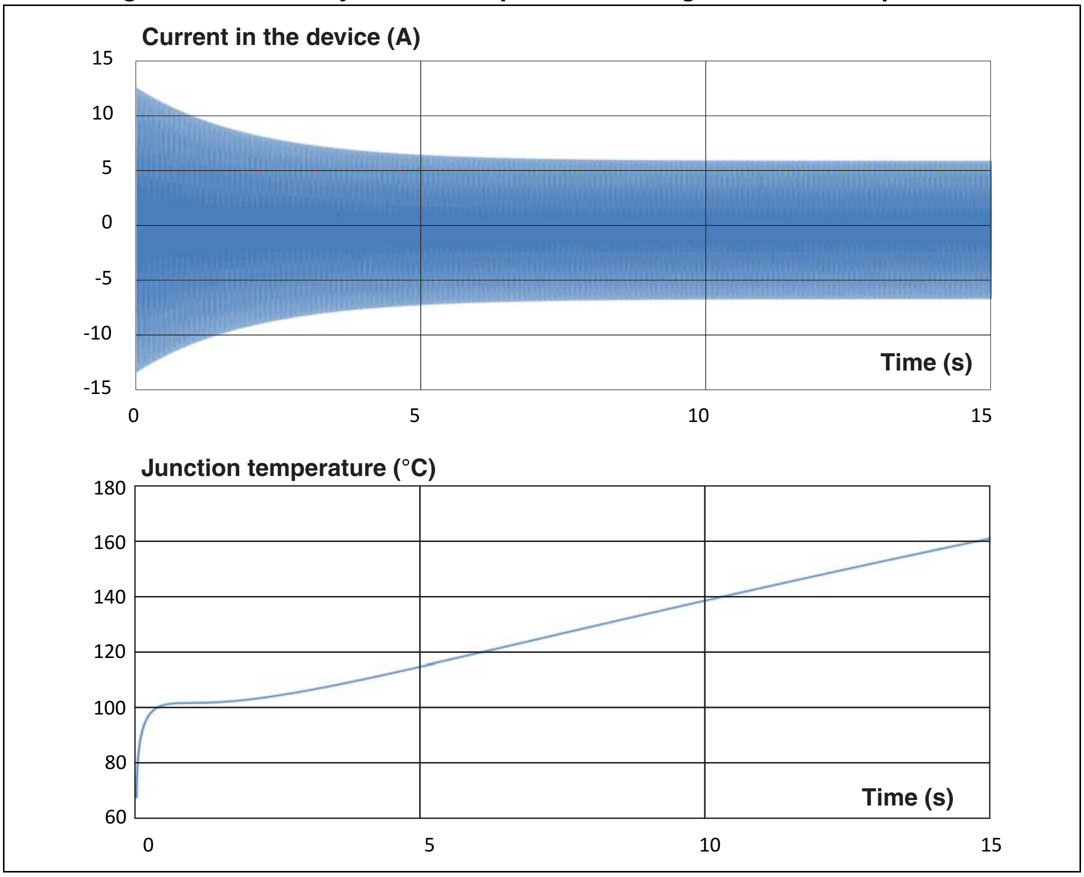
2.1 Protection by thermal cut-off

In the case of a stalled rotor operation, the over current protection is commonly ensured by a thermal cut-off. This component, also called “klixon”, is mandatory to prevent the compressor from over-heating. Klixons are well adapted for motor protection, but not for semiconductors. Indeed, the turn-off time is in the range of 15 s. The silicon switch will withstand a high current that will only decrease thanks to the motor winding heating. In practice, the rms current can fall from 9 A rms to around 4.5 A rms, for a 150 W compressor.

The maximum junction temperature reached by the ACST610-8T can then equal 162 °C as shown by the simulation results in *Figure 7*.

As this temperature exceeds the maximum allowed steady state temperature (125 °C), reliability tests have been performed to check the robustness of the silicon switches after such stress. ACST610 devices can withstand such currents up to more than 10 thousand times. This easily covers the number of stalled rotor operations that can happen during the life cycle of a refrigerator or freezer.

