Energy Efficiency Measures for Electric Motors Systems: A Review and a Proposal for a Novel Classification

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Energy efficiency measures in electric motors systems: a novel classification highlighting specific implications in their adoption

Highlights:

- Electric motors present a considerable potential for energy efficiency in industry
- A comprehensive review of energy efficiency measures in motors systems is provided
- A new classification of energy efficiency measures in motors systems is proposed
- Specific features of energy efficiency measures may affect their adoption
- Productivity benefits from adopting energy efficiency measures are highlighted

The short version of the paper was presented at ICAE2018, Aug 22-25, Hong Kong. This paper is a substantial extension of the short version of the conference paper.

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Abstract

Electric motor systems (EMS) cover a remarkable share of industrial power consumption. Despite the wide set of apparently cost-effective opportunities to improve energy efficiency in this cross-cutting technology, often decision-makers do not take them, as the detail for a specific decision can be too high, resulting in an implementation rate quite low. In particular, little knowledge of the features that should be considered when deciding to undertake an action in this area represents a serious hurdle. In many cases, information regarding the characteristics of such energy efficiency measures (EEMs) is quite vague. For this reason, in the present study, we present a thorough overview of EEMs for EMS, basing on an extensive review of scientific and industrial literature. By highlighting their characteristics and productivity benefits, most of which impacting on the adoption decision-making process, we re-categorise EEMs for EMS, offering specific detail over single EEMs and thus support to industrial decision-makers. EEMs are presented according to four main groups, as follows: hardware, motor system drives, management of motors in the plant, and power quality. The novel classification is helpful to support research for the development of a new framework to represent the main factors that affect the adoption of EEMs for EMS. Further, it may help the identification and quantification of productivity benefits for those EEMs. Finally, it could result in a valuable tool offering different perspectives in the decision-making of industrial managers and technology suppliers, as well as industrial policy-makers.

Keywords:

Energy efficiency; electric motor systems; energy efficiency measures; classification; non-energy benefits.

1 Introduction

Industrial energy efficiency is crucial as, amongst the four main sectors (transport, industry, residential and services), industry covers the highest share of primary energy consumption (more than 30%), within a global trend of energy consumption of increase by 49% in the 2011-2035 horizon [1]. Moreover, the industrial sector is responsible for the major share (55%) of world delivered energy consumption [2]. About two-thirds of industrial power consumption are attributable to Electric Motor Systems (EMS) [3], with an

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extensive potential for improved energy efficiency. Extensive campaigns have increased the awareness that, by taking an EMS life-cycle costs perspective, the vast majority of its costs are due to operating costs (i.e., energy consumption) and, therefore, improving their energy efficiency will be abundantly cost-effective, also bringing additional productivity benefits [4]. Thus, improving their profitability for final users. Nevertheless, studies [5], [6] indicate a striking difference between their potential implementation rate and their effective one (e.g., [7]), confirming the existence of an energy efficiency gap [8], [9]. Therefore, it seems that, beyond awareness, other barriers, attributable to the specific characteristics, information and set of competencies to effectively implement EEMs in EMS may hinder their widespread adoption (e.g., [10], [11], [12]). On the one hand, industrial literature has so far developed classifications of EEMs in EMS [7], nevertheless without highlighting some relevant factors, such as specific implications at operational level, that, beyond energy and monetary savings, are crucial for a wise decision-making. On the other hand, scientific literature has also conducted cost-benefit analyses of EEMs in EMS, nevertheless without sufficient detail over the specific EEMs to be considered at operational level [13]. Further, despite the relevance of cost-benefit analysis, as authors note [10], [14], economics represents an important barrier, but not necessarily the main one [15] and the knowledge itself of financial and economic performance indicators [16], [17], if not complemented by a thorough analysis of the impacts on production, does not offer the full picture [18].

In fact, beside awareness that the majority of EMS life-cycle costs is covered by operating energy expenditures (therefore strongly proportional to the kWh consumed), recent studies over EEMs in EMS have highlighted that other information-related, behavioural and competence-related barriers could represent major issues for companies. In this regard, literature has conducted general overviews over EEMs in EMS (e.g., [13]), but without sufficient detail to support effective decision-making.

Hence, what on a first look seems a low hanging fruit [19] is instead a much more complex challenge; in many cases, the lack of a thorough and clear understanding of the factors and features [20] that should be taken into account to undertake conscious decisions, prevents industrial decision-makers from adopting EEMs in EMS. In this regard, sector heterogeneity and huge presence of small and medium-sized enterprises (SMEs) [21], being affected by a lack of standard procedures as well as internal competences [14], [22], represent additional contextual elements amplifying the aforementioned challenges.

Therefore, on the one hand, it is essential to support industrial decision-makers in understanding which specific EEM in EMS they should adopt to improve EMS energy efficiency, knowing that EEMs in EMS cover a large number of aspects, referring not only to a specific technology, rather spreading on several different applications. On the other hand, decision-makers should be supported in obtaining a better picture of the main features to consider when undertaking a decision of adopting them. In fact, despite the wide discussion on energy use (e.g., [13]) and policies to promote EMS (see, e.g., [23]), very little knowledge is offered to the understanding of the broad set of opportunities for energy efficiency and their characteristics [24], [25] and, to authors' knowledge, not yet specifically designed for EMS.

To do so, in the present study we present a thorough review of EEMs in EMS, so to better highlight their characteristics and related productivity benefits. Stemming from this review, we aim at giving suggestions for a novel and more accurate classification of EEMs in EMS considering other interventions also related to different technologies than EMS but closely bonded to them, combining different classifications in a unique, exhaustive description of EEMs targeting EMS.

We believe that, through this review, we could give a relevant contribution to the academic discussion towards the evaluation of energy saving potentials in industry [26], as well as indication and quantification of the so-called non-energy benefits [18], [27], [28]. Furthermore, we could support decision-makers and policy-makers in fostering the adoption of EEMs in this area. For this reason, the remainder of the paper is structured as follows: Section 2 discusses the literature background and presents the research issues, whilst in Section 3 we introduce our list of EEMs. We review in the following Sections (from 4 to 7) the broadest set of EEMs in EMS and point out related productivity benefits. We conclude the paper in Section 8 with recommendations for industrial decision-makers and policy-makers, as well as with avenues for future research.

2 Literature background and research gaps

EEMs in EMS have been widely addressed by scientific literature. Saidur [13] has reviewed a large body of literature on electrical motor energy uses, together with losses, efficiency and energy saving opportunities. Nevertheless, despite a quite detailed analysis of losses, the indications do not span the whole set of EEMS for EMS, with much of the focus of this work given to VSD, plus some general indications such as, e.g., switching motor off, cleaning and lubrication. Research has also discussed techno-economic potential for energy savings in EMS. In particular, De Keulenaer has discussed the Motor Challenge Programme promoted by the European Commission [29]. Further, studies have discussed energy efficiency standards for electric motors in industry (e.g., Europe [23], Brazil [30], Malaysia [31]), as well as compared different countries in terms of technology, regulatory and trend aspects regarding motor systems [32], [33]. Studies have conducted energy-driven technological assessments of higher efficiency electric motors and related cost-effectiveness [34], [35] (also considering their transmissions, e.g., belts [36]), but also more detailed analyses over cost-effectiveness of selected EEMs in EMS. For instance, research [37] has discussed about induction motor oversizing, simulating the behaviour of different IE-class motors and showing that, for most IE-3 and IE-4 class ones, oversizing does not represent a cost-effective option. Research has analysed potential impact from increased efficiency and reliability of large VSD motors [38]. Studies have addressed the energy and cost savings coming from improving energy efficiency in electric drives [39]. Further, studies have addressed energy use, and energy savings, together with emission analysis and cost-effectiveness of EMS, with focus on different type of industries: to name a few, Malaysian rubber producing and cement industries [40], [41], garment industrial building in Bangladesh [42], cement manufacturing [43], Swiss chemical and pharmaceutical industry [44], and petrochemical one [45]. Further, experience in US case studies has been reported, by looking at retrofitting standard efficiency motors with higher efficiency ones [46]. Research has also tried to review specific techniques related to the EMS management, as done, e.g., on variable speed control techniques for efficient control of single-phase induction motors [47]. Similarly, previous studies have reviewed direct torque control of industrial motors, looking at and modelling their effect in terms of increased reliability and efficiency of electric drives [48], [49].

Moreover, specific applications have also been previously discussed, such as case studies in big industrial facility's pumps [50], or improving the energy efficiency in a Vietnamese footwear manufacturing enterprise by acting on the compressed air system, including substitution of overloaded motors [51].

Researchers have preliminarily started to open up the discussion on the need to overcome traditional cost-effectiveness analysis approaches limited to energy savings, introducing multicriteria methods, by encompassing in the decision-making system also considerations over operation factor, reliability and service conditions [52], also in connection to production management issues (e.g., value stream mapping [53]). The importance of encompassing such considerations is in some cases crucial to be considered in a broader analysis, such as those on economic and environmental impacts of local utility energy-efficiency rebated programs [54], [55], and also for non-industrial decision-makers [56]. Further, studies have attempted to offer a framework able to identify and discuss production implications (e.g., [4], [18]). Nevertheless, on the one hand, they still represent preliminary approaches barely diffused in industrial literature, on the other hand, they lack specific metrics to effectively quantify such implications.

Within the world's largest industrial energy efficiency program, the Industrial Assessment Center (IAC) of the US Department of Energy (USDOE) [7] has developed the broadest and most comprehensive list of EEMs within EMS, dividing EEMs according to 5-digit Assessment Recommendation Codes (ARC). As rationale, the classification of EEMs follows a mixed approach: on the one hand, it is cross-cutting with respect to specific technologies (e.g., motor systems or thermal systems); on the other hand, it has a horizontal layer channelling all the streams in a series of heterogeneous applications, such as maintenance, alternative energy usage, etc. By analysing all ARCs [57], 24 EEMs may be referred to deal with EMS (reported in Table 1).

