White paper

Induction motor energy efficiency regulations

Benefits of using soft starters with high efficiency motors

Racquel Ellul
Product Sales Support Engineer

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Benefits of using soft starters with high efficiency motors

1.INTRODUCTION

To reduce drastically CO_2 emissions, the European Union (EU) has set forth a set of regulations referred to as the Ecodesign regulation.
Through Ecodesign initiatives the estimated potential of final energy savings is 260 TWh by 2030. Electric motors are one of the groups that are addressed within this regulation. Electric motor driven systems in the industry consume up to 70% of the industrial electricity consumption [1]. Moreover, electric motors consume about 50% of the world's electrical energy consumption. Efficiency improvement of industrial motors can therefore bring about significant annual energy savings. The current regulation on Ecodesign for electric motors (EC) no 640/2009 will be repealed and replaced by Regulation (EU) 2019/1781 starting from July 2021. The revised regulation will increase the annual savings to 110TWh by 2030.
These EU regulations are forcing electric motor manufacturers to design motors with higher efficiency [2]. However, these standards are creating challenges for engineers, as motors have to be redesigned in order to improve their efficiency and in turn these improvements are causing other challenges, mainly high starting currents.
High efficiency (IE3, IE4) motors may require starting currents in the region of 10 times the motor rated current which is almost twice that of lower efficiency motors.
High levels of starting current bring with them issues related to voltage drops as well as false triggering of protection devices such as motor starters and circuit breakers.
This paper discusses the induction motor efficiency regulations imposed by the EU and the National Electrical Manufacturers Association (NEMA) on motor manufacturers, the consequences of these regulations and solutions to overcome such consequences

2. THE INDUCTION MOTOR

The induction motor, which is also referred to as asynchronous motor, consists of two main parts; the rotor and the stator. The stator is the stationary part and it consists of a three-coil winding which is passed through slots known as poles.
While, the rotor is the rotating part and there are different types of rotor constructions.

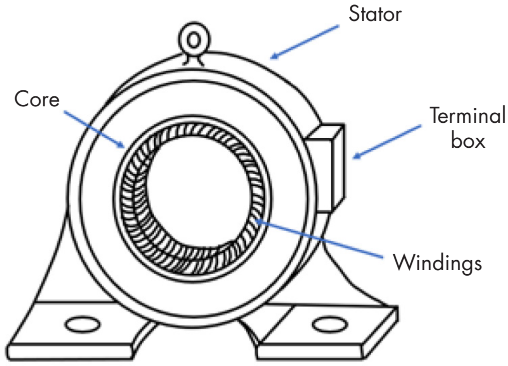

Figure 2.1 Stator [1]

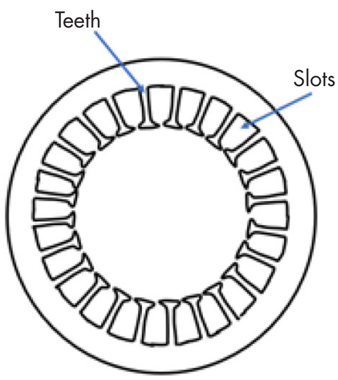

Figure 2.2 Stator core [1]

The construction and the operation of the induction motor leads to the motor characteristics shown by Figure 2.3, where it demonstrates the current drawn by an induction motor from when supply is given to the motor until it reaches synchronous speed.

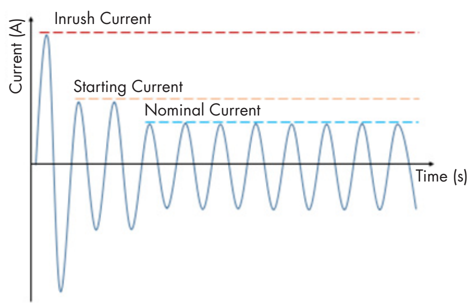

Figure 2.3 current drawn by an induction motor

As the motor is connected with the power supply, it will draw an inrush current for the first few power supply cycles. The inrush current often reaches more than twenty times the nominal current of the motor. Typically, after one power supply cycle, the motor starts to turn and the current reduces down to the starting current, which can reach from five up to fifteen times the nominal current of the motor. The motor increases in speed whilst, the starting current always decreases until it reaches synchronous speed. Once synchronous speed is reached, the current drops down to the nominal current of the motor. The nominal current is drawn for as long as the motor is left running.

