Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 3346–3351

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

A review of Energy Efficiency Measures Within Electric Motors Systems

Andrea Trianni [a,*], Enrico Cagno [b], Davide Accordini [b]

[a]*School of Information, Systems, and Modelling, Faculty of Engineering and IT, University of Technology Sydney, 81 Broadway, Ultimo 2007, Australia*

[b]*Department of Management, Economics and Industrial Engineering, Politecnico di Milano, P.za Leonardo da Vinci 32, Milan 20133, Italy*

Abstract

Electric motor systems (EMS) play the lion's share in industrial power consumption. Many opportunities for energy efficiency - most of which apparently cost-effective - can be found, but often decision-makers do not take them as the detail for a specific decision can be too high. In many cases, information regarding the characteristics of such energy efficiency measures (EEMs) is quite vague. For this reason, in the present study we offer a thorough overview of EEMs for EMS, basing on an extensive review of scientific and industrial literature, aimed at 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 new categorization could be helpful to support research for the development of a novel framework to represent the main factors the affect the adoption of EMS for EMS.

Keywords: electric motor systems; energy efficiency measures; industrial energy efficiency; classification framework.

1. Introduction

Electric motor systems (EMS) are the most power consuming technology in industry [1]. Therefore, it is important to support industrial decision-makers in understand which specific energy efficiency measure (EEM) in EMS they

* Corresponding author. Tel.: +61 (2) 9514 2626
E-mail address: andrea.trianni@uts.edu.au

10.1016/j.egypro.2019.01.964

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 related to the motor itself. Nevertheless, despite the wide discussion on energy use (e.g., [2]) and policies to promote EMS (see, e.g., [3]), very little knowledge is offered to the understanding of the broad set of opportunities for energy efficiency in EMS. Such knowledge would support decision-makers in understanding relevant characteristics of EEMs in EMS that should be considered for more conscious decisions over adopting them. Therefore, the present study aims at contributing to the discussion by conducting a thorough overview of EEMs in EMS.

2. USDOE Industrial Assessment Centre database and EEMs in EMS

One of the broadest and most comprehensive list of EEMs within EMS has been developed by the Industrial Assessment Centre (IAC) of the US Department of Energy (USDOE) [4], dividing EEMs according to 5-digit assessment recommendation codes (ARC). The classification of EEMs is done following 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 channeling all the streams in a series of heterogeneous applications, such as maintenance, alternative energy usage, etc. By analyzing all ARCs, and also following previous research on the topic [5], we can find 24 EEMs.

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. Just for a matter of 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 the 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 support a decision-maker when considering an EEM in EMS.

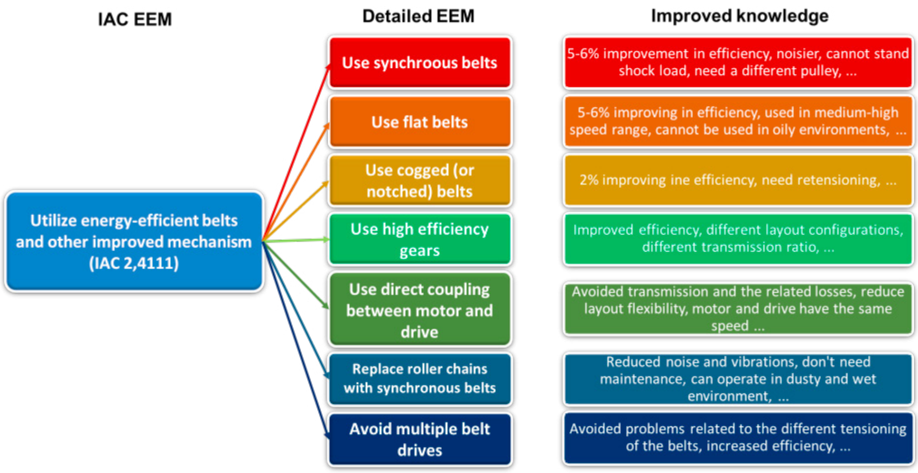

Fig. 1 Comparison between EEM as indicated by USDOE Industrial Assessment Centre and detailed EEM. Improved knowledge by adding further detail in the type of EEM.

Moreover, by looking at single EEMs from USDOE IAC database, we could see that, in some cases, they were either too vague or vast. Therefore, it would be more appropriate, in order to support a decision-maker, to divide such EEM in 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 but closely bonded to it, combining different section of the IAC framework in a unique, exhaustive description of EEMs targeting EMS.

