APEC-CAST MOTOR REPAIRS PROJECT

ON BEHALF OF THE APEC EXPERT GROUP ON ENERGY EFFICIENCY AND CONSERVATION

With support from the International Copper Association, the China National Institute of Standardization, CLASP and the Super-efficient Equipment and Appliance Deployment Initiative

Task 1: Existing and Best Practices in Motor Repair

Final Report

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ECONOLER

ACRONYMS

AC	Alternating current
AEMT	Association of Electrical and Mechanical Trades
APEC	Asia-Pacific Economic Cooperation
CLASP	Collaborative Labeling and Appliance Standards Program
DC	Direct current
EASA	Electrical Apparatus Service Association
EGEE&E	Expert Group of Energy Efficiency and Conservation
GMI	Green Motor Initiative
ICA	International Copper Association
IEA	International Energy Agency
ODP	Open Drip Proof
TEFC	Totally Enclosed Fan-cooled
US	United States of America

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EXECUTIVE SUMMARY

Background of the Study

Electric motors in motor-driven systems represent a major energy end usage, and account for between 43% and 46% of all global electricity consumption[1]. In industry applications at the global level, it is estimated that motors consume approximately 64%[2] of the energy consumed by all electric motor-driven systems across sectors (industrial, commercial, residential and transport as well as agriculture).

A large number of motors in various sectors fail during operation each year; as a result, the majority of failed motors are repaired and put back into service. In most developing countries, these failed motors are typically repaired by using poor[3] practices, which degrade the initial motor efficiency when there are still new. By contrast, in developed economies, such as the United States (US) and western European countries, advanced repair and re-winding practices allow maintaining or slightly increasing the efficiency of motors. Quite often, these advanced techniques do cost the same as those less refined techniques to perform. If improved motor repair practices are adopted, they could generate enormous energy savings in developing countries.

The primary aim of this study is to estimate the energy efficiency improvement potential related to available technical solutions by adopting best motor repair practices, which can later be included in related standards. The study can benefit policy-makers and standard-setting bodies because it can help raise their awareness regarding the potential for energy savings related to repair and preventive maintenance of installed motors. The study team is comprised of Econoler experts and an industry specialist from the Research and Development (R&D) laboratory of ABB, one of the international market leaders in the field of motor and electrical machinery repair techniques.

This report documents and analyzes current best practices in motor rewinding and repair as well as evaluates the gap between these best practices and practices being used in five representative APEC economies: China, Japan, New Zealand, the US, and Vietnam.

The data collection methodology to support the gap analysis was based on a literature review of research conducted in the field of motor repair practices, field research through in-person interviews conducted by experts at motor repair facilities, phone interviews and email surveys with other key stakeholders, such as government agencies, motor experts, etc. The key findings are presented in the following sections.

[1] International Energy Agency (IEA), 2011, "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems", Energy efficiency Series, p.11
[2] Ibid.
[3] Based on interviews with motor experts (March 2013)

Motor Failure Causes

Three main types of factor, namely mechanical, electrical and improper selection can cause electric motors to fail. Mechanical factors are associated with bearing failures and other mechanical factors. Results of several studies suggest that the primary cause of motor mechanical failures is a bearing problem, which can be caused by a combination of contamination, lubrication, improper assembly, misalignment of the rotor shaft, or overloading.

As for electrical factors, they are mainly associated with winding failures, mostly due to excessive temperature increases caused by overloading leading. Winding failures are stator insulation failures, which include ground insulation failures and inter-turn insulation failures. Other factors which can also contribute to winding failures are supply voltage variations and particularly low voltage, improper or poor electrical connections, vibration and insulation contamination. Sometimes, electrical failures also occur in motors because of misapplication, which is the failure to correctly match a motor's characteristics with the load requirements of the driven equipment (e.g., starting current, improper and substandard motor starter, starting torque requirements, etc.).

Considering the prevalence of failure modes in electric motors and the potential effects of each failure repair method on the efficiency of the repaired unit, this study primarily has focused on electrical failures, especially stator winding failures and rotor failures. It should be mentioned that the stator is composed of laminations of high-grade sheet steel. The rotor consists of laminations of slotted ferromagnetic material; the rotor can be either the squirrel-cage type or the wound-rotor type. Bearing failure is not given the same amount of attention as that given to electrical failure because the former is not so serious in terms of impact on motor efficiency. Bearing losses are taken into account in friction and windage losses, which can increase after motor repair and rewind using bad practices.