3.MOTOR LOSSES AND EFFICIENCY

The energy efficiency of an electric motor is a measure of the ability of the electric motor to convert the electrical energy supplied to it into mechanical energy. Hence, motor efficiency is defined as the ratio between mechanical output power of the motor and the electrical input power supplied to it. The portion of the input power that is not used to do useful work, is lost through losses in the motor itself. These losses can be split in five: 1) the stator core (iron) losses; 2) stator copper (I2R) losses; 3) rotor core (iron) losses; 4) rotor copper (I2R) losses and 5) mechanical losses. The stator core and rotor core losses include eddy current losses and hysteresis losses which do not change with the load but depend on the frequency of the power supply, whilst the stator copper and rotor copper losses depend on the load.
Once the motor is supplied by the input power from the power supply, current starts flowing in the stator winding, and this will produce stator copper losses. Then, a rotating magnetic field takes place which causes stator core losses. This magnetic field crosses the air gap between the stator and the rotor, and couples with the rotor. Once the magnetic field is coupled with the rotor, it produces rotor copper losses and rotor core losses, the latter is negligible. The output power from the rotor produces mechanical power which rotates a bearing. Hence, friction losses and windage losses are produced.

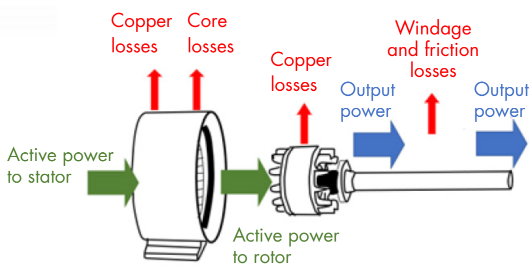

Figure 3.1 Losses in induction motor [2]

As aforementioned, the copper losses depend on the load. Therefore, the loading percentage plays a large role in the efficiency of the motor, as can be seen from Figure 3.2.

Most electric motors are designed to run at 50% to 100% of the rated load.The maximum efficiency normally is at around 75% of the rated load and when the load falls below 50% the motor efficiency falls drastically.
Therefore, when for example there is a load of 10 horse power (hp) and the installer installs a 20 hp motor to keep a safety margin.
This is a very inefficient solution since only 50% of the rated motor load capacity will be used.
High rated power motors always have higher efficiencies than smaller rated power motors.
This is because high power motors are normally bigger in size and therefore, more copper and more coil windings will be available. Hence, they have lower resistance.

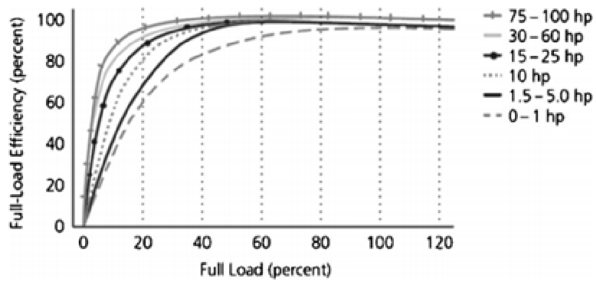

Figure 3.2 Motor efficiency vs load [2]

The efficiency can either be calculated directly using the input and output powers or indirectly through the use of the sum of losses which are subtracted from the input power thus, giving the useful output power to do work.

4.MOTOR EFFICIENCY REGULATIONS IN THE EU

In motors, the energy efficiency level is expressed in international energy efficiency classes (IE), where IE1 is the least efficient class which is also defined as the 'standard efficiency class' and, IE4 is currently the most efficient class. In fact, it is known as the 'super-premium efficiency class'. IE2 and IE3 are also defined as the 'high efficiency class' and the 'premium efficiency class' respectively [4].
As aforementioned, IE3 and IE4 motors have a higher efficiency than IE1 and IE2 motors.
However, as the power rating of the motor increases, this discrepancy in efficiency always decreases, as can be noted from Figure 4.1 below.
This is due to the fact that the high-power motors in general already have a high efficiency especially compared with the low power motors.
Hence, it is difficult to increase their efficiencies by a significant amount.