<< Table 1>>

As shown in Table 1, the list of EEMs suggested by IAC, despite being in general sense comprehensive of the broad set of technologies for EMS, nevertheless does not seem to be sufficiently specific in terms of detail to support an industrial decision-maker when deciding to undertake a specific EEM within EMS. For example, the ARC 2,4111 ("Utilize energy-efficient belts and other improved mechanisms") does not specify which belt or mechanisms should be used within the transmission system to improve energy efficiency. In this regard, several different EEMs could be found, ranging from synchronous, flat or cogged (or notched) belts, up to high-efficiency gears, direct coupling between motor and drive, or even replacing roller chains with synchronous belts or avoid multiple belt drives. Thus, as shown in Figure 1, for the aforementioned EEM ARC 2,4111, having a greater detail about which specific EEM should be implemented could bring much more knowledge on the effective compatibility with the extant production systems, the complexity of implementing the EEM, its energy savings, as well as its impact within the operations, in terms of implementation and service phase of the technology. In a nutshell, such enhanced knowledge would better support a decision-maker when considering an EEM in EMS.

<<Figure 1>>

Moreover, even by looking at the single EEMs developed in the broadest review by USDOE Industrial Assessment Center, we could see that, in some cases, they were either too vague or vast. Indeed, the list offers a generic overview of EEMs in EMS, without really offering adequate detail over them for decision-making purposes. Therefore, as research gap, it would be more appropriate, in order to support a decision-maker, to divide such EEM into more EEMs. For the same reason, in some cases multiple EEMs from USDOE IAC database look really similar one to each other, thus not providing any additional insights to decision-makers: in this case, it would seem more appropriate to incorporate them into a single EEM. As therefore can be inferred, a more accurate classification is necessary, which should consider other interventions, according to the information of industrial and scientific literature, also related to different technology than electric motors, combining different section of the IAC list in a unique, exhaustive description of EEMs targeting EMS. As further research gap, in developing such review of EEMs in EMS, it would be important to highlight some important features and characteristics of EEMs in EMS that may affect their adoption rate, beyond their energy features or their cost-effectiveness, so to facilitate decision-makers and policy-makers over their adoption. In fact, by encompassing such considerations in the review, taking benefit from the large body of scientific and industrial literature, decision-makers could be more effectively supported regarding the adoption of EEMs in EMS.

3 A novel Classification of EEMs in EMS

Following this approach, we have conducted an extensive review of scientific and industrial literature on EMS. As sources of information, we have reviewed peer-reviewed journals, conference proceedings, books, manuals for practitioners, reports for industry and experts, technical notes as well as websites of major EMS manufacturers. In case of multiple publications addressing the same topic by the same set of authors, we have preferred the version published on peer-reviewed journal publications to e.g. conference proceedings. We have limited our research to contributions published after year 1990, so to account for technological development and avoid earlier studies already encompassed in most recent research. We included keywords as, e.g., “industrial motors”, “electric motor systems”, “electric drives”, “energy efficiency measures”, “energy efficiency intervention”, “energy efficiency opportunities” limiting our research, for the scope of the present study, to industrial applications. After a preliminary screening based on content, a total of 125 sources has been selected and further analysed. As presented in Figure 2, we can note that there is a consistent portion of contributions (about a half) comes from peer-reviewed journal publications, as well as that of technical notes such as, e.g., from the USDOE Energy Efficiency and Renewable Energy – Advanced Manufacturing Office. Overall, we can see that about 54% of the contributions (journal papers and conference proceedings) coming from scientific literature, whilst the remaining 46% from industrial one.

<< Figure 2>>

By analysing in detail each specific EEM in EMS, taking inspiration from previous literature [13] we have proposed a list of 63 EEMs, re-organised according to four main groups as follows: (i) Hardware; (ii) Motor systems drives; (iii) Management of the plant; and (iv) Power quality. The four main groups have been determined, on the one hand, by the aim of clearly pointing out the relevance played by the hardware component of electric motors and drives as well; on the other hand, by highlighting the existence of a set of interventions that, without strictly changing the hardware, may affect the whole efficiency when putting an EMS into operation. Moreover, as rationale for rearranging EEMs into the different groups, we have tried to take the perspective of an industrial decision-maker, which is interested in better understanding the specific implications of a given EEM as well as the main factors to be considered for its adoption. Therefore, rather than referring EEMs according to technological affinity, we have decided to list and group EEMs according to the type of operational issue they were addressing. Following this rationale, e.g., the installation of variable speed drives (VSD) can be done for different purposes, such as reduced energy consumption, avoid nuisance tripping, improved power factor. Nevertheless, according to each purpose, the beneficial impacts and the factors to be considered for its adoption may be different. Therefore, in our proposed list of EEMs, the installation of VSD is found both in Hardware group (Section 4.3.2), as well as in Motor system drives (Sections 5.1.1 and 5.2) and Power Quality (Section 7.1.5).

The whole list of EEMs in EMS can be found in Table 2. Detailed information on the single groups and related EEMs, along with associated productivity benefits from their adoption, is presented and discussed in the next Sections. It is important to remark that there is no intended priority in applying any of the listed EEMs, Indeed, the EEMs to be applied depend on each specific case and according to the major specific implications that will be detailed in each sub-section. Therefore, the table does not represent a guideline for effective implementation.

<< Table 2>>

4 Hardware

The following EEMs address the hardware part of an EMS, dealing with modifications ranging from a simple change, such as the replacement of the transmission, to more complex and extensive interventions, e.g. the installation of a controller.

4.1 Optimize transmission

This group of EEMs, aimed at minimizing the energy losses in the transfer of the rotary motion to the equipment, is closely related to the IAC measure "Utilize energy-efficient belts and other improved mechanisms (2,4111)": however, due to large and heterogeneous variety of information included in that intervention, which could lead to different results on the system, in our classification we have divided it in a set of different alternatives, so to better identify and point out the specific benefits, as shown in Figure 1.

4.1.1 Use synchronous belts

“Synchronous belts (also called timing, positive-drive, or high-torque drive belts) are toothed and require the installation of mating grooved sprockets” [58]: they rely on tooth grip instead of friction to efficiently transfer power, operating with very high efficiencies (even 98%) for a wide load range [58], [59], differently from V-belts, which present a sharp reduction in efficiency at high torque due to increased slippage [60]. A positive tooth/groove engagement prevents a synchronous belt drive from slipping, while V- belt drives, no matter how well maintained, will exhibit some amount of slip. As a consequence, if properly installed, synchronous belt could further reduce downtime and maintenance expenses, with payback in usually less than one year [60]. As noted by USDOE in technical sheets, synchronous belts can operate in wet and oily environments, which is an important factor to be considered, but compared to V-belts are noisier [58]. Additionally, according to studies they are deemed to be less suited for use on shock-loaded applications, also because, considering their stiffness, they transfer more vibration [58], [59]. Finally, specific design concerns taking into account the synchronous belt drive and the rotating equipment speed, as pointed out by technical documents by USDOE [59], [61], should be carefully paid.

4.1.2 Use flat belts

As discussed by USDOE in a technical document, in case vibration damping is needed, flat belts may represent a more suitable choice compared to synchronous belts [59]. Other situations for the application refer to torque changes, led by shock loads, that could shear a synchronous belt's tooth [59]. Shock loads are mainly caused by either equipment start-up, or variable loads [36]. The installation of flat belts requires special pulleys: nevertheless, according to De Almeida and Greenberg [36], their costs are considerably lower compared to the price of synchronous belt sprockets. Further, as previous literature discussed [62], the efficiency of the flat belt is not only higher than standard V belts, but the efficiency gap widens for light loads [36],

4.1.3 Use cogged (or notched) belts

Notched belts can use the same pulleys as cross-section standard V-belts, with benefits in terms of temperature, durability and 2% improved efficiency [58], [59], [63]: similar findings have been reported by a UK policy report over EMS [62]. Nevertheless, as De Almeida and Greenberg discussed when surveying the characteristics of several belt types, they need severe periodic maintenance [36].

4.1.4 Replace roller chains with synchronous belts

Except for high-torque, very-low-speed applications, synchronous belts represent a successful replacement to chain drives, presenting an efficiency similar to a well-maintained chain drive, as previous research suggested [36]. Furthermore, considering that the requirements for lubrication and maintenance are very low compared to metal chains, they are suitable solutions for applications in dusty or wet (water or oil) environments [36]. Also, according to a case study conducted by an EMS manufacturer in composite and coatings industry [60], synchronous belts grant lower noises and vibrations compared to a chain.

4.1.5 Avoid multiple belt drives

In case of multiple belt drives, the replacement of one belt implies the replacement of all, in order to avoid as much as possible differences in tension, thus representing an expensive option. As from recommendations reported in UK policy report, therefore, whenever possible, multiple belt drives should be avoided, since the tension is hardly the same on each belt [62].

4.1.6 Use high-efficiency gears

Gear reducers are classified according to gear ratio (i.e. the ratio of the input to the output shaft speed, [61]), and present different performance characteristics according to the type of application, beyond simple energy efficiency considerations. USDOE has interestingly discussed the choice of worm gears in selected applications such as packaging machinery, conveyors, and material handling applications, noting that they find application despite they do not represent the very highest energy efficiency option [61]: in this case, it seems crucial for decision-makers to consider also, e.g., capability to offer a finer speed control and a different service life, therefore pointing out the need to operate a wise and accurate decision to maximize the possible lifetime efficiency and related benefits.

4.1.7 Use direct couplings

Given that direct couplings represent the easiest and most energy efficient transmission method, they are characterised by reduced maintenance. According to industrial pump inventory data by USDOE [64], many of the belt drives can be replaced with direct couplings, leading to an estimated energy saving of about 1%. Similar findings have been found by Worrell, Masanet and Angelini in US manufacturing context [65].

4.2 Replace DC equipment with AC equipment (IAC 2,3311)

Some of the benefits of DC drives include a simpler structure and low noise and heat generation in operating conditions, but can also provide very high starting and accelerating torques and handle high-impact loads [66], [67]. They are also characterized by lower weights and smaller sizes compared to AC motors. This feature is crucial for specific uses, where the motor needs to be moved together with the load, or in very compact systems, also according to manufacturers' recommendations [68].

