

Technical and Economic Benefits of Integrating a Smart Electronic Star-Delta Commutator inside the Terminal Box of “Ex d” Line-Operated Three-Phase Induction Motors

Fernando J. T. E. Ferreira¹, Pedro M. R. A. Maia²

¹*Institute of Systems and Robotics, Department of Electrical and Computer Engineering, University of Coimbra, Portugal*

²*WEGeuro Indústria Eléctrica, S. A., Portugal*

Abstract

The dominant solution for soft-starting line-operated, three-phase, squirrel-cage induction motors (SCIMs) is still the electromechanical star-delta starter. This solution requires three contactors, a timer, a cabinet, and six cables from the starter to the motor. In this paper, a novel, low-cost, ultra-compact, self-powered, smart, electronic device for soft-starting and performance improvement of SCIMs is described. This device can be installed inside the motor terminal box, which is a unique feature. The major benefits associated with this solution in the scope of areas with risk of explosion are pointed out, including motor telemonitoring, protection, fault diagnosis, soft-starting and input power reduction at light loads by means of an automatic load-based star-delta/delta-star commutation strategy that optimizes operating condition. This capability is an important benefit in variable-load, fixed-speed applications, such as conveyors, mixers, presses, pumps, etc., and may lead to 5-15% energy savings and to a significant increase in the power factor. Experimental results for two 7.5-kW SCIMs are presented, demonstrating the efficiency and power factor improvement potential at light loads. Another innovative characteristic of this device is the fact that it can be installed inside the “Ex d” motor terminal box, therefore, halving the number of conductors from the switchboard to the motor and eliminating the need for a dedicated space in the cabinet for the motor starter or, in some cases, eliminating the need for the “Ex” cabinet. The cost of an “Ex” cabinet/enclosure exceeds significantly that of the proposed device, leading to a virtually zero payback time.

1. Introduction

World industrial electric motor market is moving toward IE4 and IE5 efficiency classes. New three-phase motor technologies are being developed and introduced in the market, such as line-start synchronous motors. Nevertheless, the three-phase squirrel-cage induction motor (SCIM) still dominates the line-operated motor market for fixed-speed applications, being available from IE1 to IE4 classes [1-7].

The dominant solution for soft-starting line-operated SCIMs is still the electromechanical star-delta starter, which requires three contactors, a timer, a cabinet/switchboard, and six cables from the starter to the motor. The use of electronic soft-starters is also increasing, but they are more expensive than the electromechanical star-delta soft-starters. Both solutions are only to be used during the starting period and do not offer any energy saving possibility during the steady-state operation of the motor. Actually, the electronic soft-starter is by-passed after the starting period to avoid the respective losses and the associated harmonic distortion. Modern electronic soft-starters also offer advanced motor protection and have several communication interfaces.

In this paper, a novel electronic device, named InSwitch¹, for starting and performance improvement of SCIMs is presented, and its technical and economic advantages and application in environments with risk of explosion are discussed.

¹ “InSwitch” is a trademark. This device has been developed and is being commercialized by OptiSigma – Energia & Ambiente, Lda. (www.optisigma.pt).

2. InSwitch

InSwitch is a low-cost, ultra-compact, self-powered, smart, electronic device (Fig. 1) for soft-starting and performance improvement of line-operated SCIMs. This device can be installed inside the motor terminal box, as it can be seen in Fig. 2, which is a unique feature.

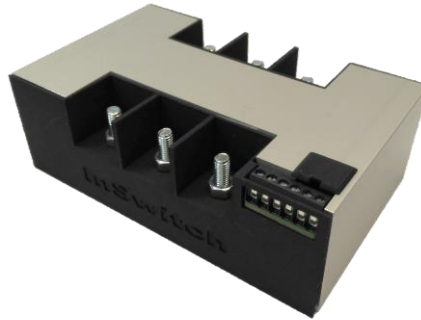


Fig. 1. 24-kVA model of InSwitch.



Fig. 2. InSwitch installed inside the terminal box of a 7.5-kW, 4-pole SCIM.

A detailed description of the device can be found in [8]. The basic topology of InSwitch is presented in Fig. 3. To perform the star/delta connection mode change, 5 or 6 bidirectional switches (S1-S6) are needed, depending if 2 or 3 switches are used for the star connection mode. To operate the motor in star mode, the switches S1, S2, and S3 are in ON state, and the switches S4, S5, and S6 are in OFF state. To operate the motor in delta mode, the switches S1, S2, and S3 are in OFF state, and the switches S4, S5, and S6 are in ON state. The use of 3 bidirectional switches (instead of 2) in the star connection mode reduces the voltage stress over/through them, increasing the reliability of the device, which is an advantage, but produces more conduction losses and increase the cost of the device. If the rotating direction is to be reversed, 4 additional switches are needed. In order to suppress transients and protect the power switches, filters, snubbers and varistors are used.

In the InSwitch, similarly to the commercial low-voltage solid-state contactors/relays, TRIACs are used as bidirectional switches. Alternatively, twin antiparallel thyristors or combined bidirectional IGBT-diode sets can also be used. The motor magnetizing flux adjustment is made on the basis of the winding connection-mode change and not on the phase-angle firing control (used in the electronic soft-starters). Hence, in practice, it can be considered a sinusoidal technology (negligible current and/or voltage harmonic distortion at the input and output) and used in motor steady-state operation, not requiring an electromechanical by-pass relay/contactors.