Figure 7. ACST610 junction temperature during stalled rotor operation



2.2 Protection by microcontroller

In order to secure the life expectancy of a refrigerator, the stalled rotor protection can also be provided by the electronic board. In this case, the over current is applied to the motor and the switches for less than 1 s, as opposed to 15 s with a thermal cut-off. The maximum junction temperature will then reach 102 °C, for a 60 °C ambient temperature, instead of 162 °C, eliminating any stress on the ACST.

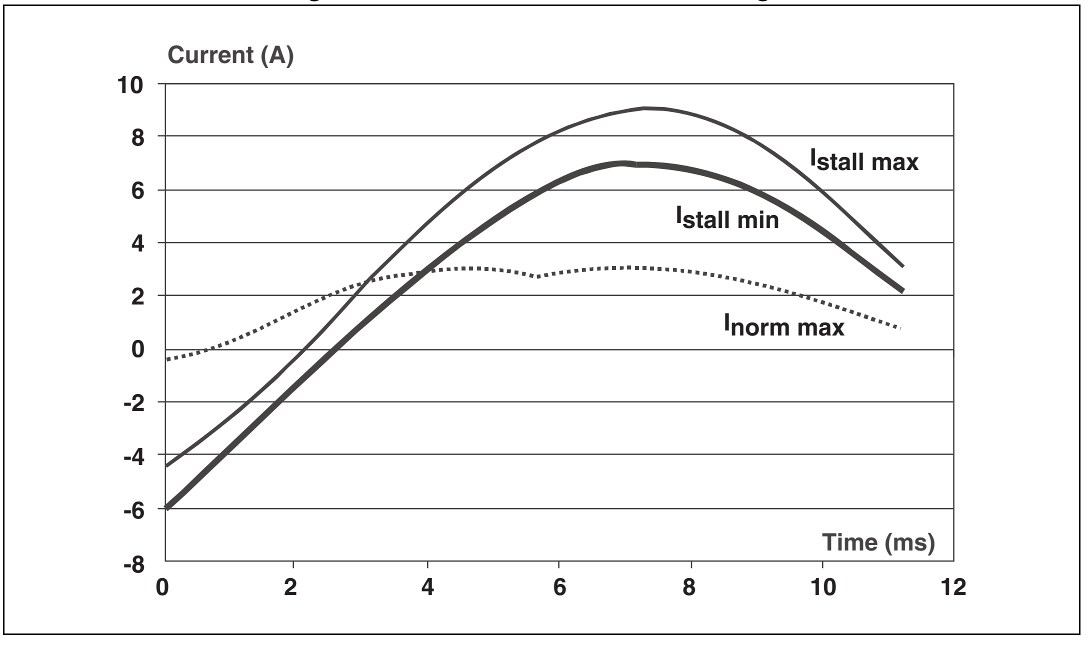
This 1 s duration is chosen in order to differentiate an abnormal over-current from the start-up current, as explained below.

To sense an over current, it is possible to measure the voltage across a shunt resistor placed in series with the run ACST. Then, as the current is alternating, it must be clearly defined at which moment it must be measured. Furthermore, this moment must be chosen in order to differentiate the over-current from the normal current. *Figure 8* gives the maximum and minimum currents for both operating conditions. These curves come from experimental results where the mains voltage has been varied from 198 to 264 V rms, with and without a start capacitor.

Figure 8 shows that, in a stalled rotor condition, the current is still above 5.6 A between 6 and 8 ms after zero voltage crossing. For information, in normal condition, the load current is always lower than 3 A at this moment.

The 5.6 A value is chosen as the condition for a stalled rotor status. The MCU must then be able to perform A/D conversions between 6 and 8 ms. Several measurements can be performed to filter measurement noise.