However, beside the advantages, DC motors have some drawbacks in terms of maintenance, purchasing costs and efficiency. Further, the presence of brushes make them less suited than AC motors with VSDs for high-speed operations (over 2,500 rpm) and, according to present technology, they need to change brushes every 7,000-12,000 hours, depending on the application and operating conditions [68]. DC motors also present lower power factors, as analysed by technology providers [67], and are more difficult to install and start up with respect to AC motors, requiring suitable expertise [66]. The diffusion of DC drives was much larger prior to VSDs, although still being adopted for specific uses (e.g., in case of variable speeds with high starting torques [66]).

4.3 Turn off equipment when not in use (IAC 2,6218)

Unfortunately motors, often 'hidden' within machinery, are left running even when they are not producing any effective work [63]: for this reason, switching motors off can be a very simple way to save energy. According to field data analysed by technology providers [69], a reduction by about 10% of motor operating time could be more effective than the replacement of a standard efficiency motor with a premium efficiency one.

Switching off may be controlled in many forms [62], from the simplest (although often less reliable) one consisting of manual control, to more complicated systems using controllers, as suggested by IAC (2,6231, Utilize control to operate equipment only when needed): (i) Manual switching off; (ii) Interlocking [63]; (iii) "Bang-bang" control; (iv) Time switch; (v) Sequencing of multiple motor load; (v) Load sensing [62] .

To reduce starting stresses and overheating, two common harms for motors due to frequent switches on-off, it is warmly recommended to implement one of the following strategies when a frequent starting and stopping of the motor is needed.

4.3.1 Use soft starter

According to [63], a soft starter looks particularly suitable to enable the frequent motors stopping and starting. To reduce the high starting current, a soft starter may be set in current limitation mode [62]. This device enables a limitation of the current drown during start up and achieves a smoother acceleration profile, even if the drawback is a reduction of the starting torque. This type of starting is usually used in turbomachines applications (e.g., centrifugal pumps, fans). It is also possible to use the soft starter in torque limitation mode, penalizing the starting current; this is done when a constant torque is required. Thus, a soft starter may extend the motor's lifetime, by reducing wear on the mechanical parts. Furthermore, it may the electrical components from overheating. Often, motor's lifetime may be augmented as well thanks to the reduced acceleration stresses at start-up. Additionally, the overall kVA requirements may be reduced [70], with related monetary benefits, as e.g. noted by UK research conducting a case study in industry producing components for the motor industry [63].

4.3.2 Use Variable Speed Drives (VSD)

When a motor is connected to a VSD, wear on the motor and on the system can be drastically reduced, so to allow a more frequent starting. As a consequence, by the reduction of the starting current, a lower electricity consumption can be achieved due to a reduced maximum in contracted power demand [63]. In this regard, previous research in Malaysian rubber industries [40] has discussed the energy and monetary savings stemming from the adoption of VSD for frequent starting, and similar considerations were drawn by Lawrence and Miller by analysing US industrial case studies [46].

4.3.3 Use an autotransformer

An autotransformer (or "autostep down transformer"), being an electrical transformer with only one winding, is, therefore, smaller, lighter, and cheaper than typical dual-winding transformers. Nevertheless, as disadvantage, the electrical isolation between primary and secondary circuits is not provided [71]. It is possible to reduce the required starting voltage according to the transformation ratio, thus using autotransformers as soft starting for induction motors. After the starting phase is concluded, the autotransformer is disconnected from the system. This type of starting does not require to turn off the current, thus there will be no transients, as EMS manufacturers have also discussed [72].

4.3.4 Use Star Connection

In star connection (or "wye-delta starting"), the voltage across the phase winding is reduced to 58% of the nominal star voltage [62]. Due to the connection, even the torque, which is proportional to the squared voltage, is one third of the starting torque compared to delta connection, and hence power consumption, leading to immediate savings at very no costs, as discussed by previous literature studying this EEM in a fan on an air handling unit [62]. Consequently, transition from star to delta connection is usually made by a timed contactor [62], [72].

4.4 Size motor correctly

Sizing correctly a motor could enable great improvements in terms of performance and savings, thus representing a critical knowledge that every decision-maker should possess. However, literature depicts a different situation in reality, in which the majority of motors are incorrectly sized [73]. In this regard, research has recently investigated this issue over Swiss industries [17], and similar considerations were drawn by Ferreira and De Almeida [74].

Customers often use the size of the failed motor being replaced as a key factor in selecting the size of the new motor, leading to persistent motors oversizing [64]. In reality, much more information is required in order to enhance the energy savings, such as motor load and related operating efficiency, the full-load speed of both the motor to be replaced and that of the downsized one for replacement [75]. Induction motor downsizing may represent a valuable low-cost strategy to save energy, as modelled by Ferreira and de Almeida for squirrel-cage, induction motors in EU [76]. Authors have interestingly modelled motor efficiency and power factor as a function of load, before and after winding redesign, proposing a large-scale motor downsizing strategy. The following EEMs describe how to correctly size motors either when adopting new devices, or by a correction of those already implemented.

4.4.1 Size electric motors for peak operating conditions (IAC 2,4132)

Motors should be sized to operate in their optimal efficiency range. Therefore, although in some situations may be perceived as needed for peak loads, the common practice of oversizing results in less efficient motor operation. In fact, even in those cases, correctly sized motor backed up with a pony motor [73] is recommended as alternative strategy, since oversized motors tend to incur in higher costs, including purchasing costs, maintenance and operating costs.

For both standard and energy-efficient motors, the efficiency typically present its peak close to 75% of full load, being relatively flat down to the 50% load point [75], whilst larger size motors may usually operate at loads down to 25% of rated load still keeping a relatively high efficiency [75].

At low load, the so-called *iron losses* can be reduced by lowering the voltage across each of the motor windings, by using a smaller high efficiency motor. Other possible solutions include implementing a permanent connection in star or using a motor voltage controller, but the savings in these cases may be lower than the iron losses [62].

4.4.2 Replace oversized and undersized motors

Iron losses, largely reactive, are proportional to the amount of iron to be magnetized. For this reason, the benefits of smaller motors are two-fold: on the one hand, the minimisation of iron losses, as well as voltage reduction, with in turn further positive impact on the power factor [62]. Motor oversizing represents a quite diffused misapplication, therefore a specific road map and approach to evaluate this issue are needed [77].

Motors that are consistently under loaded should be replaced with smaller motors, as also suggested by IAC 2,4131 (although this EEM extends the analysis on pump applications, which is outside the scope of the present work). The smaller motor will run closer to its higher full load efficiency thanks to a better match between motor power and the actual load, thus consuming less energy, also benefitting from technological advances in the structure of the newest models [64]. Taking into consideration all these advantages, the substitution of an oversized motor provides a relatively short payback time. Besides a lower operating efficiency, other drawbacks of an oversized motor include [78]: (i) higher motor/controller costs; (ii) higher installation costs; (iii) lower power factor; and (iv) Increased operating costs [79].

Undersizing motors can bring issues as well, especially in terms of higher winding temperature with consequent reduction in the lifetime of its winding insulation. As a guideline, motor life is reduced by half if the motor operates on a continuous basis at the *service factor* level (which is, usually, around 1.1-1.15 [66]), mainly for short-term or occasional overloads [78]: therefore, relying on the service factor rating of the motor for continuous operation is usually not recommended.

4.4.3 Use permanent connection in star for lightly loaded motors

As previously described (Section 4.3.4), a permanent star connection is recommended when load does not exceed 40-45% of rated power [62], e.g., in case of some air compressors through an automatic arrangement [62], experiencing valuable energy savings.

4.4.4 Install motor voltage controller on lightly loaded motors (IAC 2,4113)

A motor voltage controller can reduce the iron loss leading to energy savings, particularly interesting when equipment is running many hours [62]. However, given that the energy savings can never exceed the total iron loss, downsizing a motor is a preferable solution, especially when running always at low load.

4.5 Use most efficient types of electric motors (IAC 2,4133)

EMS life-cycle costs may be dramatically reduced by selecting energy-efficient motors, as research notes [65]. Efficiency improvement can be substantial when increasing motor size [34]. With proper installation, energy-efficient motors can also run cooler and have higher service factors, longer bearing life, longer insulation life, and less vibration, all of which increase reliability [65], [75]. Research has also modelled in detail reliability improvement for high-efficiency motors [80]. The reduced heat also decreases the energy consumption of fans used to cool the production environment as additional benefit.

In 2014, the newest standard on electric motors (IEC 60034-30-1) has been published, replacing the 2008 one and adding the fourth efficiency level IE4 (super-premium efficiency), which enables up to 14 % higher energy savings when compared to IE1, or up to 3% if the contender is IE3 [81], [82]. Reviews report that a consistent reduction of CO_2 emissions is achievable using energy-efficient motors [83]. In support of this upgrade, several manufacturers claim that the energy costs for many motors exceed the initial purchase price after just six months in operation, thus making their upgrade quite appealing [81]. For this reason, they are highly recommended even in low energy-cost areas [84].

However, in order to take a definite decision, a specific situation has to be evaluated [85]: in fact, the choice to install a premium efficiency motor is deeply affected by additional factors. Among others, motor operating conditions and the life cycle costs represent crucial elements to the decision: usually, premium-efficiency motors look economically efficient when replacing motors operating over 2,000 hours per year [65] and it can even be worthwhile replacing fully serviceable standard efficiency with high efficiency ones [84]. But, research has recently discussed that the decision of selecting the techno-economic optimal power rating (in terms of motor operating conditions) should be carefully based on minimizing energy consumption throughout motor service life, so to minimize its life cycle costs [86].