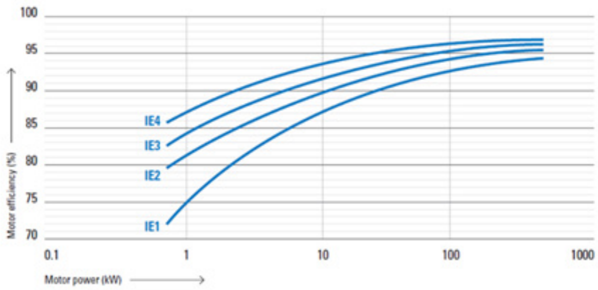

Figure 4.1 The efficiency percentage of electric motors from every class [3].

The first regulations on electric motors date back to 2009, these being Regulation (EC) No 641/2009 and Commission Regulation (EC) No 640/2009, which regulations are being revised to meet the industrial development which is rapidly taking place. The current regulations apply for induction motors with single speed, three-phase 50 Hz or 60 Hz frequency of operation and, with the following characteristics:

- 2 to 6 poles
- Rated output between 0.75 kW and 375 kW
- Rated voltage up to 1000 V
- Rated on the basis of continuous duty operation

Under the current regulations, motors must either reach the IE3 efficiency level, or meet the IE2 efficiency level and be equipped with a variable speed drive (i.e. an electric device that adjusts the speed of the motor).
Some motors designed for specific conditions are excluded from these rules, for example those that are immersed in a liquid such as in sewage systems.
However, as from July 2021, the current regulations will no longer be in effect whereby Regulation (EC) No 641/2009 will be amended and Commission Regulation (EC)No 640/2009 will be repealed by 'Regulation on electric motors and variable speed drivers (EU) 2019/1781'. These new regulations will cover more induction motors which have previously not been covered in the current regulations.
Such induction motors which will be included are:

- Smaller motors between 120 W and 750 W
- Larger motors between 375 kW and 1000 kW
- 60 Hz motors
- 8 poles motors
- Single-phase motors (the latter only as from July 2023)
- Rated voltage above 50 V up to 1 kV
- Motors capable of continuous operation at their rated power with a temperature rise within the specified insulation temperature class
- Motors marked with any ambient temperature within the range of -20 °C to +60 °C
- Motors marked with an altitude up to 4000 meters above sea level

On the other hand, the following motors are excluded from the new regulations:

- Single-speed motors with 10 or more poles or multi speed motors
- Motors completely integrated into a machine (for example pump, fan or compressor) that cannot be tested separately from the machine
- Brake motors when the brake cannot be dismantled or separately fed

The new regulations enforce more efficient motors, as three-phase motors with a rated output power between 0.75 kW and equal to or below 1000 kW must reach the IE3 level by July 2021 and motors between 75 kW and 200kW must meet the IE4 level as from July 2023 [2].
IE5 level is still being discussed.
As aforementioned, the efficiency varies with the power rating of the motor and the load. Hence, there is no single efficiency value for each efficiency class.
However, there are threshold values as specified by the regulations.

5.MOTOR EFFICIENCY REGULATIONS IN THE USA

In the US, the total electricity consumption of the electric motors is more than 50% and when considering the industry only, the consumption is approximately 85% of the total electricity consumption [3]. Therefore, the NEMA released the first set of regulations regarding motor efficiencies in 2001 which regulations are similar to those in the EU. However, the NEMA differentiates between general purpose motors and special and definite purpose motors.
The NEMA regulations cover motors that are:

- Rated between 746 kW and 373 kW
- 3-phase low voltage power supply
- NEMA design A and B
- General, special and definite purpose motors

In addition, low voltage general purpose design "B" motors from 201 hp to 500 hp must meet MG 1 (Motor and Generator Section) standard.
NEMA design A motors are special and are not used very often since, they are usually used for applications that require extremely high efficiency and extremely high full-load speed. NEMA B-design motors are considered to be normal-torque motors. In the NEMA standard, the equivalent to IE4, IE3, IE2 and IE1 efficiency levels are 'Super premium efficiency' 'Premium efficiency' level and 'high efficiency' level respectively.