3. A novel proposed set of EEMs for EMS

Following the discussion in Section 2, here we report the broad set of EEMs for EMS stemming from our re-classification of EEMs. In the end, a list of 63 EEMs have been designed, as shown in Table 1. Following the same approach, four main groups have been introduced, namely: *(i)* Hardware; *(ii)* Motor systems drives; *(iii)* Management of the plant; and *(iv)* Power quality. Detailed information on the single elements are provided in the next sub-sections, as well as main literature discussing each specific EEM. For a matter of synthesis, in this study we had to limit the detail to sub-groups of EEMs, thus without a specific discussion of each EEM.

Hardware EEMs. The following efficiency measures address the hardware part of the system, dealing with modification ranging from simple change, such as the replacement of the transmission or the use of a different type of terminals connection, to more complex and extensive intervention, including for instance the installation of a controller or the substitution of an entire class of devices.

Optimize transmission. Transmission systems are the mechanisms or devices transferring the rotary motion of the motor shaft to the equipment using the motive power. A number of EEMs are available in order to minimize those losses and increase the savings.

Replace DC equipment with AC equipment. In industry, the two main ways to adjust the speed of motor-driven equipment are adjusting the speed of the motor directly, or use a constant-speed motor with an intermediate device between the motor and the driven equipment that can change the speed ratio.

Turn off equipment when not in use. There is a variety of opportunities to control switching off, from the simplest form consisting of manual control, to more complicated systems using controllers: manual switching off; interlocking; “bang-bang” control; time switch; sequencing of multiple motor load; and load sensing. To reduce starting stresses and overheating it is warmly recommended to implement: soft starters; VSD; wye-delta starting (or star connection); and autotransformer [6].

Size Motors correctly. Sizing correctly a motor could enable great improvements for what concerns performance and savings, thus representing a critical knowledge that every decision maker should possess. However, literature depicts a different situation, in which the majority of motors are incorrectly sized [7].

Use most efficient types of electric motors. Selecting energy-efficient motors is an important strategy for reducing motor system life-cycle costs. However, in order to take a definite decision, the single situation has to be evaluated. The choice of whether to install a premium efficiency motor strongly depends on both motor operating conditions, as well as the life cycle costs associated with the investment.

Table 1. Detailed list of EEMs divided by main group and subgroup, as well as main references.

Main Group	Sub-group	Detailed EEM	References
Hardware	Optimize transmission	Use synchronous belts	[7,11-15]
		Use flat belts	[7, 12]
		Use cogged (or notched) belts	[7,11-12,14-15]
		Use high efficiency gears	[13,15]
		Use direct couplings	[15-17]
		Replace roller chains with synchronous belts	[12,18]
		Avoid multiple belt drives	[7]
	Replace DC equipment with AC equipment (ARC 2,3311)		[19-21]
	Turn off equipment when not in use (ARC 2,6218)	Use soft-starters	[7,15,22]
		Use VSDs	[15]
		Use autotransformers	[22]
		Use wye delta starting (star connections)	[7,22]
	Size motors correctly	Size electric motors for peak operating efficiency (ARC 2,4132)	[7,16,23]
		Replace over and under-sized motors	[7,16,24]
		Use permanent connections in star for lightly loaded motors	[7]
		Install voltage controllers on lightly loaded motors (ARC 2,4113)	[7]
	Use most efficient types of electric motors (ARC 2,4133)		[15,17,23, 25]