Nevertheless, despite all extant advantages, the difficulty in further achieving efficiency gains with conventional AC induction motors is growing [63]. Although their initial cost is higher, start permanent magnet synchronous (LS-PMS) motors can be more economical than induction motors in the long run, for e.g. pumps, fans and compressors where constant speeds and long operating cycles are used [87]. LS-PMS motors present higher efficiency, power factor, starting torque and show better thermal behaviour as well as lower sensitivity to frequency variations. As authors note, the magnet price – a crucial element for their costs – has decreased substantially due to high volume magnet production over the last decade, particularly in China, allowing permanent magnet to gain ground [88]. As further non-energy benefits, literature notes reduced size and an increased starting torque, as well as a wider speed range [63], [88].

5 Motor system drives

When analysing EMS, many applications require variable loads during operations [34]. For this reason, considering that AC induction motors can supply motion at a nominal speed, different technologies have been developed, as described in the following. Moreover, it should be noted that, to support decision-makers, it would be important to estimate the motor efficiency according to variable speed operations and partial load conditions, given that benefits in terms of improved motor performance change according to motor speed and load, as simulated by recent research [79].

5.1 Variable load applications

Before applying a control and a motor to a certain drive it is important to precisely identify whether the loads involved [89] are either at variable (or constant) torque [66], [90], [91], or at constant power [61], [92].

5.1.1 Use VSD for variable load

Variable loads are governed by the affinity law, thus even a small reduction in speed results in a greater amount of energy saving. This makes them eligible for the application of a VSD, as also suggested by IAC (ARC 2,4141, "Use multiple speed motors or AFDs for variable pump, blower and compressor loads") [93]. There is a huge discussion over literature regarding possible applications, such as e.g. compressed air in large and energy-intensive industrial firms [93], and for large VSD motors to be applied in pumps [38]. Specific applications are further described in Section 6.2.

5.1.2 Use multiple speed motor for variable load

Multiple speed motors, usually presenting 2-4 predefined operating speeds [66], are valuable solutions for variable load applications such as, e.g., a ventilation systems [91]. However, as suggested by IAC (ARC 2,4141), even variable pump, blower and compressors could be run by a multiple speed motor [85]. Research has also analysed, classified and compared several techniques for EMS variable speed control [47], with the aim of offering guidelines to users for the choice of the most suitable solution according to the specific needs and applications.

5.1.3 Use integrated variable speed motor for variable load

Commonly, VSD coupled with an electric motor, or motor with an integral VSD [63], represent a variable speed control. Particularly available in the range 0.75-11kW, present several advantages, including: reduced control panel space, simplified installation, straightforward electromagnetic compatibility compliance and integration of motor and drive [91]. Further, their design allows a faster response time and reduced cabling losses [63], which in turn can lead to greater cost savings over motor lifetime, also making them popular in HVAC and pumping markets [91].

5.2 Use VSD and other control strategies to replace less efficient drives

5.2.1 Use VSD to replace damper in fans applications

Pumps, fans and compressors account for a consistent share of motor electricity consumption [23] but, unfortunately, are often oversized, also because may be installed in systems with multiple operating points due to several varying process requirements, with consequent frequent unnecessary air motion [61], [94]. Despite dampers are rarely adopted to control fans' output, reducing the speed of the fan is considered a suitable energy efficient way [91].

Beside leading to a more efficient power use, using VSDs in fan applications can also result in additional benefits. Among others, it is worth considering a reduced noise in heating and ventilation air–duct systems [91]. It should be also remarked that changes in the noise levels can bring savings of up to 80% of the consumed power [91] when compared with dampers for a 50% flow application [23], although such changes can be undetectable to human's ear [91].

5.2.2 Use AFD to replace throttling systems (IAC 2,4143)

In pumps, AFD in replacement of throttling systems could lead to significant power, and therefore cost savings [91]. VSD flow control is appropriate in case of retrofitting applications, or when designing new system (e.g., specific pumping), leading to considerable energy savings [61]. The replacement of a throttling system with a VSD is however characterized by some drawbacks, such as incapability to serve the same function as a control valve at no flow or near zero-flow condition, and speed of response. Further, in applications where the torque increases at low speeds (e.g. mixing processes), the power requirements of the motor will overall be kept at lower speeds, making other control technologies, such as load shedding or sequencing, more suitable [91]. Finally, as research observes, significant energy savings can be experienced by operating all pumps at reduced speed (which may be common in case of several pumping operating in parallel), or by modulating demand through cycled on-off switches of the pumps [23].

5.2.3 Upgrade controls for compressors (IAC 2,4224)

The speed of the compressor motor can be operated at different levels by changing dynamically to suit the conditions and load [95]. Most air compressors are generally constant–torque load drives and, therefore, present less scope for energy savings, when compared to fan and pump applications [91]. Nevertheless, according to research broadly investigating EMS in the European industrial and services sector [23], if the demand is 50% of the rated capacity, VSD can save up to 38% of energy.

In some applications, where the installation of a VSD is not recommended, operating two or more motors and equipment in parallel through system control may be a suitable alternative (e.g., single master or multi master controls) [63], [95]. As controllers share information, compressor operating decisions with respect to changing air demand are deemed to be made more quickly and with more accuracy [96], and the installation of parallel systems for highly variable loads can save from 10 to 30% of energy consumption [64]. Nevertheless, the decision should be taken by carefully analysing the specific situation, as previous research notes [25].

5.2.4 Use AFD to replace mechanical drive (IAC 2,4144)

On a belt-driven transmission, variable pitch pulleys are deemed as a simple mechanical method to change the speed of the load [97], with very short payback times, in the order of a few months [91]. Other solutions are drive balls and gear systems [97], widely used in industry, since motor and driven equipment may present two different speed ratios [66]. The options nevertheless usually require a strong engineering effort for designing, sizing and scheduling future maintenance, that in some cases can become a hassle for labour and replacement costs. On the other side, as industrial research points out, such EEM is particularly suitable when the system needs to operate at any ratio [97].

5.2.5 Use Daisy chain configuration to replace motor with multiple gears

In some machinery, synchronous motion throughout the machine is provided by one motor with multiple gears [97]. By using a line shaft encoder, an unlimited amount of motors can be connected to run in a daisy chain or parallel configuration, thus significantly reducing the mechanical wear and tear. Considering that mechanical changes are unnecessary, the EEM may represent a relevant costs reduction [97] with additional productivity benefits to be specifically quantified [4].

5.2.6 Use static DC drive to replace motor-generator (MG) set

In the past years, DC drives have been introduced and are nowadays replacing MG sets in many applications [98]. Beside energy savings for operating at a higher efficiency [99], one clear advantage is represented by maintenance costs savings, as they eliminate for regular lubrication and replacement of bearings and brushes, also improving the air quality through the avoidance of the large amount of carbon dust generated [100], [101]. Further, the rewinding of the DC generator would be avoided [102], [103]. Finally, state controllers are modular, thus potentially reducing production downtime.

5.2.7 Use MC VSD

Although VSDs have been quite diffused and available, traditional ones are not suited for all applications. The use of a traditional VFDs may result not successful in specific cases that a decision-maker should carefully consider (for further information, please refer to [104]).

In contrast to a VSD, a magnetically coupled (MC) VSD does not alter the power supplied to the motor, thus allowing an extreme soft start [105]. MC VSD adjusts the speed of the load by means of a magnetic coupling, avoiding physical contact between the motor and the load. The lack of physical contact provides for a soft start for rotating equipment and minimizes vibration, shock loads, and misalignment problems

[106]. Other advantages include the facts that MC VSDs should not be kept in a controlled environment and are desirable when harmonic distortion caused by a traditional VSD cannot be tolerated. Another disadvantage is represented by load seizure protection [104]. Finally, MC VSDs are particularly suitable for high-torque applications (e.g. punch- presses or crushers), given their capability to produce more torque at low speed than any induction motor coupled with a traditional VSD [107], making them appealing for niche applications [104], also considering that MC VSD systems allow the motor to be installed in remote locations [105]. Nevertheless, compared to a traditional VSD system, the smaller savings indicate larger losses are being incurred. Other disadvantages of MC VSDs include space and weight constraints, or incompatibility. They also require intensive maintenance activities operated by technical personnel with specialized training [104].

6 Management of the plant

As many researchers note (e.g.,[11], [23]), energy efficiency in EMS can be achieved not only through the implementation of physical devices in the plant, but also implementing careful practices, such as the adoption of a maintenance plan and the development of sustainable practices for the management of the internal resources.

6.1 Motor management plan

Unfortunately, many motor decisions are made at the time of motor failure: in that case, the time available to analyse suitable options, due to production disruption, is very little. As a result, decisions to repair or replace a motor are based on availability or short- term economics, thus skipping proper evaluation and planning. This may cause huge costs due to poor equipment performance, unreliable service and elevated operational costs [92], also considering that a consistent share of the lifecycle costs is due to its electricity consumption. For this reason, studies have recommended to implement a motor management plan (MMP) prior to motor failure, so that decisions can be both quicker and more cost-effective, and additional benefits such as reduced downtime and increased motors availability for critical processes [63], [65], [92]. In this regard, a clear motor repair decision flowchart, as presented and discussed by recent research in the field [108], can be particularly useful to support decision-makers.

In fact, a proper MMP, among the others, should include a plan for repairing or replacing failed motors, a plan for preparing a premium efficiency-spares inventory and for purchasing new and more efficient motors. Additionally, it should be backed by a schedule for motor maintenance, both preventive and predictive.

Note that, for any MMP scheme to be successful, sufficient resources for both planning and implementation and commitment from senior management should be allocated. Other important elements include clearly defined responsibilities and built-in review periods, so to monitor the motor market on a continuous basis [63].

6.1.1 Standardize motor inventory (IAC 2,4155)

Given their widespread use in many core and ancillary processes, motors represent an important asset. For this reason, a proper motor management plant requires a specific knowledge of their number, their type and their location, by creating a standard motor inventory [92]. The inventory might be based on nameplate data, or it might include measured data in case of uncertainty about the actual load; in fact, according to [64] a large percentage of motors operates at load levels below 40%. It may also include motor history information. According to industrial literature and practice [92], it is crucial to have information not only about motors running in critical applications, but also e.g., which motors are running for the most hours, or which ones present the highest failure rates [92]. Once having established a motor inventory, it is crucial to perform a motor tracking, which helps identify recurring problems with specific motors or previously unrecognized application, so to offer decision-makers (e.g. facility managers) additional information to be used in case of a motor failure [92].