6.HIGH EFFICIENCY MOTORS CONSTRUCTION

The overall aim of high efficiency motors is to decrease stator ion losses, stator copper losses, the rotor ion losses and windage losses. Engineers are making motors more efficient through the use of thicker magnet wires in the stator, as well as thicker rotor bars and shorting rings to decrease the resistance.
An optimized lamination cross-section reduces stray-load losses. Stray-load losses are losses that are not accounted for by copper losses, core loss, friction or windage losses. Moreover, higher-quality lamination material reduces hysteresis losses too.
A copper cage for the rotor is preferred, rather than aluminum since, copper has lower resistance than aluminum. Therefore, in high efficiency motors, the rotor resistance is lowered to reduce the copper losses.
However, copper has higher density than aluminum therefore, motors with copper rotor cage have higher weight. The larger weight makes them more tolerant to short-term thermal transients.

7.CHALLENGES CAUSED BY HIGH EFFICIENCY MOTORS

The decrease in resistance for higher efficiency motors is causing higher locked rotor currents, as can be observed from Figure 7.1.
However, the continuous current (i.e. once the motor reaches full speed) for IE3 motor is less than for IE2.

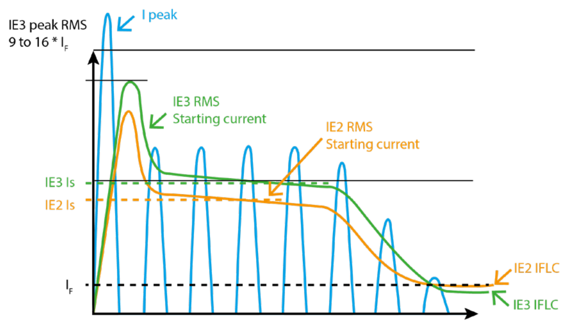

Figure 7.1 Starting Current of IE3 and IE2 motors

This high inrush current can cause different problems. A common problem is the false tripping of protection equipment such as contactors, circuit breakers and overload relays. However, there are other consequences that are an indirect cause of the high inrush current such as high initial torque which can cause damage on some loads, and voltage drops (also known as voltage dips or voltage sags) in the mains power supply.
A voltage dip happens when the voltage drops below 10% of the usual mains power supply. Such voltage dip can cause flicker in light which in some cases may result in the burning the light bulbs/LEDS and malfunction of some equipment powered from the same mains power supply. Equipment that use electronic power supply might fail to operate when the power supply output voltage drops below a specified value.
Examples of such failures are errors in electronics and shutdown of electronics due to under-voltage detection algorithms.
Some equipment sensitive to voltage dips in the industry include: programmable logic controllers, adjustable speed drives, contactors, relays and control equipment. Failure in operation of any of the mentioned equipment can put the production to stop.
Another indirect consequence of the high inrush current is high temperatures which can cause tripping of protection equipment and also cause aging on the motor windings.
Apart from the above-mentioned damages, the high inrush current can cause customers to have issues with the power supply utilities and will end up incurring penalties due to a failure of following the regulations to keep a clean and stable grid.

8.USING SOFT STARTERS TO MITIGATE THE DISADVANTAGES OF HIGH EFFICIENCY MOTORS

A soft starter as shown in Figure 8.1 is a device that reduces the inrush and starting current drawn by a motor. While the motor is still starting, the soft starter uses triacs which are two back to back thyristors.
Thyristors are semiconductor switches and they are used to control the voltage supplied to the motor and hence, the current drawn by the motor will be controlled.
Once the motor reaches full speed, the soft starter will give the total supply voltage to the motor though the use of mechanical relays instead of the thyristors.
This is done because thyristors have a high-power loss which in turn generates heat.

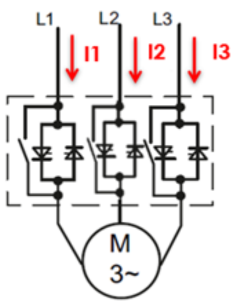

Figure 8.1 3-phase controlled (bypass switching) Soft Starter configuration

The reduction in current when starting a motor with a soft starter can be observed from Figure 8.2 to Figure 8.4.