Presently, the InSwitch is available for three rated powers, namely, 12 kVA, 24 kVA and 48 kVA (Fig. 4), and customized solutions can be produced for higher power levels. The respective indicative/list prices are 300 €, 600 € and 900 €. The all-in-one multi-feature concept (Fig. 5), offers motor telemonitoring/telemetry, protection, fault diagnosis, soft-starting, and input power reduction and power factor improvement at light loads by means of an automatic load-based delta-star commutation strategy that optimizes the motor operating condition, as it can be seen in Fig. 6 [9-11].

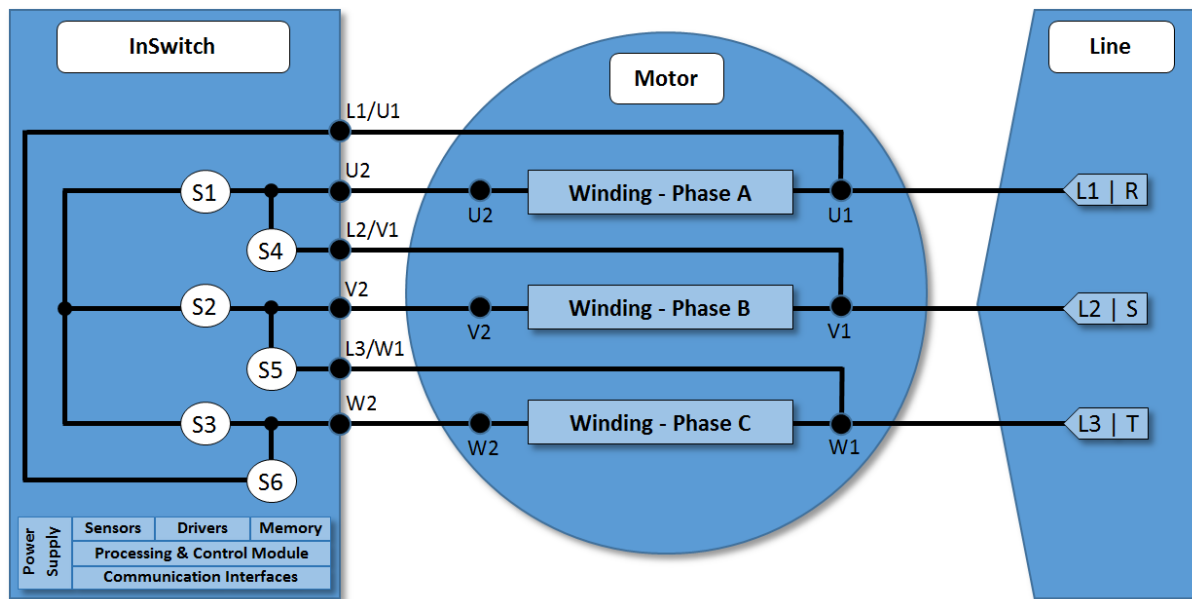


Fig. 3. Basic topology of InSwitch (S1-S6 represent bidirectional power switches).

With InSwitch, the energy savings are only possible in variable-load, fixed-speed SCIMs. For low load levels (lower than 40-50%), the device changes the connection mode to star, reducing the motor phase voltage 1.73 times and, consequently, improving the respective efficiency and power factor (Fig. 6). The efficiency improvement is mainly due to the core losses and saturation level reduction [9-11]. The power factor improvement leads to a reduction of the line current and, consequently, of the Joule losses in the upstream power cables and transformers, ultimately contributing to an additional reduction of the active energy consumption. Therefore, the longer the light-load operating periods are, the higher the energy savings will be.

Furthermore, having wireless (Bluetooth; optional external Wi-Fi and ZigBee modules) and by-wire (RS-485/Modbus) communication capability, the described device also fits into the Industry 4.0 concept, which is the current trend of automation and data exchange in manufacturing technologies, including cyber-physical systems, the Internet of things and cloud computing. In Figs. 7 and 8, the InSwitch as a technology for Industry 4.0 concept and its possible integration in industrial communication/data networks is illustrated. The major advantages associated with InSwitch are summarized in Fig. 9.

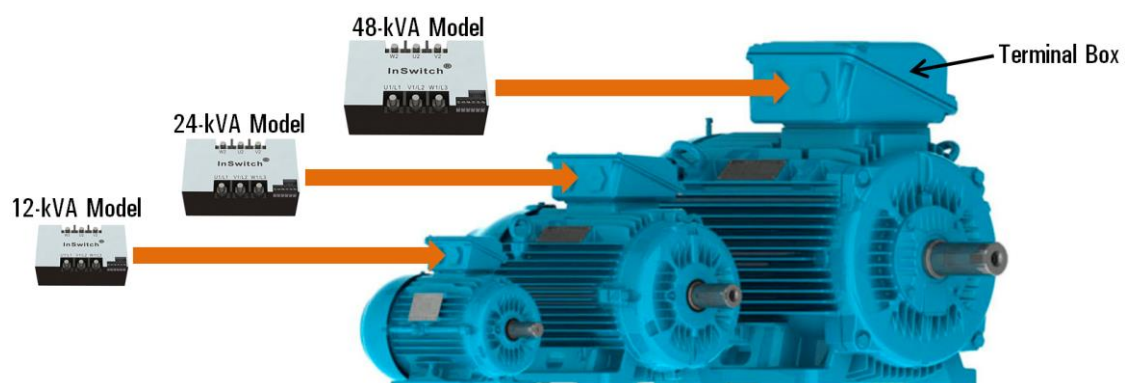


Fig. 4. Commercial models of InSwitch.