6.1.2 Develop a repair/replace policy (IAC 2,4151)

When dealing with an electric motor failure, as common practice an industrial user can either opt for motor replacement or for a motor repair. Repair is generally seen as the greenest "end of life" treatment option for a retired product. Remanufacturing can be considered as an effective option, then usually claiming a credit for the avoided resource use, thus representing a win-win strategy [109]. However, several other factors should be considered when choosing between replacement versus repair, such as e.g. current operational needs and life cycle costs, thus questioning whether to replace with a motor of different size or type [63], [66]. Nevertheless, decisions are subject to some contextual factors such as, e.g., applied load with respect to motor dimensions and number of working hours [63], [66], as also shown by research in Malaysia over rewinding and replacement of industrial motors [102].

6.1.3 Use only certified motor repair shop (IAC 2,4152)

The choice of a motor service centre following best-practice motor rewinding standards is crucial to minimize potential efficiency losses [64]. According to sources, best rewinding practices can reduce efficiency losses to values typically less than 0.5% to 1% [65], [110]. However, as such selection after a motor failure could imply a longer (and expensive) production disruption, it should be planned and conducted in due time [66].

6.1.4 Avoid emergency rewinding of motors (IAC 2,4153)

In emergency situations, the most efficient solution would be to replace the failed equipment with one stored appositely in the ready spares inventory or with a new one, thus avoiding rewinding motors with no adequate time to perform efficiency checks, leading to possible misuse and inefficiencies when in operation. Once repaired, as noted by reports collecting industrial recommendations, storing the repaired motor is crucial [61], [64], [92].

6.1.5 Avoid rewinding motors more than twice (IAC 2,4154) or more than once if done before 1980

Rewinding generally causes a reduction in the efficiency of a motor. Consequently, rewinding more than twice is absolutely to be avoided, especially with very old motors. The old and inefficient techniques, coupled with the poor performances of an old motor, makes it advantageous to replace the device as research and industrial literature widely shows (see, e.g., [60], [62], [64], [73], [95]).

6.1.6 Establish a premium efficiency – ready spares inventory

Having understood the replacement requirements, it is crucial to guarantee, through a spares inventory, the availability of a proper motor in replacement, in case of failure. Such inventory would as well ensure that decisions are well-grounded, through proper evaluation and planning, rather than availability and initial costs [66]. As additional benefit, production disruption can be reduced: this aspect is crucial especially when the motor is coupled with a machine that is critical to plant operations [66], as also practitioners research over pumps has shown [103]. Nevertheless, a premium efficiency-ready spares inventory is crucial in case of unavailability from local distributors to avoid possible production disruption of even several weeks when motors are specifically customised. Inventory costs can be reduced by not storing repaired motors that could become obsolete before they are needed again [103], at the same time guaranteeing that, over time, older and less inefficient motors are no longer put in operation [66].

6.1.7 Accelerate the replacement of standard efficiency motors

Improving the efficiency of motor-driven equipment by replacing standard efficiency motors with premium efficiency models at the time of failure may take up to 20 years to complete [61]. Furthermore, economies of volume coupled with immediate substitution could lead to maximum energy and cost savings. However, due to negative impacts on plant production, group motor replacements are rarely implemented, as pointed out in an industry-oriented guidebook developed by the USDOE [61].

6.1.8 Place motors in adequate environment

Being in some cases exposed to contaminants that are severely corrosive, abrasive, and/or electrically conductive, motor lifetime can be severely reduced even with excellent selection and care [111]. Thus, the operating environment, together with conditions of use, as well as quality of preventive maintenance may affect how quickly motor parts degrade. It is important to take into account not only the operating motors, but also the ones out-of-service, by protecting them from humidity, vibration, and corrosion exposure [111].

6.2 Establish a preventive maintenance program (IAC 2,4156)

Preventive motor maintenance may deeply help prolong motor lifetime [65], also in terms of foreseen potential failures, in the light of preventing unexpected downtime production disruption and downtime [112]. These measures include voltage imbalance minimization, load consideration, motor ventilation, alignment, and lubrication [65]. The most important activities that have to be performed according to a preventive maintenance program are:

- *Termination Maintenance:* studies indicate that in-plant electrical distribution system losses can account for less than 1% to more than 4% of total plant electrical energy consumption. Losses include e.g., voltage unbalance, over- and under voltage, low power factor [66], with severe economic consequences [113]. Therefore, maintenance of connections (known also as termination maintenance) may lead to significant energy savings, as estimated by the USDOE [114];
- *Keep equipment clean (IAC 2,6125):* motors should be kept clean, especially when they are located in dirty environments. This has been noted as a crucial element by a recent review over energy savings in motor systems [13]. Additionally, motors' cleanness is crucial also in case of coated motors, when the airflow is extremely reduced, according to tests [115];
- *Improve lubrication practices (IAC 2,4312):* a correct motors lubrication can save about 1-2% energy [13], and similar considerations are reported by industrial literature [95]. According to [116], a lubrication consultant should be hired to help select lubricants for the specific case.
- *Use synthetic lubricants (IAC 2,4314)*: the great majority of electric motors used in industrial plants are lubricated with petroleum-based lubricants, resulting in an unnecessary loss of energy. It is warmly advised to begin a practice of using synthetic lubricants, at least on larger motors. Conservative savings of 3-7% are recommended [116], due to the lack of independent data currently available.
- *Maintenance of the transmission:* industrial belt drives, when well maintained, are often capable of operating for several years at good efficiency. Losses in belt power transmission performance (that, in some cases, can account for even more than 10%, as noted by [63] for V belts) may happen due to e.g., worn out belts and pulleys, unequally tensioned belts and excessive environmental temperature, which could be detrimental especially for belt transmission, causing belts to harden and develop cracks, halving in cases the lifetime [63].
- *Maintenance of stored idle motors:* motors operating infrequently (e.g. for backup applications), should be activated periodically. By doing so, the aim is to keep the bearing surfaces lubricated, as recommended by USDOE in guidebook for industry [66].

6.3 Establish a predictive maintenance program (IAC 2,4157)

Predictive maintenance or condition assessment programs are designed to increase the reliability of motor and drive systems. These methods are intended to identify problems that are developing but have not yet created a failure, minimizing the unscheduled downtimes as well as determining the root causes of failures and, ultimately, save money by extending the service life of motors and rotating equipment [117]. Knowing the condition before failure also permits to have the motor reconditioned at a far lower cost than a post-failure rewind or extensive mechanical restoration [92].

According to industrial literature [117], motor systems should be tested both while they are not running (static test) and during operating conditions (dynamic test). In *static test*, the components of motors are tested at voltage levels similar to those in normal operations, as part of the motor circuit analysis [115]. *Dynamic test* encompasses vibration analysis [111], lubricant analysis, and thermography [63].

6.4 Contracting out maintenance (IAC 4,6120)

"Vertical contracting concerns the outsourcing of activities that facilitate the production function within an organization" [118]. According to maintenance literature, outsourcing of maintenance activities is deemed as common practice for organizations with internal maintenance function [118]. This may happen due to several causes. First, when the available maintenance capacity is insufficient to meet peak demand (*short-term contracting out*). Second, literature refers to *strategic contracting out* when maintenance activities are contracted out in case of too small expected volumes, or the maintenance is considered as too random, or in case of specific expertise required [118]. Also, technological advancements, increased safety and environmental legislation in production processes imply continuous and expensive training for the maintenance workforce. Further, an increase in operational flexibility may be achieved via contracting out. Three basics types of maintenance contracts [118] can be found, representing extremes on a more continuous scale: work package contract, performance contract, and facilitator (or lease) contract. In the first, the client has full control over the design of the maintenance concepts, planning and control and spare parts management. In the second, the client concentrates on the definition of the performance statements associated with the systems which have been contracted out. In a facilitator contract, the client is predominantly a user of the system, while the contractor is its owner and maintainer, therefore accepting some additional business risks.

7 Power Quality

This group of EEMs concerns all actions aimed to the quality improvement of the transmitted power inside the plant, from the avoidance of nuisance tripping and harmonic distortion, to the improvement in the power factor, so to avoid significant reductions in efficiency and, in the worst case, compromising the conditions of the equipment.

7.1 Optimize plant power factor (IAC 2,3212)

A high power factor (approaching unity) in companies usually indicates an good and efficient use of the electrical distribution system, whilst a low power factor is deemed as a proxy of poor use [61].
Low power factor is caused by inductive loads, which are a major portion of the power consumed in industrial sites [66], [119]. Another main cause of low power factor is represented by motors not fully loaded [61], or idle motors [66]. Low power factor may lead to overheating and premature failure of motors and other inductive equipment. It also causes extra losses in stator windings of induction motors [120]. Thus, power factor correction equipment will not only decrease energy use, but will also significantly increase the lifetime of the equipment [121], [122]. Power factor can be corrected with the following strategies: *(i)*

minimize idling of electric motors (a motor that is turned off consumes no energy); *(ii)* replace motors with premium-efficient motors properly matched with the load driven; *(iii)* avoid operation of equipment above its rated voltage; *(iv)* use a motor with the highest speed that an application can accommodate; *(v)* install capacitors in the AC circuit; *(vi)* use a PWM ASD; and *(vii)* use synchronous motors as capacitors [13], [61], [66], [78], [122], [123]. Finally, as previous research notes, overcorrection may lead to greater problems, such as over voltage and insulation breakdown [13].