As a result, the study covered repair practices associated with stator and rotor failures. These practices include: (i) rewind practices, such as winding removal, winding configuration and modification, impregnation, etc.; (ii) lamination repair or replacement; and (iii) rotor repair or replacement.

Review of Best Practices in Motor Rewind or Repair

Unlike a high-quality repair, a poor one degrades the original efficiency of an AC induction motor by increasing motor losses (copper, core, stray and mechanical losses). Poor repair practices are mostly the result of a lack of know-how, proper tools or poor-quality material used by repair shops.

As part of the efforts to prevent an increase in these losses after rewind/repair and thereby promote provision of high quality rewind/repair services to motor users, the motor repair industry, represented by Electrical Apparatus Service Association (EASA), and quality assurance programs, such as the Green Motor Initiative (GMI), issued repair recommendations that can be considered to illustrate best practices for the electric motor repair industry. According to the specifications, motor repair facilities should follow specific procedures to avoid motor efficiency degradation after rewind/repair. These include:

- Record winding data after winding removal to reproduce the winding initial configuration;
- Perform a core loss test before and after rewind/repair. Core losses can be measured in a dismantled motor, using a flux loop test;
- Avoid lamination damages when removing the winding;
- During the new winding installation, ensure that no mechanical modifications or changes are made to the conductor length, number of turns and cross-sectional area as designed by the original manufacturer; and
- Perform mechanical repair according to manufacturer specifications, when available. Mechanical repair include shaft checking for wear, cracks, scoring and straightness, as well as repair related to bearings.

Bad repair practices overlook these recommendations because of the reasons mentioned above (lack of know-how, lack of proper tools or use of poor-quality material). It is worth noting that one of the major problems causing concern is the lack of knowledge about the defect of reduced motor efficiency due to repeated repair and rewinding. The motor is scrapped only when the motor is beyond repair.

Regarding rotor replacement, a common best practice recommendation is to replace worn rotor bars with bars made from the same materials used in the original design. Currently, one of the considerations in trying to reduce overall loss in electric motors is to replace the aluminum rotor with a copper rotor during a repair activity. The replacement of the aluminum rotor by a copper rotor has the potential to increase the repaired motor efficiency compared to its nominal specification, but this practice is contingent on the availability of a copper replacement rotor from the motor manufacturer (or a built-up unit at the shop).

Summary of Findings from Shops Survey in the Five APEC Economies

A survey was conducted at 45 repair shops in the countries covered by the study. There were 10 shops interviewed in China, 10 in Japan, 10 in New Zealand, 7 in the US and 8 in Vietnam. The survey findings suggested that there were wide differences in how repair shops in different countries repair electric motors.

Not surprisingly, the US appeared to be most advanced in terms of repair practices and adoption of repair technology. Shops in Japan and New Zealand were closely comparable to those in the US. The observed differences in the usage of tools or equipment and practices between U.S. shops and those in Japan and New Zealand could be a result of cultural differences and attitudes towards motor repair. An example of culture would be following rules prescribed by original equipment manufacturers (OEMs). The “Run to failure”, a maintenance policy that allows a motor to run until it breaks down, is an example of this attitude.

China, however, displayed an interesting array of contrasts among its surveyed shops. While some Chinese shops seemed to use old technology, some others used modern technology, which was a pattern that differed from what was observed in other countries. It was expected that the survey results would suggest the existence of best practices in rewind/repair only in shops in the industrialized countries surveyed, rather than in those in emerging economies like China or developing one like Vietnam; findings of the survey suggest a more balanced reality. Indeed, it appears that Vietnamese and Chinese shops, in general, were also well equipped and followed some good practices, though there was still room for improvement which can result in increased efficiency of the repaired units. This general trend observed may be due to the small sample of shops interviewed in these countries. To illustrate the need for improvement, it is worth mentioning that many shops surveyed across the five economies (slightly less than one third of all the shops surveyed) have none of the tools associated with good repair practices. Most of the shops lacking these tools were in China and Vietnam.