Fig. 5. InSwitch concept.

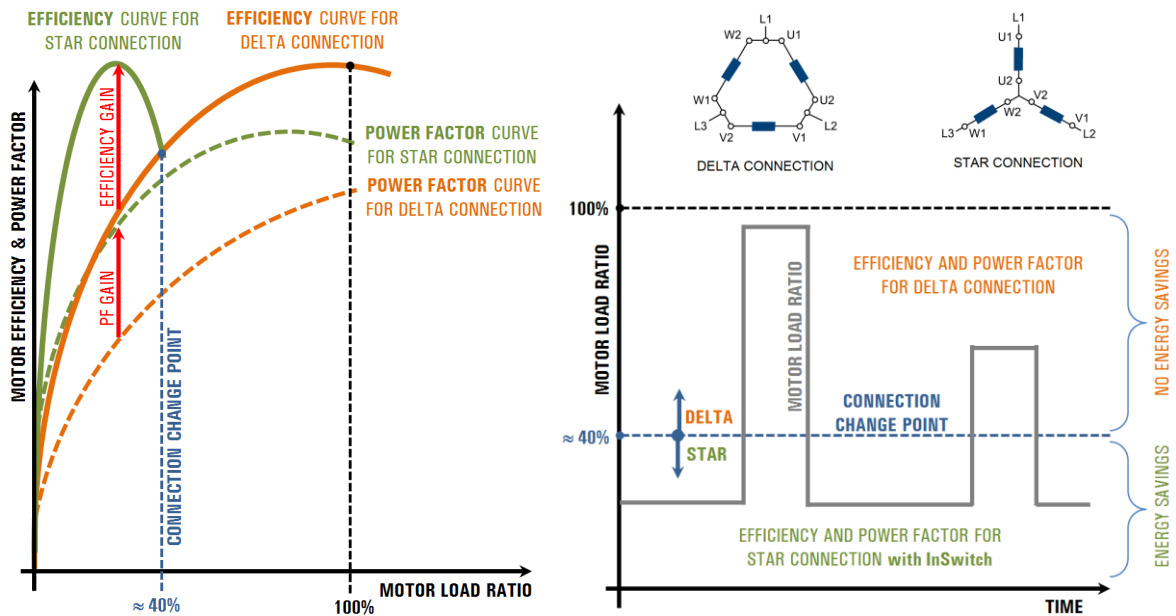


Fig. 6. Principle of efficiency and power factor improvement by means of automatic load-based star-delta commutation strategy.



Fig. 7. InSwitch as a device to integrate SCIMs in the Industry 4.0 concept.

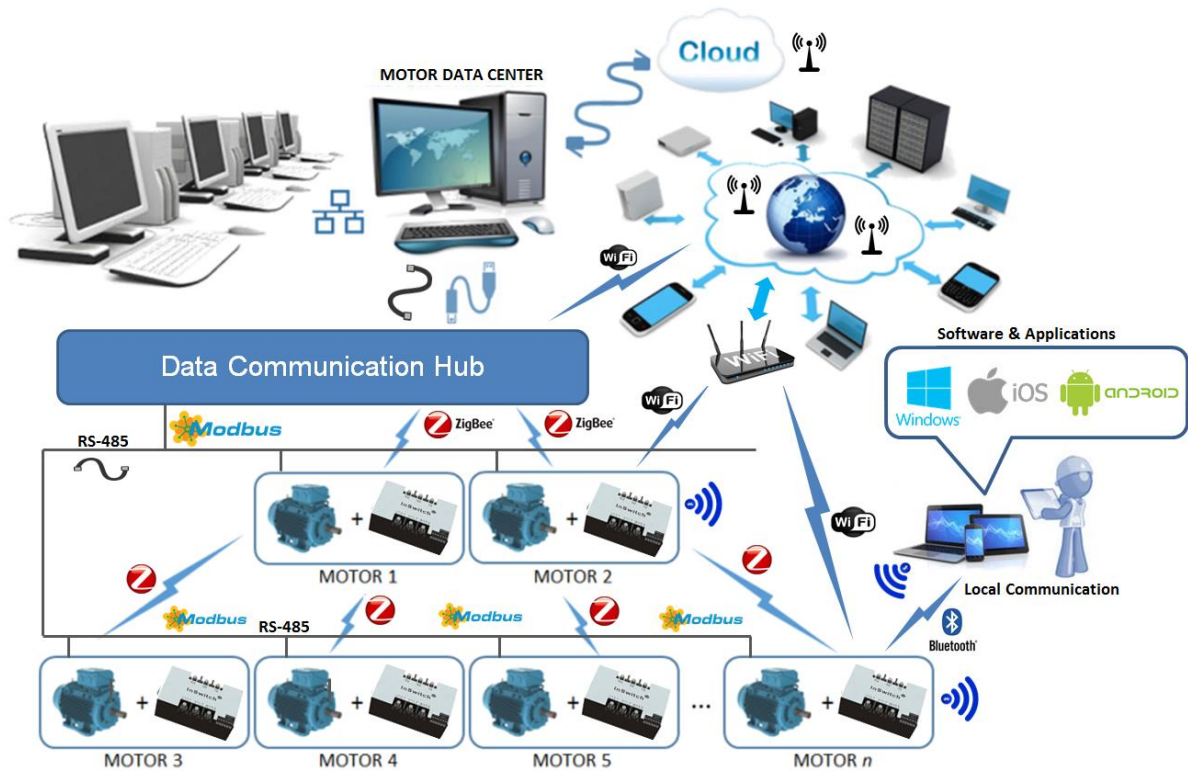


Fig. 8. InSwitch integration in new or existing industrial communication/data networks.