7.1.1 Install capacitors

By installing capacitors, the magnitude of reactive power in the system can be reduced [78]. By restoring operating voltage to proper design condition, the efficiency and operating life of the equipment are increased [61], [65]. The major advantages of individual capacitors at the load include a reduction in line losses, an increase in in-plant electrical distribution system capacity, as well as in the motor performance, thanks to reduced voltage drops. On the other hand, bank installations reduce costs of implementation and of kVAR, and improve the total plant power factor, thus avoiding penalty charges. Further, automatic switching ensures the exact amount of power correction and eliminates over capacitance and resulting overvoltage [61]. Nevertheless, as studies highlight [124], the number and size of motors could be critical factors affecting the choice of either installing capacitors at each motor, or grouping the motors and placing single capacitors.

7.1.2 Use synchronous motors as capacitors

Large synchronous motors may be used in industrial facilities to add a leading-power factor component to the distribution system [13], [66], [122]. A synchronous motor indeed can be run in leading or lagging mode by adjusting the excitation current. This method could be cheaper than using capacitors, since the synchronous motor may already be installed in the system for any other purposes. However, if this is not the case, other solutions should be preferred (e.g., corrective capacitors characterized by lower costs and higher efficiencies), as noted by previous research conducting an experimental study on reactive power compensation [119].

7.1.3 Minimize idling of electric motors

As already mentioned, a major cause of low power factor in most industrial premises is the presence of a large number of induction motors. Low power factor issues will be enlarged by lightly loaded or idle (i.e., with no load) electric motors. To prevent this issue, induction motors should be appropriately loaded and idling of the motors should be discouraged.

7.1.4 Replace standard with correctly sized premium efficiency motors

A lightly loaded motor requires little real power, whilst a heavily loaded one requires more. Since the reactive power is almost constant, the ratio of real power to apparent power varies with induction motor load, being deemed to range from about 10% (at no load) to as high as 85% or more (at full load) [66].

7.1.5 Use VSD to optimize plant power factor

As NEMA notes, the installation of any power factor correction capacitors on the input to the control, if applied, should be carefully analysed, to avoid harmonic frequency resonance conditions [90]. In fact, a harmonic study of the power distribution system should be conducted to determine the harmonic resonance frequencies, even if the use of capacitors on the load side of an electronic control connected to an induction motor is generally not recommended [90]. As also shown by previous industrial literature [124], analysing the context of application prior to make any decision over this EEM is crucial.

7.1.6 Avoid operating equipment above its rated voltage

According to [125], operating the equipment above the nominal voltage leads to a reduction in the power factor. For instance, an overvoltage of 10% can decrease its value up to 7%. Vice versa, an undervoltage causes power factor improvement, but at the same time it leads to other disadvantages, e.g. increase in the total current that may be necessary to deliver, at reduced voltage, the real power [125], leading, in turn, to increased resistance and power losses, with consequent reduced motor efficiency (plus possible overheating at rated load conditions [125]).

7.1.7 Use motors with the highest possible speed

Research [126] claims that power factor has a slight dependence from the speed of the motor, in particular the higher the speed, the better the quality. This is even more critical when considering older motors. Nevertheless, such EEMs looks more oriented in creating awareness in the decision maker, who should consider this insight when deciding on the installation of new motors in the plant, especially if power factor is an issue, rather than representing a viable and convenient method for improving power quality of an already installed device.

7.2 Avoid off design voltages

The motor voltage must match the rated system supply voltage. A mismatch between the motor voltage and the system voltage, although quite uncommon and often related to distribution system problems, can lead to severe operating problems, including equipment failure [66].

As shown by [127], undervoltage causes power factor improvement, leading to increased resistance, reduced motor efficiency, and possible overheating at rated load conditions [61]. Nevertheless, in order to specifically understand which action in this case is needed, the type of variation, as well as type of motors, together with the context of application, represent crucial element to be carefully considered.

7.2.1 Change the tap settings – use an auto-tap changer transformer

Industrial practice recommends to adjust the delivered voltage to the desired value by appropriate changes to the tap settings [66] when variations do not exceed the range 3-5% from the normal values [61], but being constantly either too low or high. Further, the use of a "auto-tap-changer" transformer when daily voltage variation occurs at the service entrance is recommended [125].

7.2.2 Use medium voltage distribution line

Medium voltage distribution lines to the remote areas [125] may be quite effective solutions e.g. in case of constant voltage at the service entrance and daily voltage variation occurring within the facility (load variations or distance from the transformer [66]).

7.2.3 Use power factor correction capacitors

Finally, in case of single motors attached to more conventional motor starters, industrial practice recommends to reduce voltage drops by installing power factor correction capacitors at the points of use [125].

7.3 Avoid voltage unbalance

Unbalanced voltages may represent critical causes for motor's premature failure [63], in fact they are responsible for the creation of current unbalance, which magnitude may be 6 to 10 times as large as the voltage unbalance. According to USDOE, unbalanced currents may be a source of torque pulsations, increased vibrations and mechanical stresses and increased losses [128].
An imbalance of 3.5% in the supply voltage can decrease motor efficiency by up to 2% [63]. Voltage unbalances may be caused by faulty operation of power factor correction equipment [65], and may be identified either by a more regular monitoring of the voltages at the motor terminal, and through regular thermographic inspections [65]. Energy and cost savings occur when corrective actions are taken.

7.4 Correct Outages

Outages are often momentary power losses caused by faults [66]. However, after the importance to identify and clarify whether the case for the fault is internal or external events, it is important to use devices such as, e.g., switchgear, so to properly realign and provide power. As noted by recent research, several resilience enhancement strategies are available and should be adequately considered to avoid outage risk and mitigate consequences [129].

7.5 Avoid transient and surges

A large switching activity could lead to transients and surges, causing several issues to the electrical system [66]. In the following subsections, we present and discuss two opportunities to avoid them.

7.5.1 Use transient voltage surge suppressors

Transient voltage surge suppressors (TVSSs) can protect e.g. sensitive equipment from causes, such as surges and transient, that may increase the cumulative wear on the equipment, shortening its operating life [66]. In this regard, research has analysed response time and its relevance to surge protective devices, also providing insights through case study application of such devices [130].

7.5.2 Use isolation transformers to avoid transient and surges

Isolation transformers are common techniques adopted to represent a filter for damaging signal surges, noise, and harmonics [66], particularly critical for, e.g., sensitive equipment. Authors have recently discussed benefits of such installations for low voltage AC micro-grid applications [131]. Nevertheless, being additional equipment, they present, as drawbacks, related increase of installation costs, maintenance activities, and introduction of another possible failure mode [66].

7.6 Avoid nuisance tripping

A nuisance trip happens when a safety device is activated without existence of real danger. In most cases, an upgrade to premium efficiency motors does not bring a noticeable impact on the electrical system [90]. However, in rare cases, nuisance trips can occur during a start-up [66], [132]. Nuisance tripping has primarily been associated with peak inrush current, while is not largely affected by the so-called locked rotor current, which follows the initial peak inrush [73]. In the following paragraphs, the most common techniques to avoid nuisance tripping will be presented. Notably, in some cases, the EEM recommended represents the installation of equipment (e.g. use of soft starter or VSD in Sections 7.6.2 and 7.6.3, respectively) that have been previously analysed (Sections 4.3.1 and 4.3.2, respectively). Nevertheless, as rationale for our classification, we have reported such EEMs also here to highlight that the considered equipment can be used as a mitigation strategy for nuisance tripping with specific benefits.

7.6.1 Adjust the trip settings – replace the circuit protection

Beyond the first (and relatively cheap) option to simply adjust the trip settings, other alternatives are available, such as correctly sizing the protected part for the specific safety device, or protecting each with a separate safety device (that would only need to deal with a small individual load). However, as this solution is not always viable, a second approach consists in correctly sizing the safety device for the given application, but it requires specific expertise due to the associated safety risks [132].

7.6.2 Use soft starter (IAC 2,4112)

Large in-rush current could be caused by giving power to large motors [66] and may cause, among other problems, voltage sags [66]. This effect has been analysed in detail by previous studies, through simulation of the behaviour of induction motors and loads [133], together with economic implications [134]. The efficiency gains obtained with newer motors largely derive from a reduction in the rotor circuit resistance, compared to that of older, conventional motors [90]. Hence, the starting of large motors, causing non negligible stresses to the electrical system, prompted a demand for equipment that "softens" motor start-ups [66].

7.6.3 Use VSD to avoid nuisance tripping

Soft-starters may include special motor controllers and most VFDs, severely limiting the starting currents

[66], [132]. Note however that the introduction of non-linear load, such as VSD, will result in harmonics generation [135] and eventually the nuisance tripping of the driver itself [136]. Thus, AC line reactors or drive isolation transformer should be installed, as suggested by IAC (2,4145).

7.6.4 Use Isolation transformers to avoid nuisance tripping

Isolation transformers enable the user to separately ground the transformer secondary, which prevents ground current from transferring back through the primary ground system, a well-known undesirable characteristic of motor drives which can cause, among others, nuisance tripping of the equipment [137].

7.6.5 Use an uninterruptible supply system

Uninterruptible power supply (UPS) systems (either in static or dynamic configurations) could represent valuable options when voltage sags or power interruptions can be particularly expensive [66], as discussed by research on high-tech buildings [138].

7.7 Avoid line harmonic current

Harmonics are generated by nonlinear loads [139], such as DC drives, variable frequency drives and uninterruptible power supplies (UPS) [70], [140], [141].

Until recently, most factory loads were primarily linear, with current waveform closely matching the sinusoidal voltage waveform and changing in proportion to the load. More recently, however, factory loads with major nonlinear components have increased dramatically [139]. Harmonics are a steady-state phenomenon and should not be confused with short-term phenomena lasting less than a few cycles, such as transients, electrical disturbances, overvoltage surges, and undervoltage sags in the supplied voltage. Harmonics negatively affect the performance of inductive machines [66], in particular transformers and induction motors, since they are designed to operate at the fundamental frequency, also causing overheating of cables, generators and capacitors [13], [23], [142], [143] and interfering with the accuracy of sensitive control equipment. Some of the negative effects of AC line harmonics if not properly addressed are: *(i)* possible interference with communication equipment, which is more sensible to harmonics than motors; *(ii)* possible overheating of transformers and other branch circuit equipment; *(iii)* possible increased heating in motors connected across-the-line due to copper and iron losses; and *(iv)* possible resonance with power factor correction capacitors. Consequently, practice indicate to minimise the distance between a VFD and a motor [66]. To reduce the harmonic voltage and current distortion values, several further techniques are available, as detailed in the following. Nevertheless, it is important to note that, being EEMs strictly related to the nonlinear loads, most of the studies do limit their considerations to the consequences on the local distribution network stemming from the adoption of the EEMs, with very little or no discussion even about cost-effectiveness, heavily depending on the context of application.