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Figure 8.2 shows the current drawn by the motor when it was started Direct-On-Line reaches 200 A peak. On the other hand, Figure 8.3 shows the current drawn by the motor when it is started with an RSGD (25 A rated, 2-phase controlled) Carlo Gavazzi soft starter and Figure 8 4 shows the current draw by the motor when it was started with an RSGT (25 A rated, 3-phase controlled) Carlo Gavazzi soft starter. When the motor was started with the RSGD the starting current was decreased to 120 A peak and when it was started with the RSGT it was decreased to 85 A peak. Therefore, there is a reduction of 40% and 57.5% respectively when compared to Direct-On-Line.

This proofs that a 3-phase controlled soft starter can reduce the starting current more than a 2-phase controlled soft starter can. The blue plot which is the contour of the current drawn when connected Direct-On-Line, on both plots, gives a more visual representation of the decrease in the starting current when using a soft starter.

The decrease in the starting current reduces the high starting torque since, the torque of an induction motor is directly proportional to the current squared.

High starting torque may cause machinery to get damaged due to sudden jerk such as wear and tear or damage of gears, chains or couplings. Also, belts may slip and the material being processed on the conveyors may get damaged. It follows that soft starters are needed to start the motor more smoothly and thus, protect both the motor and the load.

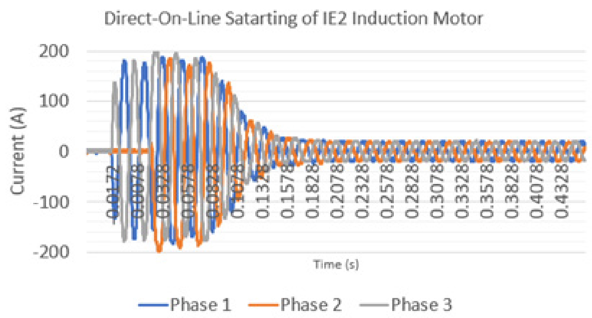

Figure 8.2 Direct Online Start

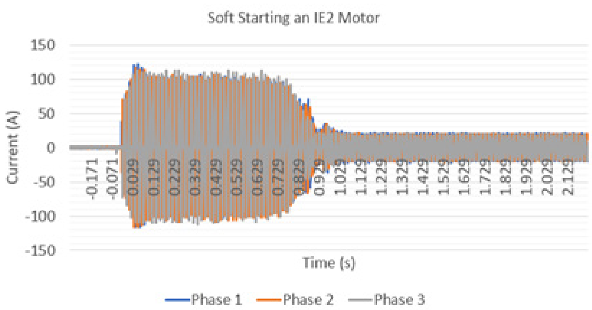

Figure 8.3 Starting with a 2-Phase controlled soft starter

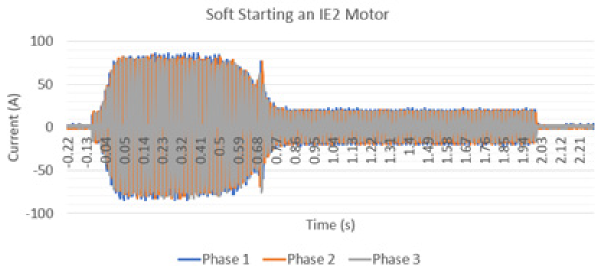

Figure 8.4 Starting with a 3-Phase controlled soft starter

An intelligent soft starter like the RSGD (25 Amp rated soft starter) offers current monitoring and through the use of this closed loop current monitoring, the starting characteristic of the motor can be improved.

For example, if a load is required to start within two seconds but the soft starter is sensing that the load is starting in one second, it will adjust the firing angle of the thyristors in order to reduce the starting current further and start the load more smoothly.

The soft starters of Carlo Gavazzi will also trigger an alarm if it senses that the current exceeded a certain threshold in order to protect the winding of the motor from overheating and other damages. Thus, with the current monitoring loop, high efficiency motors are always protected from the inrush currents which could be drawn if a soft starter is not used and, the pocket of the entrepreneurs is also more protected when they come to pay their electricity bills and do their maintenance.