Figure 8. Motor current maximum ranges



3 Electronic thermostat versus mechanical thermostat

3.1 Temperature regulation

One main advantage of electronic thermostats versus electromechanical ones, is their adaptability. For mechanical thermostats, it is a gas compression and decompression that switches the compressor on or off. This does not allow a hysteresis threshold adaptation during the refrigerator operating cycle. Moreover, this gas effect yields to the fact that the refrigerator may not work properly depending on the ambient atmospheric pressure.

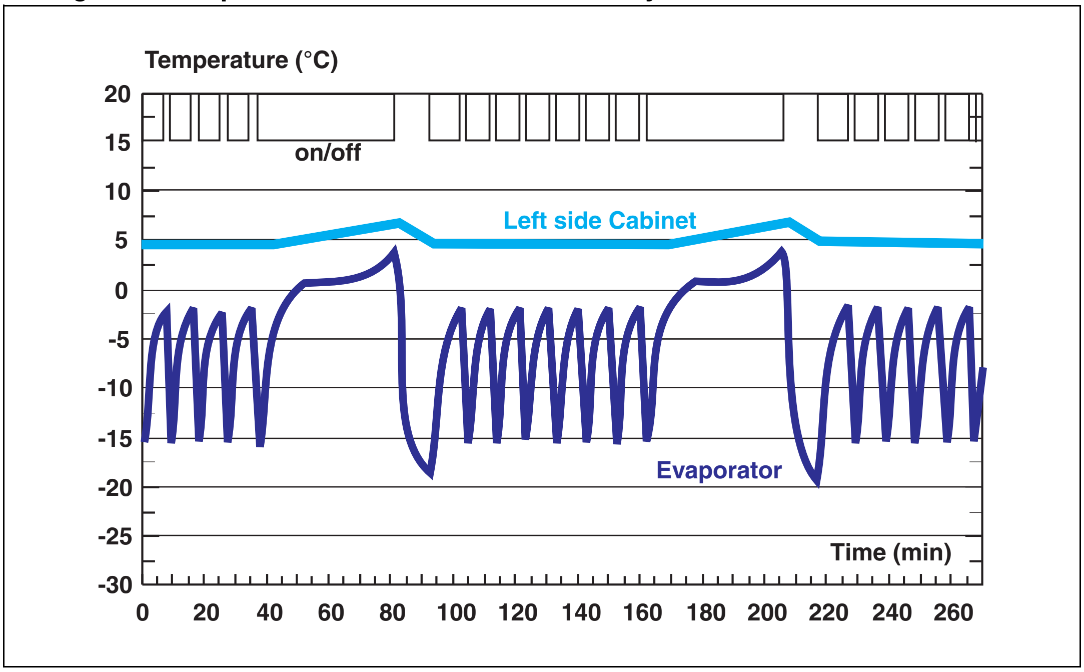
For electronic thermostats, the temperature information is measured accurately and at all times, contrary to electromechanical thermostats where the only available information is that the temperature is over a fixed level or not. This enables the temperature fluctuation inside the cabinet to be reduced with electronics.

A reduction of the temperature ripple presents three main advantages:

- Better food preservation
- Thermodynamic efficiency improvement (lower evaporator temperature ripple; higher evaporator minimum temperature; better compressor use (see *Section 3.2.2: Motor duty cycle*)
- Compressor and evaporator downsizing

A particularly interesting feature can also be implemented thanks to electronics - the hysteresis levels can be changed during the freezing process. This allows automatic defrosting operations to be implemented. For example, *Figure 9* shows that the upper hysteresis level is increased every 8 cycles in order to let the evaporator temperature become higher than 0°C. This allows the ice deposit on the evaporator to be removed. This may be very helpful to increase the refrigerator efficiency as this ice layer plays a real insulation role.