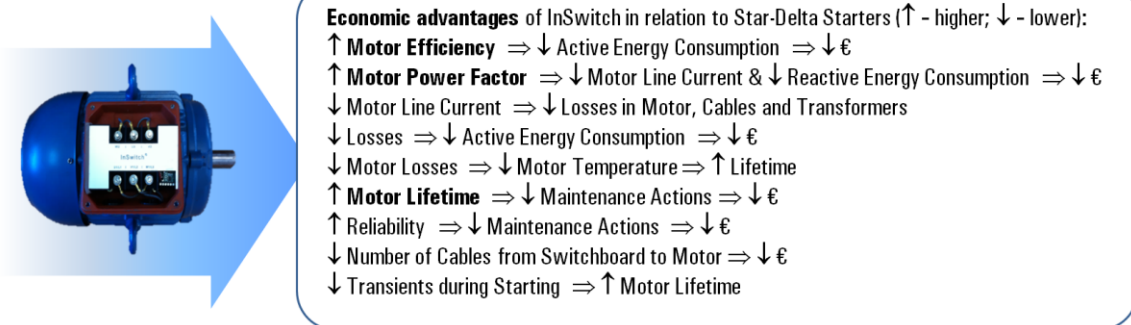


Fig. 9. Summary of the main economic advantages associated with InSwitch.

3. Experimental Results

The 24-kVA InSwitch model has been experimentally tested with two 7.5-kW, 4-pole SCIMs. In Fig. 10, the experimental efficiency of InSwitch is shown. In delta mode, the efficiency exceeds 99.5%. In Figs. 11 and 12, the efficiency and power factor gains that can be obtained with InSwitch at light loads for the tested motors are shown. The motor active and reactive power reduction is presented in Fig. 13. For the studied cases, the motor active power reduction is maximized at circa 20% load, and it is higher for the IE2-class SCIM.

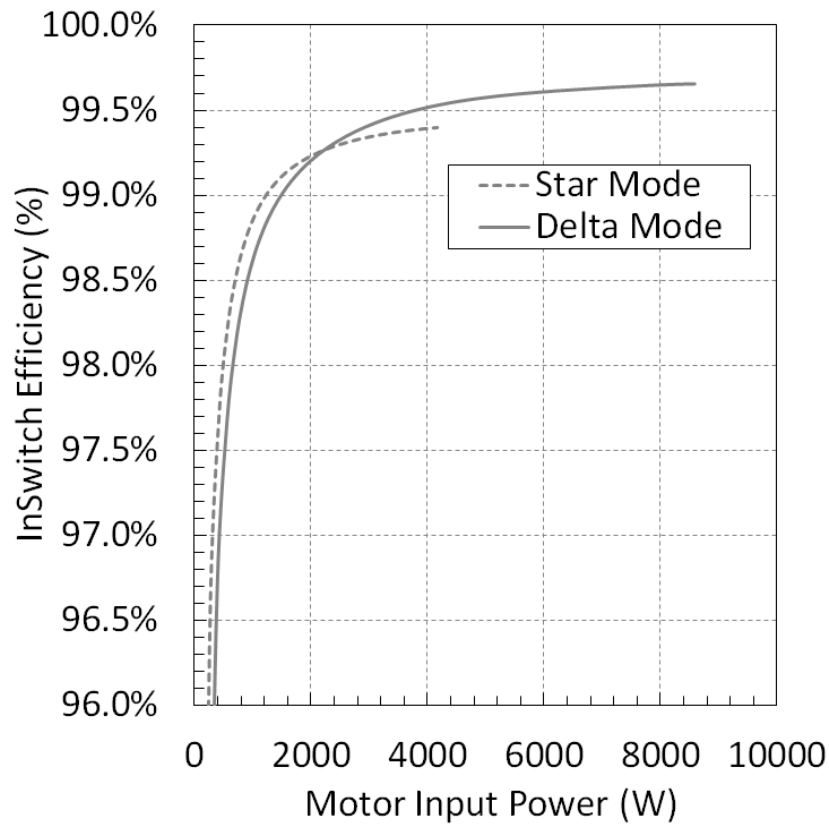


Fig. 10. InSwitch efficiency [12].