7.7.1 Impedance – AC and DC reactors

Reactors for VFDs are marketed as either AC reactors or DC reactors {also called DC link chokes). Both reactor types serve the same primary purpose, to smooth the current flow to the VFD, and reduce damaging harmonics produced on the power line. Further, reactors will improve the power factor by as much as 20% as a consequence of adding reactance to the line. AC reactors may also provide some protection from voltage transients created by power factor capacitor switching and lightning surges because they are installed before the VFD [136], [144], [145]. However, AC line reactors have several side effects which need specific and careful consideration, such as voltage drop (that could potentially nuisance fault trip the VFD), and less significant core losses from eddy currents and hysteresis effects, if a ferromagnetic core inductor is used [136], therefore requiring a thorough analysis of the context prior to their application [145]. A DC link choke is very similar to the AC line reactor: since DC reactors are typically located after the input diodes and before the DC bus, they do not provide protection from possible voltage transients. Also, by locating the reactor in the DC Link, the condition of overlap of diode conduction is avoided. Therefore, these reactors do not drop voltage to the drive, avoiding nuisance faults [136], [144], [145].

7.7.2 Impedance – drive isolation transformer

As aforementioned, to reduce the effects of motor drives on other loads in the electrical system one common technique is to add reactance in the incoming power to the motor drives, e.g., by adding line reactors or installing drive isolation transformers. By reducing current harmonics, two main benefits can be gained: first, it improves the power factor of the motor drive load; second, it reduces voltage waveform distortion. The latter can prevent motor drives from affecting sensitive loads, including other motor drives, elsewhere on the service. Also, potential tripping of the equipment is avoided [90], [136], [137].

Further, drive isolation transformers provide additional benefits because their wye-connected secondary can be grounded. This protects the motor drive system from common-mode transients and noise originated from the primary source. These transformers also protect the primary source from common-mode energies that originate from the motor drive system. Finally, separately grounding the transformer prevents secondary ground currents from transferring back through the primary ground system, thus avoiding potential tripping. Line reactors alone do not provide any of these features [136], [137]. The drawbacks of isolation transformers, as aforementioned, include added equipment costs, slight efficiency losses, and the additional maintenance required for the transformer itself [66]. This intervention could be seen as the generalization for all types of non-linear loads of the efficiency measure suggested by IAC (ARC 2,4145, "Install isolation transformer on adjustable frequency drive"). Nevertheless, prior to the application, an analysis of the specific context of application should be conducted [136], [144].

7.7.3 Use Passive filters

Sophisticated passive filtering devices are often used in combination with VFDs [66]. The benefits of those solutions include the prevention of high-frequency harmonics [66]. Many designs exist, including series, shunt and broadband filters. However, passive harmonic filters present a major disadvantage. Indeed, considering that they are tuned on the frequency they must avoid (or on the frequency range they have to dampen), their action is efficient only for the specific system where they are implemented, meaning that the addition or removal of loads could compromise their work [70]. Therefore, the effective benefits of this EEM strongly depend on the plant flexibility, as industrial research shows [70].

7.7.4 Use Active filters

This device, also called active harmonic conditioner, injects equivalent harmonic currents acting on real time on the harmonic generated by the non-linear load. For this reason, it is more flexible and efficient compared to a passive filter, offering better performances and being adaptable to a change in the system [70]. In fact, active filters represent one of the most effective types of harmonic attenuation. However, due to their complexity, they are also one of the most expensive and take up more space compared to the passive counterpart, therefore needing to carefully consider the layout prior to their application [136]. Different solutions for the installation can be adopted, according to the specific situation, such as total or, in case of few and high-power loads, local compensation [70].

7.7.5 Use Multi-pulse method

Multi-pulse rectifiers provide a good solution for harmonics suppression because they are able to theoretically eliminate (or, in practice, significantly reduce), some harmonics of important orders. Even-ordered harmonics and orders with multiples of three are generally not a problem because they cancel each other out [146], but harmonics with prime-numbered orders remain to distort the incoming voltage signal, with the greatest disturbance from the fifth and seventh orders [136]. By manipulating the phase of the incoming power, it is possible to cancel these more prevalent harmonics, by means of multi-pulse transformers [136], [147]. Studies have shown that 12-pulse drives may reduce total harmonic distortion (THD) by up to 90%. Well-configured 18-pulse drives can even reduce THD by up to 95%. However, due to additional rectifiers and the larger, more advanced transformer, the cost and size of the unit will increase. Also, line losses may increase, with a decrease in efficiency. Therefore, this 18- pulse drive- transformer duo may be a better performer in terms of harmonic mitigation, but also imply additional costs, thus making a cost/benefit analysis really crucial for the specific case.

8 Concluding remarks

Reaching a high rate of adoption of EEMs for EMS is of paramount relevance for grabbing a larger share of the energy efficiency potential still existing in the industrial sector. Nonetheless, the adoption of EEMs represents also a huge challenge for industrial decision-makers and understanding their main characteristics is thus fundamental. Therefore, based on an extensive review of scientific and industrial literature, in this study we have provided a complete and comprehensive classification of all the most widespread EEMs addressing EMS, highlighting their characteristics, most of which impacting on the adoption decision-making process. On this basis, we re-categorised EEMs for EMS, offering specific detail over single EEMs and thus support to industrial decision-makers. Our approach is able to more specifically point out and address the productivity benefits stemming from the adoption of specific EEMs, therefore better supporting industrial decision-makers in analysing the profitability of those EEMs.

Moreover, our novel classification could pave the way to further academic research wishing to address the characteristics of EEMs in EMS. In fact, in order to guide decision-makers toward a specific selection of a given EEM in EMS, it is crucial to further develop research towards a clearer understanding of the factors mostly leading to their adoption in industry. By more specifically describing the implications and productivity benefits, the present study represents a first step of a process aimed at identifying the main factors affecting the adoption of EMS for EMS that further theoretical and empirical research could explore and deepen. We believe this may represent a useful instrument with relevant potential to support industrial decision-makers, as well as policy-makers, in adopting and fostering EEMs within EMS.

We nonetheless would like to acknowledge some study limitations. First, we have limited our classification to EEMs in industrial EMS, therefore not addressing EEMs that would be specifically designed for the residential or commercial sectors. Nevertheless, we believe that further research could further explore this element and see whether and to what extent EEMs for the above sectors really differ from those encompassed in the present study. Second, we have neither specifically discussed nor quantified whether the simultaneous adoption of multiple EEMs could lead to synergies. Third, in the presentation and discussion, we have not highlighted whether there might be a specific priority in the adoption of certain EEMs as preliminary steps for the adoption of further EEMs. Fourth, we have not specifically identified metrics for quantification of the identified productivity benefits stemming from the adoption of the selected EEMs.

To conclude, partially stemming from the study limitations, we can sketch some further research avenues. As next steps, basing on the new classification of EEMs for EMS, future research could develop a framework to characterize all relevant factors related to EEM, company and context features, affecting their adoption, helping industrial managers in assessing all the key features through their decision-making process. Also, policy-makers will get an advantage from such framework (and a related broad empirical investigation) in identifying common behaviours of companies (e.g., whether all not implemented EEMs present a specific value for a factor), better defining regulating instruments and leverages to get the industrial sector to an improved energy efficiency. Moreover, future empirical studies could investigate barriers and drivers to EEMs in EMS with respect to the different impacts (either positive or negative) on production and operations, in contrast with studies according to the previous set of EEMs (e.g., proposed by USDOE IAC), to gather field evidence to what extent the proposed list would lead decision-makers to more aware decisions regarding the adoption of those EEMs. Additionally, the current lack of quantitative studies clearly modelling the implications, from an operations management perspective, stemming from the adoption of an EEM in EMS, calls for future research. In this respect, we believe that academic studies should much more deeply address the quantification of the productivity benefits stemming from the adoption of EEMs in EMS, understanding in detail the metrics also in relation to specific scenarios (such as, e.g., type of production, firm size, production schedule, etc.). Through a better and more specific understanding of the profitability and sustainability of those EEMs, final users could take more conscious decisions, in the end leading to an improved energy efficiency in EMS.

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Figure 1 - Comparison between EEM as indicated by USDOE Industrial Assessment Centre and detailed EEM according to new classification. On the side, evidence over the improved knowledge by adding further detail in the type of EEM is offered.