As expected, repair practices also varied according to shop size. It was observed that large shops were better equipped and possessed a wider variety of tools as compared with small and medium shops. With a few exceptions, large shops also appeared to follow better repair practices as compared with small and medium shops.

Technical and Economic Analysis Model

To estimate the energy savings potential resulting from the adoption of best repair practices, three interrelated models (technical, economic and market potential) have been developed, taking into account the variation in repair practices in the five countries surveyed. This report only presents the technical and economic models. The market potential model is not presented in this report. It will use the results of the technical and economic models, as well as market data, such as the number of failed motors by category in each country and will be further improved in the third phase of the study, which will be about the potential for energy efficiency improvement during motor repair and refurbishment related to available technical solutions.

The technical model will determine the gain in efficiency associated with the introduction of best repair techniques for a single motor. As for the economic model, it will combine output from the first model with economic market data to determine the economic impact of the following scenarios: 1) motor replacement; 2) motor rewinding without lamination repair; 3) rewinding and lamination repair; and 4) rotor replacement. The figure below presents an overview of the technical and economic models and their associated data input.

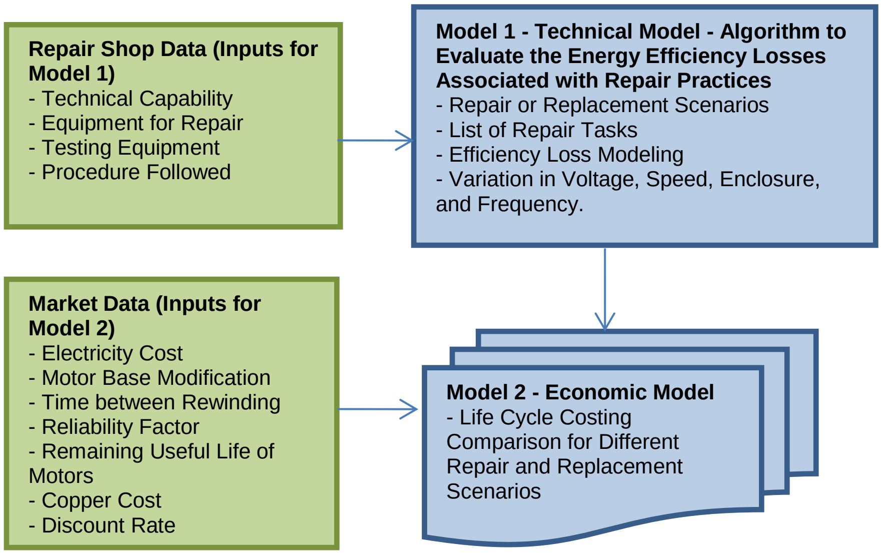

Figure 1: Energy Efficiency Modeling of Motor Repair Techniques

The technical model has an internal algorithm which links a reduction in energy efficiency (compared to the nominal efficiency of the motor when it was new) to each motor repair activity, if the repair is not performed according to best practices. The association is based on a weighing grid that translates the answers from the shop survey into input representing the likelihood that each interviewed shop applies best practices for a given motor repair activity or not. The likelihood that a given shop applies best practices is deduced from the type of equipment it owns and specific questions asked about how its technicians perform some of the critical repair activities. Thereafter, the result (which indicates the percentage of efficiency decrease of a given motor under specific repair conditions representing bad practices), as well as market data such as the electricity cost, the time between rewinding, the material cost, the weighted average cost of capital (WACC), etc., is used as input for the economic model.

INTRODUCTION

After repair and rewinding, electric motor efficiency is generally affected by poor repair practices in repair shops around the world. At the beginning of 2000, there was a common belief that rewinding or repairing an AC induction motor systematically resulted in its original energy efficiency reduction by up to 2 percent, depending on rating of the motor.[4] However, advanced practices in motor rewinding and repair exist, and unlike traditional poor practices, they have the potential to reduce the losses without any substantial reduction in the energy efficiency level compared to the to the efficiency level when it was new. Even though technical solutions for improving repair or rewinding practices exist, most motor repair shops in developing economies still apply poor practices. Obviously, this situation results in substantial wasted electrical energy as motors are by far the largest end-usage for electricity. Indeed, according to the International Energy Agency (IEA), electric motors account for between 43 and 46 percent of global electricity consumption.[5] This level of electricity consumption is not surprising as electric motors are used not only in a wide range of industrial systems, but also in many types of applications such as pumping, ventilation and compressors, in the commercial, residential and agricultural sectors.