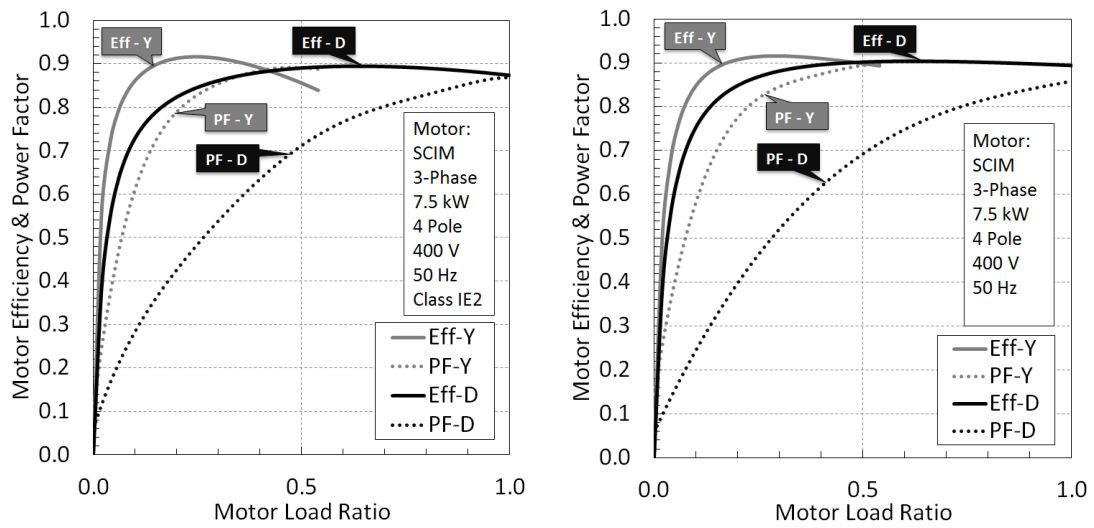


Fig. 11. Motor efficiency and power factor of 7.5-kW, 4-pole SCIMs: (left) Class IE2; (right) Class IE3 [12].

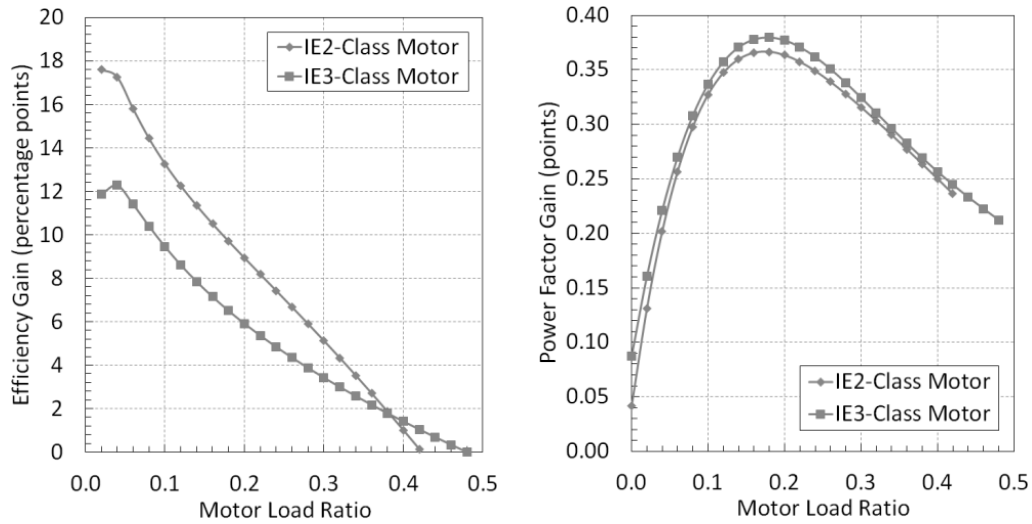


Fig. 12. Motor efficiency and power factor gains of 7.5-kW, 4-pole SCIMs: (left) Efficiency; (right) Power Factor.

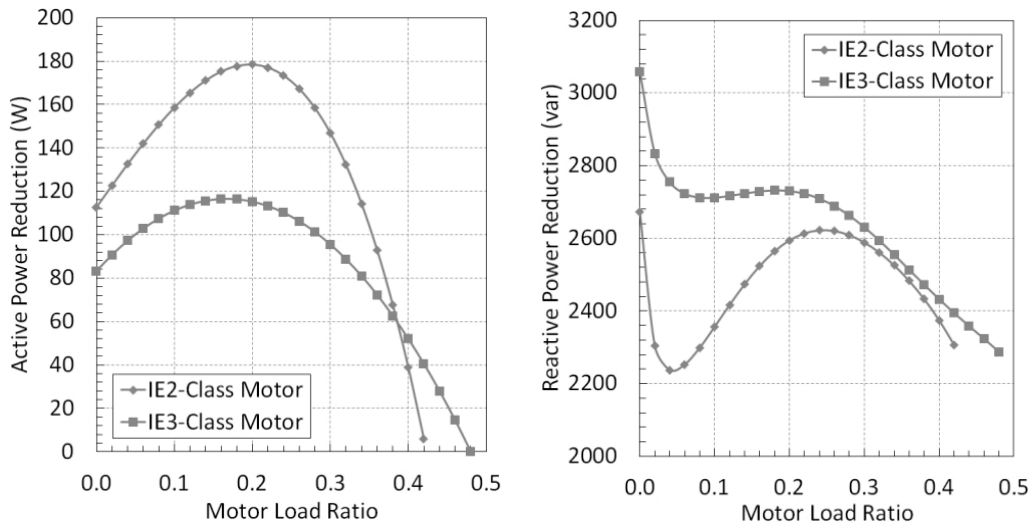


Fig. 13. Motor input active power and reactive power reduction of 7.5-kW, 4-pole SCIMs: (left) Active power; (right) Reactive power.

4. Application of InSwitch in Facilities with Potentially Explosive Atmospheres

An interesting application of InSwitch is in SCIMs operating in facilities with potentially explosive atmospheres, since it may lead to a reduction in the overall installation cost, including power cables, enclosures/cabinets, and protection and control devices.

The risk of explosion of gases and dust exists in many situations and industries, from sugar refineries and grain mills to offshore oil platforms. The use of incorrect components and installations inside hazardous areas will cause a potential harm in both personal and machinery, thus reducing the quantity of equipment inside such area is reducing the latent risk associated with the installation.