Soft starters can be split in two main groups: the 3-phase controlled soft starters and the 2-phase controlled soft starters.

The difference between these two groups is that with a 3-phase controlled soft starters, the current on all the three phases is monitored and controlled.

While, with 2-phase controlled soft starter, only two phases have the current controlled, the other phase would be just shorted (i.e. a direct link from the mains supply to the motor). Yet, even though only two phases are controlled, soft starters like Carlo Gavazzi's family, the algorithm would still make sure that the current on all 3-phases is balanced. However, when compared with the 3-phase controlled soft starter the current unbalance between the phases would be slightly higher.

Furthermore, a 3-phase controlled soft starter can offer better current reduction.The only draw back of a 3-phase controlled soft starter when compared with 2-phase controlled is that it is more expensive to purchase, but in the long run, the additional reduction in current might lead to lower electricity bills.

As mentioned earlier, the high inrush current drawn by high efficiency motors might lead to false tripping of some protection equipment which in turn might lead to long down time of the production and thus, loss of profit.

Thus, this situation would force the plant engineer to buy new protective equipment which can withstand the high currents and hence, more money has to be spent. While, with the use of a soft starter, the same protection equipment that was already present in the building could still be used, eliminate down time and reduce the electricity bills.

9.SOFT STARTERS VS VARIABLE FREQUENCY DRIVES

A variable frequency drive (VFD) as shown in Figure 9.1 is another means to reduce the inrush current drawn by motors. A VFD is also referred to as variable speed drive, adjustable speed drive or adjustable frequency drive. A VFD reduces the inrush current by controlling the frequency and the voltage applied to the motor – known as V/f control.
Thus, with a VFD the motor speed can also be adjusted to match the load requirements such as flow control in pumps. By lowering the load speed, energy can be saved, since according to the Affinity laws, the change in power consumed is proportional to the cube of the change in shaft speed as shown in Figure 9.2.

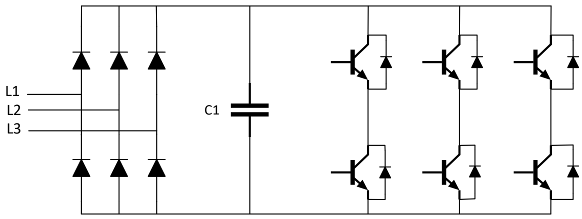

Figure 9.1 Variable frequency drive (VFD)

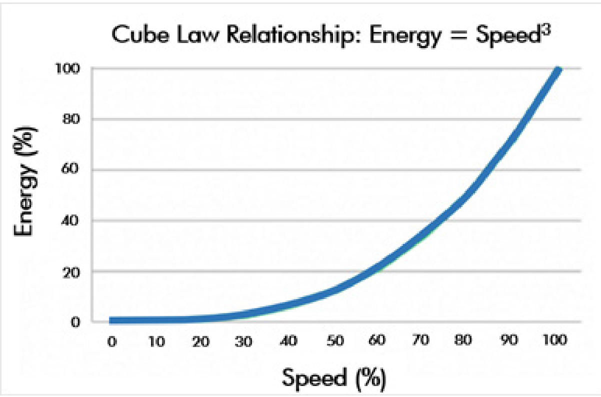

Figure 9.2 Cube law relationship (Affinity laws)

However, VFDs are not always the most convenient solution to limit the inrush current drawn by the induction motor. If a load always runs at constant speed (50 Hz), the VFD is less efficient compared to the soft starter due to the losses in the transistors and the diodes. On the other hand, soft starters have much lower losses since bypass relays are used to conduct the current during normal operation.