In many developing countries, a significant portion of the installed stock of electric motors fails every year, and most of the failed motors are repaired and put back into service. For example, in China it is estimated that 10 percent of all electric motors in industrial applications fail during operation each year. Out of these, 87 percent are repaired and put back into service. Motors are usually repaired 3 to 4 times before being replaced. The potential for energy savings from improved motor repair practices in economies, especially in developing ones, is enormous.

The primary aim of this study is to estimate the energy efficiency improvement potential related to available technical solutions through the adoption of best practices which may later be included in related standards. More specifically, the study seeks to: (i) document and analyze current best practices in selected APEC countries; (ii) establish the market characteristics concerning motor repair in each country; and (iii) estimate the potential for energy efficiency improvement during repair and refurbishment related to the best available technical solutions, with reference to industry best practices. The study will benefit policy-makers and standards-setting bodies at the national level as it will raise their awareness regarding the potential for energy savings related to repair and preventive maintenance of installed motors.

The study team is composed of Econoler experts and an industry specialist from the Research and Development (R&D) laboratory of ABB, one of the international market leaders in the field of motor and electrical machinery repair techniques.

[4] Motor Challenge Fact Sheet at http://www1.eere.energy.gov/manufacturing/tech_deployment/pdfs/mc-0382.pdf
[5] International Energy Agency at http://www.iea.org/newsroomandevents/news/2011/may/name,19833,en.html

This report, which is the first in a series of three, summarizes the findings of a literature review of studies and documents published by manufacturers, repair industry associations or published under efficient motors market transformation and demand side management (DSM) programs implemented by government agencies, as well as not-for-profit organizations. Also, the report identifies current recommended best practices in motor rewinding and repair as well as evaluates the gap between these recommended best practices and practices used in five[6] representative APEC economies including China, Japan, New Zealand, the United States and Vietnam. In compliance to the terms of reference and prior to the project kick-off meeting, the study team defined the project methodology and scope which were discussed and approved at the meeting by the CLASP and its partners including the APEC Expert Group on Energy Efficiency and Conservation (EGEE&C), the China National Institute of Standardization (CNIS) and the International Copper Alliance (ICA). The methodology and key characteristics for AC motors are presented in Appendix I of this report.

[6] Initially, the study covered eight countries (Australia, China, Indonesia, Japan, New Zealand, South Korea, Vietnam and the US), but, due to the lack of sufficient data gathered through literature review and surveys in some countries, the number has been reduced to five by excluding Australia, Indonesia and South Korea.

1 ENERGY LOSSES IN AC INDUCTION MOTORS

Before undertaking the analysis of the effect of repair maintenance practices on motor efficiency, it is important to discuss the main sources of motor inefficiency so they can be later associated with one or several motor repair practices or procedures.

The presence of energy losses in different components of an AC induction motor, during its operation, results in a difference between the motor's electrical input and shaft output power which determines the motor efficiency. Energy losses in AC induction motors can be classified into five main categories: (i) stator copper loss; (ii) rotor copper loss; (iii) stator iron loss; (iv) friction and windage loss and (v) stray loss. In the literature, testing procedures and research paper, the stator and rotor copper loss are often incorporated under the label of Joule losses because they appear as heat generated by resistance to electric current flowing in the stator windings and the rotor conductor bars and end rings (for a squirrel cage design). However, with respect to repair and refurbishment of motors, we will be interested to discuss separately the two sources of joule losses, as different repair techniques apply to stator and rotor.

1.1 STATOR COPPER LOSS

This loss, also referred to as stator "I^2 R"[7] loss, appear as heat generated by resistance to electric current flowing in the stator windings. Of all the component of losses in an AC induction motor, stator I^2 R loss is the most important. According to tests results conducted on motors of 30 kW and above by the Electrical Apparatus Service Association (EASA)[8], the average stator I^2 R loss represents 30 percent of the total loss with a range varying between 22 and 46 percent.