Motor systems drives	Variable load applications	Use VSDs	[11,13,15,24,26-27]
		Use multiple speed motors for a discrete number of load conditions	[11,13,15,24,26-27]
		Use integrated variable speed drives	[11,13,15,24,26-27]
	Use VSDs and other control strategies to replace less efficient drives	Use VSDs to replace dampers in fans applications	[3,13,26
		Use VSDs to replace throttling systems (ARC 2, 4143)	[3,13,26]
		Upgrade controls for compressors (ARC 2,4224)	[16,24,26,28-30]
		Use VSDs to replace mechanical drives (ARC 2,4144)	[26,31]
		Use Daisy-chain configurations instead of motors with multiple gears	[26]
		Use static DC drives to replace-motor generator sets	[31-32]
		Use VSDs to replace MC VSDs	[33-36]
Plant Management	Motor management plan	Standardize motor inventory (IAC 2,4155)	[16,38]
		Develop a repair / replace policy (ARC 2,4151)	[3,13,15,23-24,38-40]
		Use only certified motor repair shops (ARC 2,4152)	[16-17,19]
		Avoid emergency rewinding of motors (ARC 2,4153)	[13,16,37]
		Avoid rewinding motors more than twice (ARC 2,4154) or more than once if done before 1980	[7,16,18,23,28]
		Establish a premium efficiency - ready spares inventory	[13,19,41]
		Accelerate the replacement of standard efficiency motors	[13,23]
		Place motors in adequate environments	[34]
	Establish a preventive maintenance program (ARC 2,4156)		[2,15,17,24,34,37,42-44]
	Establish a predictive maintenance program (ARC 2,4157)		[34,37,44]
	Contracting out maintenance (ARC 4,6120)		[43]
Power quality	Optimize plant power factor (ARC 2,3212)	Install capacitors and use Power factor controller (ARC 2,3211) in the case of banks of condensers	[13,17,24,45-46]
		Use synchronous motors as capacitors	[2,24,47-48]
		Minimize idling of electric motors	[13,46]
		Replace standard with correctly sized premium efficiency motors	[13,46]
		Use VSDs	[13,27,46]
		Avoid operating equipment above its rated voltage	[49]
		Use motors with the highest possible speed	[50]
	Avoid off design voltages	Change the tap settings / use an auto-tap changer transformer	[49]
		Use medium voltage distribution line	[49]
		Use power factor correction capacitors	[49]
		Use VSDs	[49]
	Avoid voltage unbalances		[15,17,19,51]
	Correct outages		[19]
	Avoid transient, surges	Use transient voltage surge suppressors	[52-54]
		Use isolation transformers	[24]
	Avoid nuisance tripping	Adjust the trip settings / replace the circuit protection	[55]
		Install soft-starters (ARC 2,4112)	[24,55]
		Install VSDs	[24,55]
		Install isolation transformer	[56]
		Install uninterruptible supply systems	[24]
	Avoid line harmonic currents	Add impedance - AC and DC reactors	[27,52-54,57]
		Install isolation transformer	[24,53-54,56]
		Use passive filters	[24,57,58-59]
		Use active filters	[59]
		Use multi-pulse methods	[53,60-61]

Motor systems drives EEMs. When analyzing motor systems, the attention should not be focused only on the motor itself, but on the application the device is required to perform. In many cases motor loads are not constant but vary during operations, however AC induction motors - the most used in industry - are designed to only supply a fixed speed, i.e. the nominal one, thus often incurring in efficiency penalties. Different technologies have been developed to address this issue, but as time passes many of them became outdated, reducing the opportunities of savings. The present sub-section is almost completely devoted to the analysis of the most renowned and efficient types of controllers and their potential applications in industrial facilities, mainly as replacements of older devices.

Variable load applications. A motor "load" is the brake or shaft power requirement imposed upon the motor by the driven equipment divided by the motor's full horsepower rating [8]. Before applying a control and a motor to a certain drive is important to understand which loads (variable torque, constant torque, or constant power) is involved.

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

Management of the plant EEMs. The purpose of energy efficiency is not achievable only with the implementation of physical devices in the plant, but should be coupled with careful policies, such as the adoption of a maintenance plan or the development of sustainable practices for the management of the internal resources.

Motor management plan (MMP). The alternative to first-cost, rushed decision making is to implement a motor management plan. Having a motor plan in place before motor failure ensures that decisions will be both quick and cost-effective, reducing energy costs for years to come. The 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.

Establish a preventative maintenance program. The purpose of preventative measures is to prevent unexpected downtime. These measures include voltage imbalance minimization, load consideration, motor ventilation, alignment, and lubrication [2]. Although some equipment faults are instantaneous, the larger majority of faults that impact production are the result of a failure in the implementation of a maintenance program. This failure is primarily due to management not fully understanding that maintenance is an investment in the business and not an expense of doing business. The most important activities that have to be performed according to a preventive maintenance program are described in the following paragraphs (termination maintenance, keep equipment clean, improve lubrication practices, use synthetic lubricants, maintenance of the transmission, maintenance of store idle motors).

Establish a predictive maintenance program. 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 [9]. 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.

Contracting out maintenance. According to the necessity and the current state of the firm (e.g., peak demand or low volume of activity), different types of contract can be developed: work package contract, performance contract, facilitator or lease contract.

Power Quality EEMs. This group of interventions refers to all the interventions that are somehow related to the enhancement of quality in the transmitted power inside the plant, from the avoidance of nuisance tripping and harmonic distortion, to the improvement in the power factor. Indeed, all the devices operating in a plant are designed to work near the optimum level of efficiency when provided with certain values of current and voltage, i.e. the nominal ones, and even small variations could imply significant reductions in efficiency and, in the worst case, they can even compromise the equipment.