The ATEX (*ATmosphères EXplosibles*, in French) term/mark (Fig. 14) is commonly used to describe potentially explosive atmospheres and standard for protection systems and equipment. Two European directives, ATEX 137 - 99/92/CE (*Minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres*) and ATEX 95 - 94/9/CE (*Equipment and protective systems intended for use in potentially explosive atmospheres*), and international standards IEC60079 and IEC61241, harmonized with EN European standards, apply to this field, providing the essential “safety Ex” requirements for the classified hazardous areas.

According to ATEX, a potentially explosive atmosphere is defined as a mix of flammable substances in the form of gas, vapour or dust (cloud deposit) which, in the presence of an oxidizer (for example air), under normal atmospheric conditions, can completely or partially catch fire in the form of an explosion when exposed to a source of ignition.

Since July 1st, 2003, the European directive ATEX 94/9/CE makes compulsory the use of certified component, equipment or assembly when intended for use in potentially explosive zones/areas, gaseous or dusty atmospheres, ultimately intended to protect employees from explosion risk in those areas.



Fig. 14. Mark for ATEX certified electrical equipment for explosive atmospheres (Ex d – Explosion proof multivoltage motors; Ex de – Explosion proof multivoltage motors with increased safety terminal box).

Regarding ATEX 99/92/EC directive, the requirement is that Employers must classify areas where hazardous explosive atmospheres may occur into zones. The classification given to a particular zone, and its size and location, depends on the likelihood of an explosive atmosphere occurring and its persistence if it does. Areas classified into zones (0, 1, 2 for gas-vapor-mist and 20, 21, 22 for dust) must be protected from effective sources of ignition. Equipment and protective systems intended to be used in zoned areas must meet the requirements of the directive. Zone 0 and 20 require Category 1 marked equipment, zone 1 and 21 require Category 2 marked equipment and zone 2 and 22 require Category 3 marked equipment. Zone 0 and 20 are the zones with the highest risk of an explosive atmosphere being present. The aim of directive 94/9/EC is to allow the free trade of 'ATEX' equipment and protective systems within the EU by removing the need for separate testing and documentation for each member state. The regulations apply to all equipment intended for use in explosive atmospheres, whether electrical or mechanical, including protective systems. There are two categories of equipment 'I' for mining and 'II' for surface industries. Manufacturers who apply its provisions and affix the CE marking and the Ex marking are able to sell their equipment anywhere within the European Union without any further requirements with respect to the risks covered being applied. The directive covers a large range of equipment, potentially including equipment used on fixed offshore platforms, in petrochemical plants, mines, flourmills and other areas where a potentially explosive atmosphere may be present.

In very broad terms, there are three preconditions for the directive to apply: the equipment (i) must have its own effective source of ignition; (ii) be intended for use in a potentially explosive atmosphere (air mixtures); and (iii) be under normal atmospheric conditions.

Once certified, the equipment is marked by the 'CE' (meaning it complies with ATEX and all other relevant directives) and 'Ex' symbol to identify it as approved under the ATEX directive. The technical dossier must be kept for a period of 10 years. Certification ensures that the equipment or protective system is fit for its intended purpose and that adequate information is supplied with it to ensure that it can be used safely.

There are four ATEX classification factors to ensure that a specific piece of equipment or protective system is appropriate and can be safely used in a particular application: (1) Type of unit: mines (group I), surface industry (group II); (2) Zone classification: 0, 1, 2 (which are suitable components of category 1, 2, 3); (3) Characteristics of flammable materials present, such as gas, steam or fogs; (4) Application Group: IIA, IIB, IIC; (5) Temperature classes: T1, T2, T3, T4, T5, T6 (according to the highest allowable surface temperature of the machinery and according to the ignition temperature of the combustible materials).

The ATEX, as an EU directive, has its equivalent in the USA and Canada under the UL and CSA standards, respectively. This standard given by the Occupational Safety and Health Administration defines and classifies hazardous locations such as explosive atmospheres.

Different types of protection are defined in EN 60079 standard. They consist of different approaches to eliminate the risk of equipment explosion. These approaches include the removal of one of the corners of the fire triangle (combustible, oxidizer, and ignition) or the protection of the electrical parts by enclosure. The first approach includes protections like “Ex e” or “Ex i”, where the electrical equipment is designed/dimensioned in order to eliminate any ignition source. The second approach includes protections like “Ex d”, where electrical parts with no specific protection are placed inside a mechanical reinforced enclosure that guarantee that the occurrence of an explosion inside of it is contained and not transmitted to outside atmosphere, as illustrated in Fig. 15.

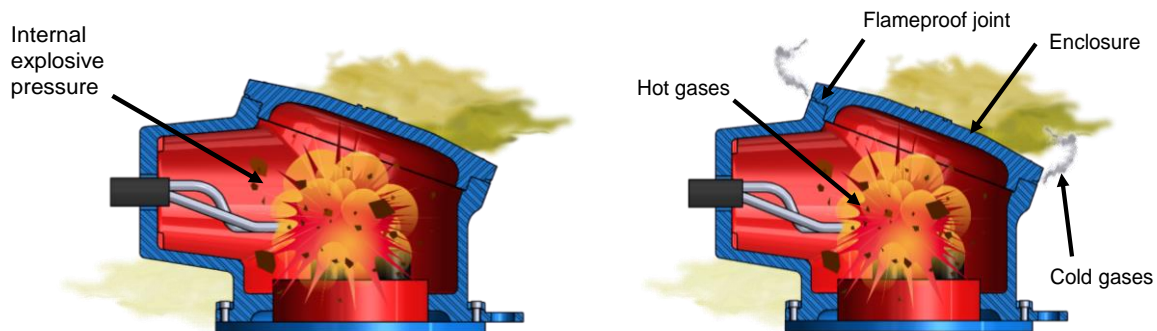


Fig. 15. The two dimensioning criteria for flameproof enclosures “Ex d”: (left) enclosure integrity; (right) non-transmission of the flame.