Because stator loss is a function of the characteristics of the electrical conductors that form the stator winding, changing the winding configuration or the size of the winding wires will affect this loss and have a significant impact on electric motor efficiency. For instance, increasing the conductor cross-sectional area and/or decreasing its length reduces stator I^2 R losses, provided that the total ampere turn remains the same. On the other hand, a reduction in conductor size and increase in length will result in increased losses.

1.2 ROTOR COPPER LOSS

Like stator copper loss, rotor copper loss is caused by heat that occurs as current flows through the rotor conductor bars and end rings. Rotor copper loss can increase due to a damaged rotor cage, poor connections between bars and end rings and wrong or improperly installed bars. This loss can be

[7] The "I" refer to ampere current while the "R" refers to winding resistance.
[8] See Electrical Apparatus Service Association (EASA) and Association of Electrical and Mechanical Trades (AEMT), 2003, ***Effect of Repair/Rewinding On Motor Efficiency***

reduced by increasing the size of rotor conductive bars and end rings to reduce resistance. Based on tests result data[9], stator and rotor I^2R losses together typically account for 50 to 60 percent of the total losses that occur in a motor.

So considering that 30 percent of the losses are associated with the stator copper, the remaining 25 percent, on average, will be associated with the rotor copper winding.

1.3 IRON LOSS

Iron loss occurs in the stator and is caused by either hysteresis or eddy currents. Hysteresis is the energy necessary to change the direction of the magnetic fields in the steel. This is reduced by creating a core material that is low in carbon, or silicone-based, magnetic grade steels[10]. Eddy current losses are due to magnetically induced circulating currents in the stator core laminations. The design factors which affect iron loss include material of the core, air gaps, saturation, supply frequency and the condition of interlaminar insulation. Such loss can increase during a winding removal operation when: (i) applying improper burnout temperature, as this can cause damage to insulations between laminations; (ii) overusing abrasive blasting with sand or a similar material, as it can lead to shorting of laminations, thereby increasing lamination thickness; and (iii) hammering the core.

1.4 FRICTION AND WINDAGE LOSS

This category of losses includes the energy used to overcome bearing friction and energy used to overcome air movement from the rotor and cooling fan. These losses can increase during motor reassembly by damaging or improperly installing the bearings, applying excess greasing to the bearings and by using poor quality grease and the wrong size or type of fan.

1.5 STRAY LOAD LOSS

Stray load losses include all residual losses not fully accounted for by the sum of stator and rotor copper losses, core losses and mechanical/friction or windage losses. In general, they are attributed to leakage reactance fluxes induced by load current in the laminations and account for 10 to 15 percent of total losses.[11] It is generally assumed that stray losses as account for one percent of the power output.

Stray losses vary with the load and can increase if poor repair techniques are used for motor dismantling, winding removal, core cleaning and motor rewinding.

[9] EASA, 1999, "A Guide to AC Motor Repair and Replacement".
[10] Howard W. Penrose, "Anatomy of an Energy Efficient Electric Motor Repair", no date, http://www.motordoc.com/Library/RepairAnatomy.pdf
[11] Ibid.

2 CLASSIFICATION OF MOTOR FAILURES CAUSES

In this section, the main causes for electric motor failures are reviewed and classified to serve as a base for their systematic analysis in relation with repair techniques. The classification presented herewith is consistent with the ones used in motor academic research and motor production and testing context.

AC induction motors have two major components: the stationary or static component called the stator, and the rotating component which is the rotor. The stator is made up of laminations of high-grade sheet steel. The rotor consists of laminations of slotted ferromagnetic material; the rotor might be either the squirrel-cage type or the wound-rotor type. The latter is of a form similar to that of the stator winding while the squirrel-cage consists of a number of bars embedded in the rotor slots and connected at both ends by means of end rings.[12] It is worth noting that the bars and the rings are made from either copper or aluminum.

AC induction motors have other components which, together with the stator and rotor, are shown in

Figure 2 below.