Figure 9. Temperature fluctuation and defrost cycle with electronic thermostat



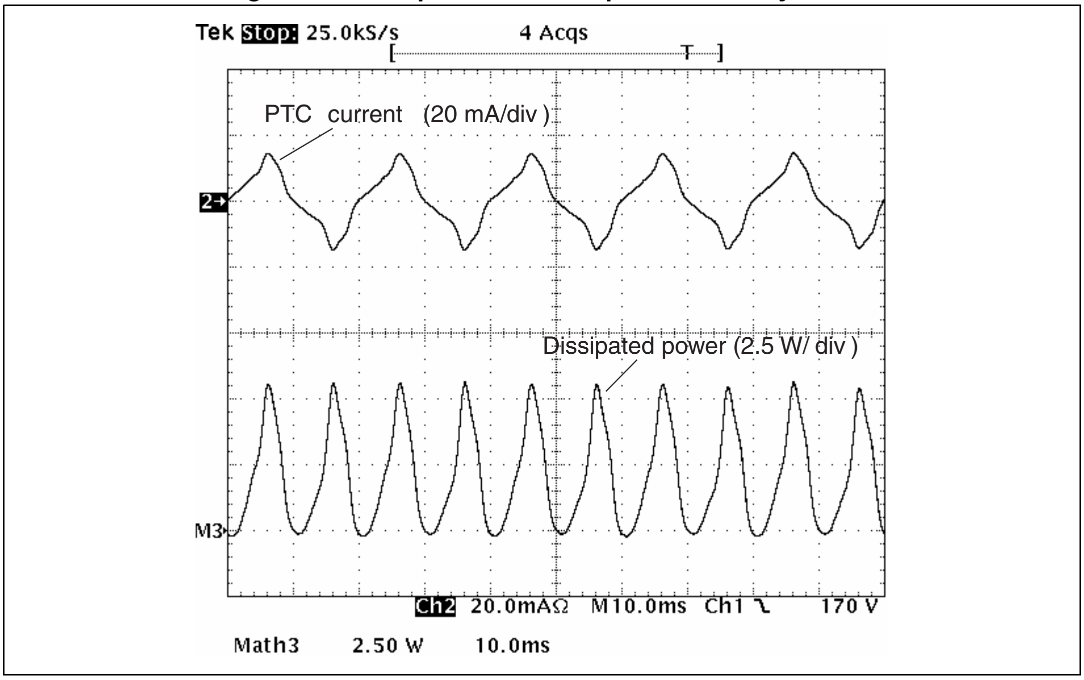
3.2 Power consumption

3.2.1 PTC losses

A PTC thermistor presents a very low resistance when it is cold (example: 10 Ω at 25 °C). This enables a high inrush current at motor start-up to be applied.

Then, the PTC begins to heat and its impedance rapidly increases. This allows the current to decrease to just a few milliamperes, compared to several amperes at the beginning. *Figure 10* shows this current at steady state. This figure also gives the dissipated power through the PTC at this moment. It can be said that the PTC continuously dissipates 2.1 W, when the motor is on. This power consumption can be reduced simply by removing this component and using two Triacs instead of one, to drive the motor.

Figure 10. PTC power consumption at steady state



3.2.2 Motor duty cycle

A very efficient way to reduce the power consumption is to control the temperature more accurately.

Some tests have been performed on a half-loaded 350 L freezer, controlled by our electronic thermostat. During the tests, the door is kept closed and the load remains the same.

Figure 11 and *Figure 12* give the power consumption and the evaporator and cabinet temperatures for respectively a 5.3 °C and 4.2 °C hysteresis threshold control.

The measurements, shown in *Table 1*, have been made for the following cases:

- Case 1: hysteresis threshold = 5.3 °C (similar to mechanical thermostat feature)
- Case 2: hysteresis threshold = 4.2 °C

Table 1. Power consumption versus hysteresis threshold

		Case 1 (hyst. thresh. = 5.3 °C)	Case 2 (hyst. thresh. = 4.2 °C)
Measure	Compressor on time	12' 50"	9' 10"
	Compressor off time	16' 20"	15' 10"
	Average power during on time	136 W	138 W
Calculation	Cycle period	29' 10"	24' 20"
	Duty cycle	0.44	0.38
	Average power consumption	60 W	52 W

It is shown that reducing the temperature ripple improves the appliance efficiency. This can be explained by the fact that the useful energy is not wasted.