The “Ex” motor compliance is related to zone classification and to flammable material characteristics at the installation site. Besides all classification factors, the nameplate of “Ex” motors must include: (i) the information for a correct choice of the proper motor and for its correct installation; (ii) the reference to the official authority involved on the certification. Technical requirements of the electric motor installation, in the classified areas, are reported by EN 60079-14 standard. The standards for type of protection are: (i) EN 60079-0 and EN 60079-1 for “Ex d”; (ii) EN 60079-0, EN 60079-1 and EN 60079-7 for “Ex de”. Hazardous area motors are specially designed to comply with official regulations concerning the risk of explosion. If incorrectly used, poorly connected or if other minimal facts occur, their reliability could be damaged. Standards related to connection and use of electric apparatus in hazardous areas must be taken into consideration. The installation of electric motors where flammable products are continuously handled, processed or storage, must comply with the most demanded safety standards in order to guarantee protection of life, machines and environment. In Fig. 16, a commercial explosion-proof SCIM is shown.

There is also an ATEX-certified range of wall-mounting enclosures/cabinets, including steel, stainless steel and polyester, ensuring safety for every application. Enclosures are certified as components. They will be assembled with other ATEX electrical, pneumatic and hydraulic components, among others to form a final solution, which, in turn, must be ATEX-certified and subjected to a declaration of conformity. In general, wall-mounting enclosures comply with standards for protection against the increased risk of explosion in atmospheres charged with gas and/or dust. ATEX-certified enclosures are in most cases much more expensive than the normal enclosures (up to 5 times more). In Fig. 17, an example of commercial normal and ATEX-certified enclosures is presented.

In Fig. 18, three different possible scenarios for the installation of a line-operated SCIM with a start-delta starter in an ATEX zone.

In the first case (Fig. 18, top), the motor switchgear cabinet is installed in the ATEX space. Therefore, the motor, the 9 cables and the cabined have to be “Ex” marked, being potentially the most expensive solution.

In the second case (Fig. 18, middle), the cabined is outside of the ATEX space, leading to a reduction in the installation cost, but 6 “Ex” cables are still needed from the cabinet to the motor.



Fig. 16. Example of an explosion proof (Ex d / Ex de) IE2-class SCIM.



Fig. 17. Enclosures for electric or electronic systems: (left) steel, 400x300x150 mm, regular environments, list price of 321 €; (right) stainless steel, 380x260x160 mm, ATEX certification², list price of 1485 €.

In the third case (Fig. 18, bottom), the InSwitch is embedded in the motor and, therefore, there is no need for a start-delta starter cabinet, and, additionally, only 3 cables are needed from the main electric cabinet to the motor. Since the InSwitch is potentially cheaper than the star-delta starter set plus basic protections (phase loss, voltage/current unbalance, over/undervoltage, overload), the “Ex” cabinet is avoided and the number of “Ex” cables is halved, the cost of the system may be reduced to less than half in relation to the first scenario. It should be noted that, since the “Ex” motor terminal box is properly certified and the InSwitch is installed inside it, there is no need for “Ex” certification of InSwitch, which is an advantage.

Even if the cabinet is maintained in the ATEX space, when using InSwitch, its size can be significantly reduced (and thus its cost) because there is no need to use external motor protection devices, soft-starters or contactors. The short-circuit protection (magnetic circuit breaker), which is mandatory in most of the electrical installation regulations (and cannot be replaced by InSwitch), is the only device that has to be installed inside the motor control cabinet.

² It should be noted that the presented ATEX-certified enclosure is not “Ex d” (explosion protection). Such “Ex d” enclosures allow the use of electronic/electrical/electromechanical parts/devices/components not designed for dangerous environments in gas or dust explosion hazardous areas as well as in harsh or corrosive atmospheres. The list price of “Ex d” enclosures is significantly higher than that of the general ATEX-certified enclosures (as the one presented in Fig. 17).