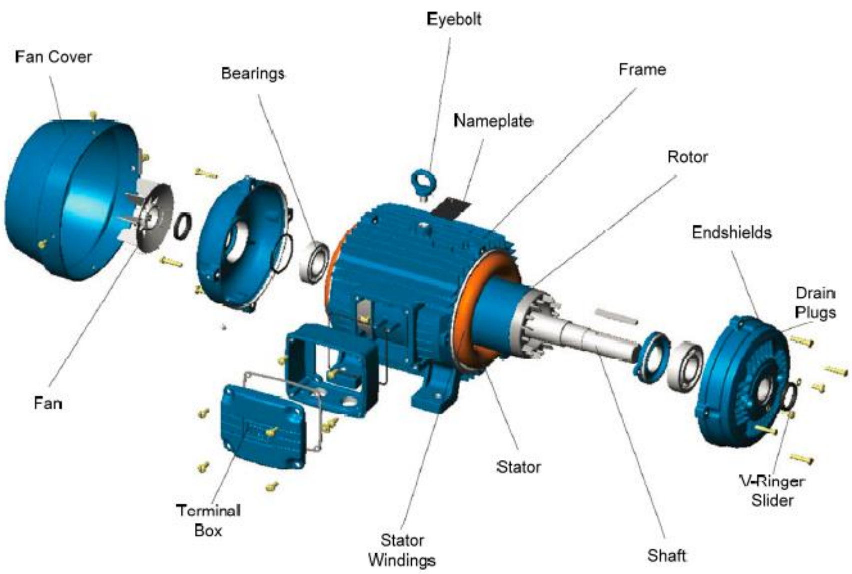

Figure 2: Components of an AC Induction Motor[13]

[12] Edward J. Thornton and J.Kirk Armintor, 2003, "The Fundamentals of AC Electric Induction Motor Design and Application", Proceedings of the 20th International Pump Users Symposium, available at http://turbolab.tamu.edu/proc/pumpproc/P20/11.pdf

[13] Source: See Aderiano M. da Silva, 2006, "Induction Motor Fault Diagnostic and Monitoring Methods", Master thesis, p.15 available at http://povinelli.eece.mu.edu/publications/papers/dasilva.pdf

Motors do fail during their lifetime, and most motor failures are due to mechanical, electrical and misapplication causes. A major energy research consortium study conducted in 1985 covering 6,000 utility industry motors revealed that 53 percent of motor failures are due to mechanical factors[14], the largest of which are associated with bearing failures (41 percent). Stator-related, rotor-related and other mechanical failures account respectively for 37 percent, 10 percent and 12 percent of problems. In conclusion, the primary cause of motor mechanical failure is a bearing problem, which can be caused by any combination of contamination, lubrication, improper assembly, misalignment, or overloading.

With regard to electrical causes, they are mainly associated with winding failures, mostly due to poor ventilation and excessive winding temperature increases caused by overload conditions. Other factors which can also contribute to winding failures are supply voltage variation, improper or poor electrical connections, vibration and insulation contamination. Sometimes, electrical failures also occur in motors because of misapplication, which is the failure to correctly match a motor's characteristics with the load requirements of the driven equipment (e.g. starting torque requirements).

Based on the prevalence of failure modes in electric motors and the potential effect of each failure repair methods on the repaired unit efficiency, the study will primarily focus on three types of failure: a) stator winding failures with lamination damage, b) stator winding failures without lamination damage and d) rotor failures. Bearing failure has not been covered, as this is not a significant issue for motor efficiency improvement or degradation.

For the previously mentioned failures, the motor owner always faces the choice of either repairing or replacing the failed unit with a new motor. The decision will depend, among other things, on the profitability of the chosen solution and the timing to proceed with the repair or the purchase of the new unit. The building user or plant owner will often make this decision based on the impact of the repair or procurement delay on its production, building operation schedule or agricultural activities. Therefore, the study will cover the following repair practices:

- Rewinding practices (winding removal, rewinding configuration and modification, impregnation, etc.)
- Lamination repair or replacement
- Rotor repair or replacement

3 REVIEW OF PRACTICES IN MOTOR REWINDING AND REPAIR

[14] Edward J. Thornton and J.Kirk Armintor, 2003, "The fundamentals of AC Electric Induction Motor Design and Application", Proceedings of the 20th International Pump Users Symposium, available at http://turbolab.tamu.edu/proc/pumpproc/P20/11.pdf

Rewind and repair practices can adversely affect motor efficiency. This section reviews existing and best practices in motor repair in the countries covered by the study.