The Case 2 allows a saving of 8 W by reducing the threshold level by little more than 1 °C. Electromechanically controlled refrigerators exhibit a temperature ripple in the range of 10 to 20 °C. A decrease to a few degrees Celsius, will allow a saving of up to 20% of energy consumption. This means a 20 W saving for a 150 W compressor (100 W average power with a 2/3 duty cycle).

Of course, reducing the temperature ripple brings one drawback. This is that the motor running cycle frequency increases. In our example, this frequency increases by around 20% (2.06 cycles per hour with Case 1, and 2.46 cycles per hour with Case 2). This is not a problem for electronic switches where the cycling capability is 10 times or more that of electromechanical switches. From the motor point of view, the higher number of cycles should not reduce its reliability as:

- Motor temperature ripple is decreased thanks to a higher cycle frequency.
- The start winding conduction length is reduced thanks to an electronic control instead of a thermal-active solution (PTC).
- An over current protection, which reduces motor stress, is provided by the MCU.

Figure 11. Temperature control (case 1)

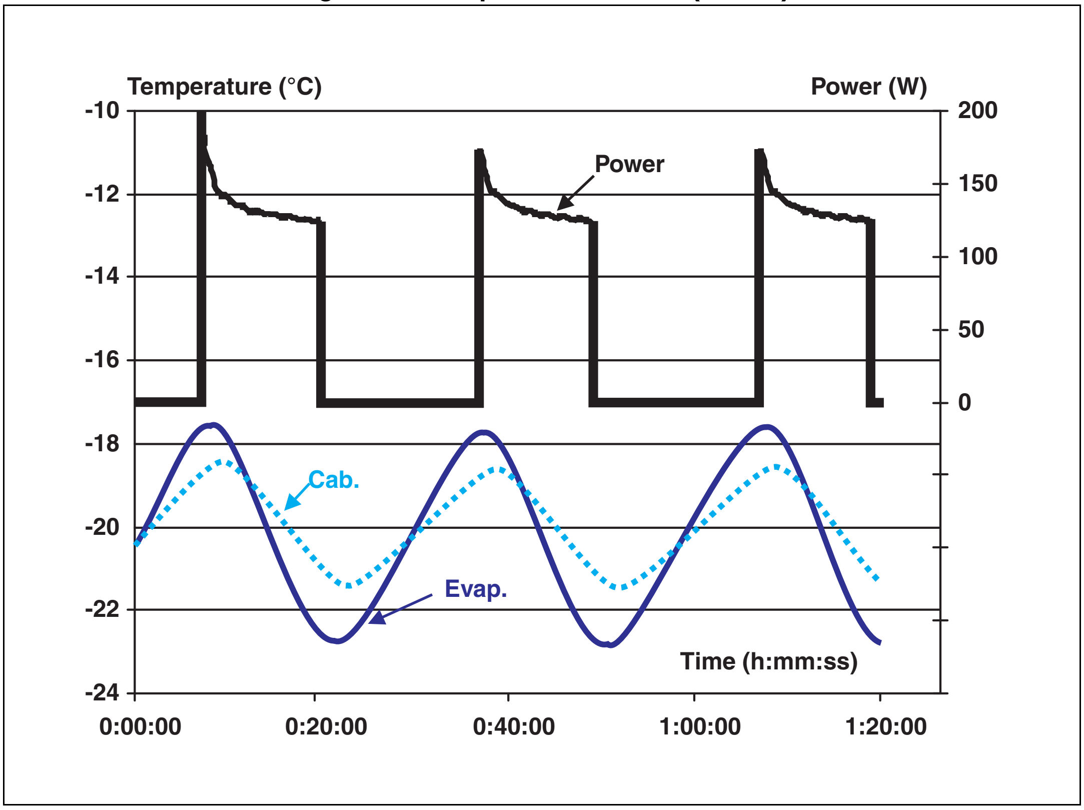
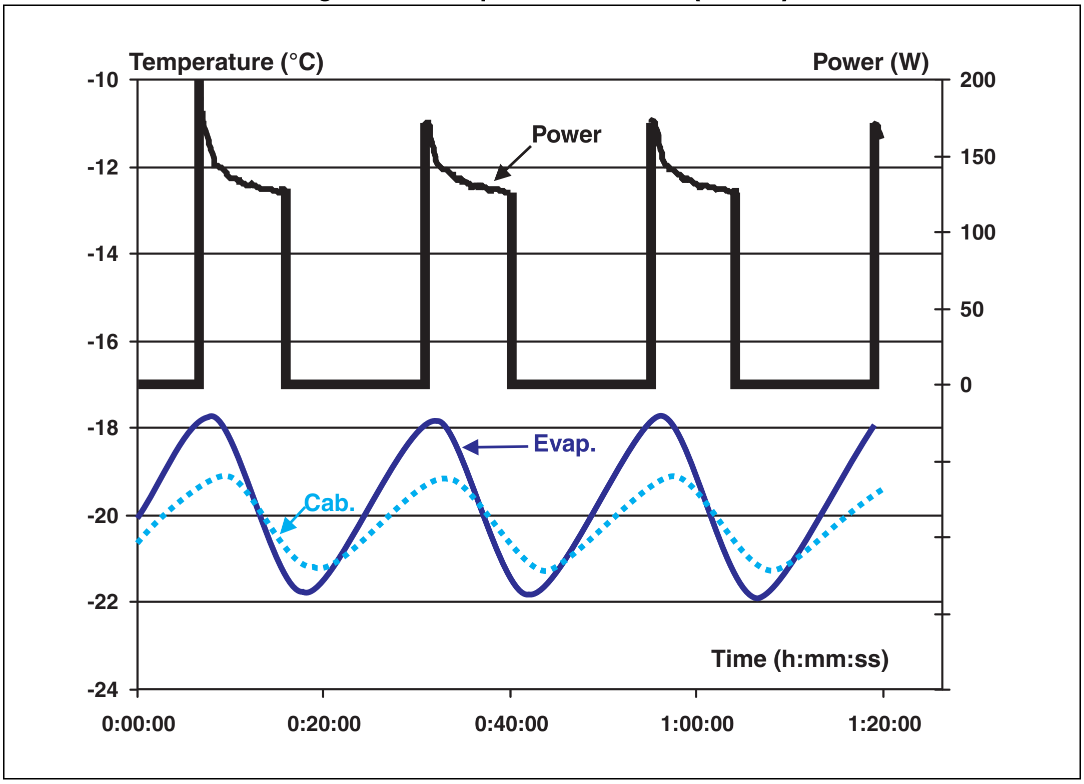


Figure 12. Temperature control (case 2)



4 Conclusion

Reliable electronic thermostats can now be used instead of older bimetallic solutions. This allows large efficiency gains to be achieved, thanks to the PTC removal and to a tighter temperature management.

These improvements can also allow downsizing of the compressor and the evaporator.

Switching to MCU based controls will allow higher flexibility and adaptability, and will help enhance the differentiation of appliances. Automatic routines (like defrost cycle) can be implemented and the end-user interface can be improved (temperature information, open door warning, temperature alarm, smooth light-up of the internal bulb by electronic dimming, etc.).

In terms of cost, electronics can now be competitive with electromechanical devices. A complete thermostat board, plus the sensor, can reach a cost similar to electromechanical thermostats. Furthermore, some features, such as extended life time or spark-free operation, come for free with electronics.

5 Revision history

Table 2. Document revision history

Date	Revision	Changes
29-May-2008	1	First issue under new code. Previously published as AN1354.
05-Sep-2013	2	Updated *Figure 4* and *Figure 7*. Replaced ACST6 with ACST610.