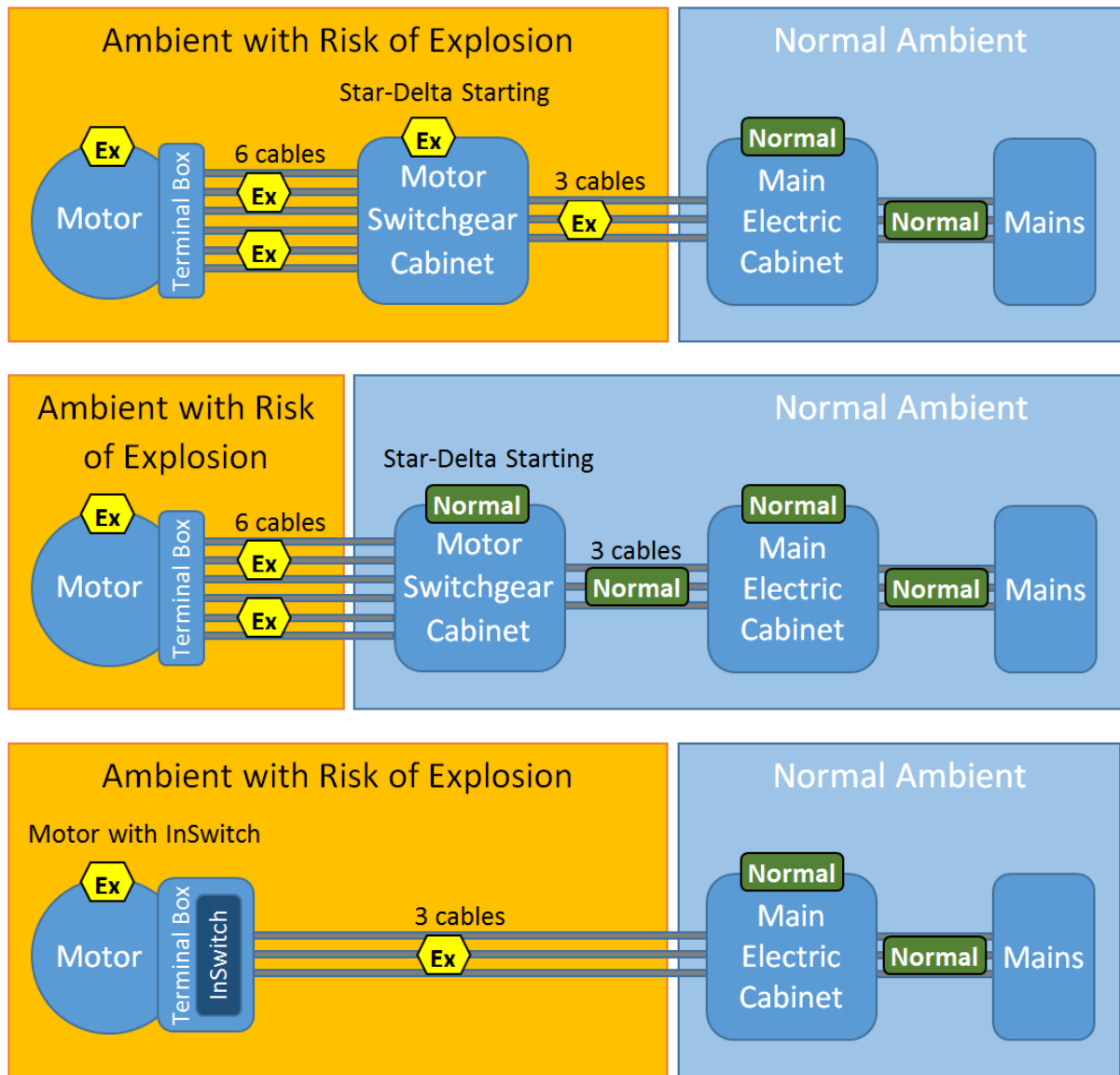


Fig. 18. Three different possible installations for explosion proof SCIMs: (top) motor switchgear cabinet inside the ATEX area; (middle) motor switchgear cabinet outside the ATEX area; (bottom) InSwitch integration into the motor, eliminating the motor switchgear cabinet.

On the top of it, InSwitch may lead to significant energy savings and power factor improvement if the driven application has a load torque as low as 20-30% the motor rated torque during a significant part of the operating cycle (as it can be seen in Fig. 6 and Figs. 11-13).

The InSwitch-based solution is therefore cheaper and potentially more efficient, leading to a virtually zero payback time. Moreover, it also offers the possibility of being integrated on a RS-485 and/or Wi-Fi/ZigBee data network or SCADA system, which is an important feature in the scope of the Industry 4.0 concept.

5. Conclusions

In this paper, a novel, low-cost, ultra-compact, self-powered, smart, electronic device for soft-starting and performance improvement of line-operated SCIMs has been presented. It was experimentally demonstrated that this device can reduce the motor input power at light loads by means of an automatic load-based connection-mode change strategy that improves the motor operating condition. When used in motors driving variable-load, fixed-speed applications, such as conveyors, mixers, presses, pumps, etc., this device may lead to 5-15% energy savings and to a dramatic increase in the power factor.

This device also offers other important features, such as motor telemonitoring, protection and fault diagnosis, and can be easily integrated in new or existing data network or SCADA systems, fitting into the “Industry 4.0” concept, which is the current trend of automation and data exchange in manufacturing technologies, including cyber-physical systems, the Internet of things and cloud computing

Since the presented device may be installed inside the motor terminal box, the number of conductors from the switchboard to the motor is halved and the need for a dedicated space in the cabinet for the motor starter is eliminated.

In the scope of facilities with risk of explosion, that unique characteristic opens the possibility of, in some cases, eliminating the need of the “Ex” motor cabinet/enclosure, since the device is installed inside the “Ex d” motor terminal box. At the same time, the installation results significantly simplified, reducing significantly the number of “Ex” power cables. The cost of an “Ex” cabinet exceeds significantly that of the proposed power electronic device (e.g. 1485 € for the “Ex” cabinet versus 600 € for the InSwitch device), leading to a virtually zero payback time. Besides that, the user will also benefit from the several useful features offered by the device.

It can be concluded that the proposed multi-feature device offers clear technical and economic advantages over the conventional star-delta starters and electronic soft-starters. These advantages become ever more relevant for industrial facilities with potentially explosive atmospheres, in which the user can reduce significantly the cost of the motor installation.

6. References

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