Moreover, the cost of VFDs vs soft starters can be 5-fold depending on the power rating. Proper supply filtering and screened cabling should be used with VFDS to avoid EMC phenomena

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OUR SALES NETWORK IN EUROPE

AUSTRIA
Carlo Gavazzi GmbH
Ketzergasse 374,
A-1230 Wien
Tel: +43 1 888 4112
Fax: +43 1 889 10 53
office@carlogavazzi.at

BELGIUM
Carlo Gavazzi NV/SA
Mechelsesteenweg 311,
B-1800 Vilvoorde
Tel: +32 2 257 4120
Fax: +32 2 257 41 25
sales@carlogavazzi.be

DENMARK
Carlo Gavazzi Handel A/S
Over Hadstenvej 40,
DK-8370 Hadsten
Tel: +45 89 60 6100
Fax: +45 86 98 15 30
handel@gavazzi.dk

FINLAND
Carlo Gavazzi OY AB
Ahventie, 4 B
FI-02170 Espoo
Tel: +358 9 756 2000
myynti@gavazzi.fi

FRANCE
Carlo Gavazzi Sarl
Zac de Paris Nord II, 69, rue de la Belle Etoile,
F-95956 Roissy CDG Cedex
Tel: +33 1 49 38 98 60
Fax: +33 1 48 63 27 43
french.team@carlogavazzi.fr

GERMANY
Carlo Gavazzi GmbH
Pfnorstr. 10-14
D-64293 Darmstadt
Tel: +49 6151 81000
Fax: +49 6151 81 00 40
info@gavazzi.de

GREAT BRITAIN
Carlo Gavazzi UK Ltd
4.4 Frimley Business Park,
Frimley, Camberley, Surrey GU16 7SG
Tel: +44 1 276 854 110
Fax: +44 1 276 682 140
sales@carlogavazzi.co.uk

ITALY
Carlo Gavazzi SpA
Via Milano 13,
I-20045 Lainate
Tel: +39 02 931 761
Fax: +39 02 931 763 01
info@gavazziacbu.it

NETHERLANDS
Carlo Gavazzi BV
Wijkermeerweg 23,
NL-1948 NT Beverwijk
Tel: +31 251 22 9345
Fax: +31 251 22 60 55
info@carlogavazzi.nl

NORWAY
Carlo Gavazzi AS
Melkeveien 13,
N-3919 Porsgrunn
Tel: +47 35 93 0800
Fax: +47 35 93 08 01
post@gavazzi.no

PORTUGAL
Carlo Gavazzi Lda
Rua dos Jerónimos 38-B,
P-1400-212 Lisboa
Tel: +351 21 361 7060
Fax: +351 21 362 13 73
carlogavazzi@carlogavazzi.pt

SPAIN
Carlo Gavazzi SA
Avda. Iparraguirre, 80-82,
E-48940 Leioa (Bizkaia)
Tel: +34 94 480 4037
Fax: +34 94 431 6081
gavazzi@gavazzi.es

SWEDEN
Carlo Gavazzi AB
V:a Kyrkogatan 1,
S-652 24 Karlstad
Tel: +46 54 85 1125
Fax: +46 54 85 11 77
info@carlogavazzi.se

SWITZERLAND
Carlo Gavazzi AG
Verkauf Schweiz/Vente Suisse
Sumpfstrasse 3,
CH-6312 Steinhausen
Tel: +41 41 747 4535
Fax: +41 41 740 45 40
info@carlogavazzi.ch

OUR SALES NETWORK IN THE AMERICAS

USA
Carlo Gavazzi Inc.
750 Hastings Lane,
Buffalo Grove, IL 60089, USA
Tel: +1 847 465 6100
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CANADA
Carlo Gavazzi Inc.
2660 Meadowvale Boulevard,
Mississauga, ON L5N 6M6, Canada
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MEXICO
Carlo Gavazzi Mexico S.A. de C.V.
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T +52 55 5373 7042
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mexicosales@carlogavazzi.com

BRAZIL
Carlo Gavazzi Automação Ltda.Av.
Francisco Matarazzo, 1752
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Tel: +55 11 3052 0832
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Carlo Gavazzi Automation Singapore Pte. Ltd.
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Tel: +65 67 466 990
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MALAYSIA
Carlo Gavazzi Automation (M) SDN. BHD.
D12-06-G, Block D12,
Pusat Perdagangan Dana 1,
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CHINA
Carlo Gavazzi Automation
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Shenzhen, China
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Unit No. 16 on 25th Floor, One Midtown,
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