Optimize plant power factor. Power factor can be corrected with the following strategies [10]: (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.

Avoid off design voltages. Undervoltage causes power factor improvement. Higher currents lead to increased resistance due to winding heating and power losses, reduced motor efficiency, and possible overheating at rated load.

Avoid voltage unbalances. Voltage unbalances may be identified by regularly monitoring the voltages at the motor terminal and through regular thermo-graphic inspections of motors. Also, it must be verified that single-phase loads are uniformly distributed, in order to have equal voltages in each phase of the three-phase motor.

Correct outages. Outages - the most noticeable problem - can be momentary power losses caused by faults from either internal or external events. However, once the fault is cleared, the switchgear can realign to provide power. Long-term outages are usually the result of a line problem, such as a damaged power line or the catastrophic failure of a transformer or switchgear component [8].

Avoid transient, surges. Transients and surges are often the result of a large switching activity, such as energizing capacitor banks. Proper system grounding is essential to minimize the risk of equipment damage; however, sensitive equipment such as computers and automated control systems usually require additional protection, such as transient voltage surge suppressors or isolation transformers [8].

Avoid nuisance tripping. Here several opportunities are: (i) adjust the trip settings – replace the circuit protection; (ii) install soft starter or VSD; (iii) use isolation transformers; and (iv) install an uninterruptible supply system.

Avoid line harmonic currents. The harmonic voltage and current distortion values may be reduced through several abatement methods as follows: impedance – AC and DC reactors, impedance – drive isolation transformer, passive filters, active filters, multi-pulse method).

4. Conclusions

Adopting EEMs for EMS represents a huge challenge for industrial decision-makers and understanding which are their main characteristics it is thus fundamental. Therefore, based on an extensive review of scientific and industrial literature, in this study we have provided a complete and comprehensive list of all the most widespread EEMs addressing EMS. Indeed, we believe that it would be crucial considered it in the decision-making process as the first phase to explore the major factors characterizing EEMs starts with the identification and classification of the EEMS themselves. Therefore, this present study represents a first step of a process of identification of the main factors affecting the adoption of EMS for EMS that further theoretical and empirical research could explore and deepen.

References

[1] Confindustria, Rapporto Efficienza Energetica 2017, Available at: http://www.confindustria.it
[2] Saidur, 2010. A review on electrical motor energy use and energy savings. Renewable and Sustainable Energy Reviews, vol. 14, pp. 877–898.
[3] De Almeida, Fonseca, Bertoldi, 2003. Energy-efficient motor systems in the industrial and in the services sectors in the European Union: characterisation, potentials, barriers and policies. Energy, vol. 28, pp. 673–690.
[4] Industrial Assessment Centers, https://iac.university
[5] Muller, Kasten, 2007. Industrial Assessment Center - Assessment Recommendation Code (ARC) System. USDOE, Office of Energy Efficiency and Renewable Energy. Available at: https://iac.university/technicalDocuments
[6] U.S. Department of Energy, 2012a. Turn motor off when not in use. Motor systems tip sheet #10. Energy Efficiency and Renewable Energies, Advanced Manufacturing Office. Available at: https://www.energy.gov/sites/prod/files/2014/04/f15/motor_tip_sheet10.pdf
[7] ETSU, Warne, 1998. Energy savings with motors and drives. Harwell, Didcot, Oxfordshire, UK. pp. 53.
[8] U.S. Department of Energy, 2012b. Adjustable Speed Drive Part-Load Efficiency. Motor systems tip sheet #11. Energy Efficiency and Renewable Energies, Advanced Manufacturing Office. Available at: https://www.energy.gov/sites/prod/files/2014/04/f15/motor_tip_sheet11.pdf
[9] U.S. Department of Energy, 2012c. Extend the operating life of your motor. Motor systems tip sheet #3. Energy Efficiency and Renewable Energies, Advanced Manufacturing Office. Available at: https://www.energy.gov/sites/prod/files/2014/04/f15/extend_motor_operlife_motor_systemts3.pdf
[10] U.S. Department of Energy, 2012d. Is it Cost-Effective to Replace Old Eddy-Current Drives? Motor systems tip sheet #12. Energy Efficiency and Renewable Energies, Advanced Manufacturing Office. Available at: https://www.nrel.gov/docs/fy13osti/56009.pdf

Additional references for Table 1 upon request.