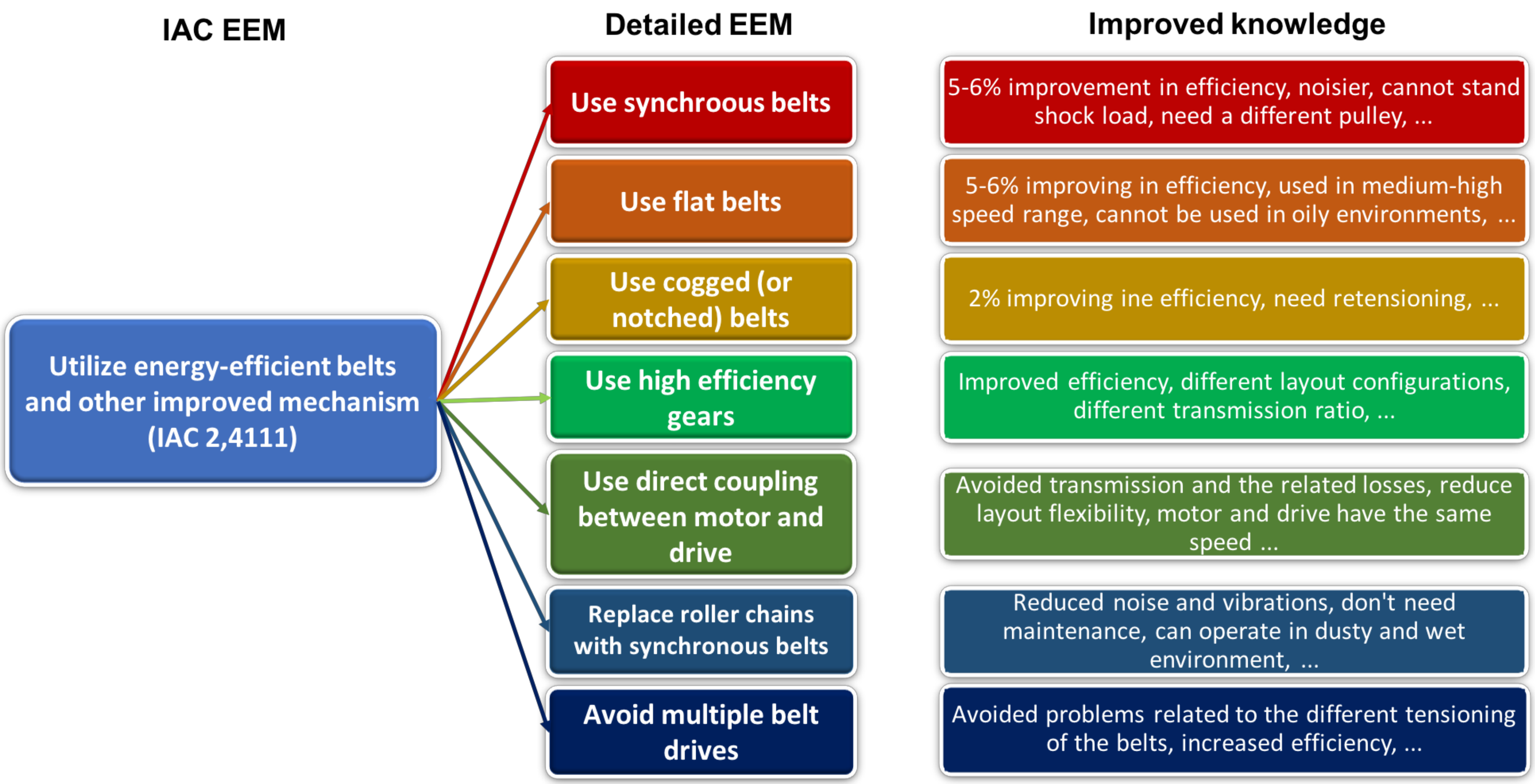

Figure 2 - Distribution of literature contributions on Energy Efficiency Measures in Electric Motor Systems

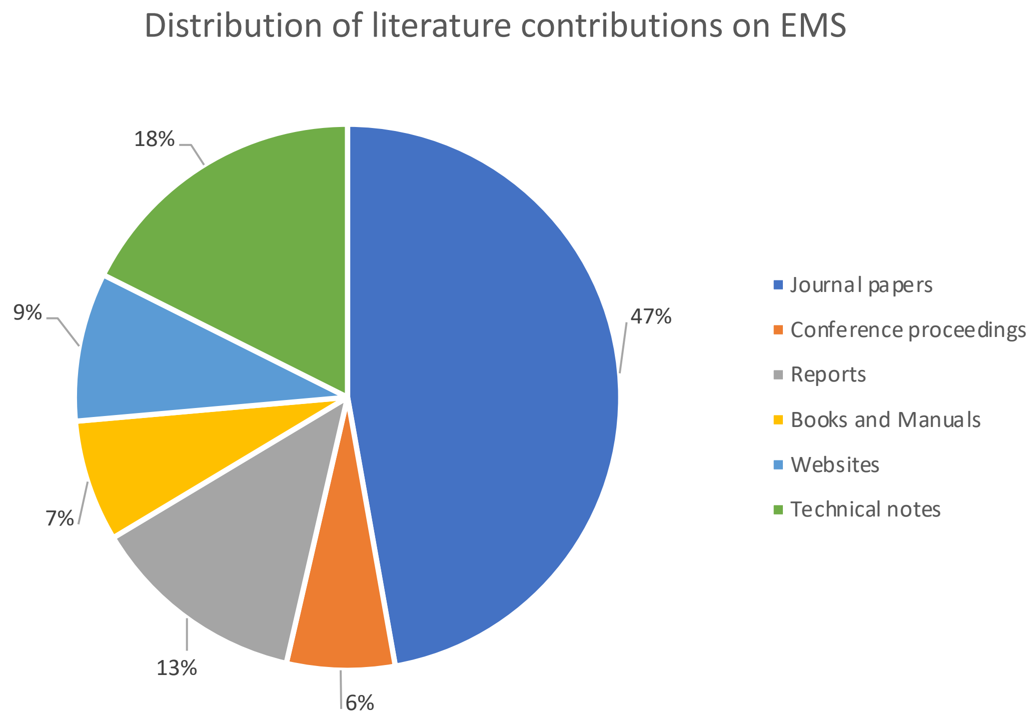

Table 1: List of EEMs for EMS according to USDOE Industrial Assessment Center database.

EEM			ARC CODE
Power factor (2,32)	General (2,321)	Use power factor controllers	2,3211
		Optimize plant power factor	2,3212
Generation of Power (2,33)	DC (2,331)	Replace DC equipment with AC equipment	2,3311
Motors (2,41)	Operation (2,411)	Utilize energy-efficient belts and other improved mechanisms	2,4111
		Install soft-start to eliminate nuisance trips	2,4112
		Install motor voltage controller on lightly loaded motors	2,4113
	Hardware (2,413)	Replace over-size motors and pumps with optimum size	2,4131
		Size electric motors for peak operating efficiency	2,4132
		Use most efficient types of electric motors	2,4133
		Replace electric motors with fossil fuel engine	2,4134
	Motor system drives (2,414)	Use multiple speed motors or AFD for variable pump, blower and compressor loads	2,4141
		Use adjustable frequency drive to replace motor-generator set	2,4142
		Use adjustable frequency drive to replace throttling system	2,4143
		Use adjustable frequency drive to replace mechanical drive	2,4144
		Install isolation transformer on adjustable frequency drive	2,4145
	Motor maintenance / repair (2, 415)	Develop a repair/replace policy	2,4151
		Use only certified motor repair shops	2,4152
		Avoid emergency rewind of motors	2,4153
		Avoid rewinding motors more than twice	2,4154
		Standardize motor inventory	2,4155
		Establish a preventive maintenance program	2,4156
		Establish a predictive maintenance program	2,4157
Air Compressors (2,42)	Hardware (2,422)	Upgrade controls on compressors	2,4224
Equipment Control (2,62)	Equipment use reduction (2,621)	Turn off equipment when not in use	2,6218

Table 2: Novel classification of EEMs in EMS divided by main group and subgroup

Main Group	Sub-group	Detailed EEM
Hardware	Optimize transmission	Use synchronous belts
		Use flat belts
		Use cogged (or notched) belts
		Use high efficiency gears
		Replace roller chains with synchronous belts
		Avoid multiple belt drives
		Use direct couplings
	Replace DC equipment with AC equipment (ARC 2,3311)	
	Turn off equipment when not in use (ARC 2,6218)	Use soft-starters
		Use VSDs
		Use autotransformers
		Use star connection
	Size motors correctly	Size electric motors for peak operating efficiency (ARC 2,4132)
		Replace over and under-sized motors
		Use permanent connections in star for lightly loaded motors
		Install voltage controllers on lightly loaded motors (ARC 2,4113)
	Use most efficient types of electric motors (ARC 2,4133)	
Motor systems drives	Variable load applications	Use VSDs for variable load
		Use multiple speed motors for variable load
		Use integrated variable speed motor for variable load
	Use VSDs and other control strategies to replace less efficient drives	Use VSDs to replace dampers in fans applications
		Use AFDs to replace throttling systems (ARC 2, 4143)
		Upgrade controls for compressors (ARC 2,4224)
		Use AFD to replace mechanical drives (ARC 2,4144)
		Use Daisy-chain configurations instead of motors with multiple gears
		Use static DC drives to replace-motor generator (MG) sets
		Use VSDs to replace MC VSDs
Management of the plant	Motor management plan	Standardize motor inventory (IAC 2,4155)
		Develop a repair / replace policy (ARC 2,4151)
		Use only certified motor repair shops (ARC 2,4152)
		Avoid emergency rewinding of motors (ARC 2,4153)
		Avoid rewinding motors more than twice (ARC 2,4154) or more than once if done before 1980
		Establish a premium efficiency - ready spares inventory
		Accelerate the replacement of standard efficiency motors
		Place motors in adequate environments
	Establish a preventive maintenance program (ARC 2,4156)	
	Establish a predictive maintenance program (ARC 2,4157)	
	Contracting out maintenance (ARC 4,6120)	
Power quality	Optimize plant power factor (ARC 2,3212)	Install capacitors
		Use synchronous motors as capacitors
		Minimize idling of electric motors
		Replace standard with correctly sized premium efficiency motors
		Use VSDs to optimize plant power factor
		Avoid operating equipment above its rated voltage
		Use motors with the highest possible speed
	Avoid off design voltages	Change the tap settings / use an auto-tap changer transformer
		Use medium voltage distribution line
		Use power factor correction capacitors
	Avoid voltage unbalances	

Correct outages	
Avoid transient, surges	Use transient voltage surge suppressors
	Use isolation transformers to avoid transient and surges
Avoid nuisance tripping	Adjust the trip settings / replace the circuit protection
	Use soft-starters (ARC 2,4112)
	Use VSDs to avoid nuisance tripping
	Use isolation transformers to avoid nuisance tripping
	Use an uninterruptible supply system
Avoid line harmonic currents	impedance - AC and DC reactors
	Impedance – drive isolation transformer
	Use passive filters
	Use active filters
	Use multi-pulse methods