3.1 POOR PRACTICES DURING AC ELECTRICAL MOTORS REPAIRS

A lack of know-how, improper tools or poor-quality material used by repair entities have resulted in a situation where motor repair is not optimized with a view to maximize motor efficiency in most developing countries. Based on a literature review and the experience of the ABB Research and Development (R&D) unit in motor repair practices, the existing poor practices that decrease motor efficiency are summarized in the table in Appendix II.

3.2 BEST PRACTICES IN MOTOR REWIND/REPAIR

There are motor repair industry specifications and quality assurance programs that summarize the best practices from the electric motor repair industry. These include the Electrical Apparatus Service Association (EASA) specifications and the motor repair specifications of the Consortium for Energy Efficiency (CEE).

Regarding quality assurance programs, they include the well-known EASA-Q, created by the EASA to help its members implement ISO 9001 quality system standards, and the SKF[15] Certified Rebuilder Program[16] which periodically audits motor service centers and focuses on training motor shop personnel on the aspects of bearing failure and replacements as well as root cause analysis about motor failures. Others quality assurance programs include the Green Motor Initiative (GMI) and the Proven Efficiency Verification (PEV) program developed by the Green Motors Practices Group (GMPG) and the private firm Advanced Energy, respectively.

The most common best practices recommended by those organizations are summarized below. A detailed discussion of the EASA and GMPG recommended best practices in motor rewind/repair as presented in Appendix II.

3.2.1 Rewind/Repair

According to best practices recommendations issued by the repair industry, EASA, and by the GMPG, in all cases where rewind/repair is called for, electric motor repair facilities should follow specific procedures to maintain the efficiency of the rewound/repaired motor. This includes:

› Record winding data prior to winding removal to reproduce the winding initial configuration. Only rewinding data related to winding connections can be obtained without removing the windings.

[15] SKF stands for Svenska Kullagerfabriken in Swedish.
[16] Electric Motor Rebuilding on SKF website at http://www.skf.com/group/index.html?contentId=687952

Details concerning the number of turns, wire size, the number of parallels and coil pitch are obtained during the process of winding removal.

- Perform a core loss test before and after rewind/repair. Core losses can be measured in a dismantled motor, using a flux loop test.
- Avoid lamination damage when removing the winding.
- During the new winding installation, ensure that no mechanical modifications or changes are made to the conductor's length and cross-sectional area as designed by the original manufacturer
- Perform mechanical repair according to manufacturer specifications, if available. Mechanical repair include shaft checking for wear, cracks, scoring and straightness, as well as repair related to bearings.

3.2.2 Rotor Replacement

The repair industry has not issued specific recommended best practices regarding the replacement of an electric motor rotor with a new one. Nevertheless, when worn rotor bars are replaced, a common best practice recommendation is to replace them with bars made from the same materials used in the original design. Also, one of the considerations in trying to reduce overall loss in electric motors is to replace the aluminum rotor with a copper rotor during a repair activity. In fact, because the electrical conductivity of copper is nearly 60 percent higher than that of aluminum, the I^2 R losses in the rotor are substantially lower when aluminum is replaced by copper as the conductive material of a squirrel cage structure. Studies conducted in the United States suggest that electric motors fitted with copper rotors have, on average, an overall energy loss of 14 percent lower and nameplate efficiency at least one percent higher than those fitted with aluminum rotors.[17] This trend is confirmed by the results (see Appendix V) obtained by the simulations of the International Copper Association (ICA) as described in Section 4 below. Replacing an aluminum rotor by a copper rotor has the potential to increase the repaired motor efficiency compared to its nominal specification, but such a practice is contingent on the availability of a copper replacement rotor from the manufacturer (or built by the shop).

3.2.3 Motor Replacement Criteria

Sometimes, repair shops do suggest replacing a failed motor if repair alternatives appear to be uneconomical. However, the repair/replace decision is handled differently by service shops, depending on their capabilities. Some shops settle on a fixed power rating (kW or HP) above which they prefer repairing a failed motor instead of suggesting a replacement option to their clients. Other variables such as the availability/quick delivery of the replacement motor, the number of times the failed motor has been repaired and replacement motor efficiency are also considered.

[17] D. J Van Son et al, "Development of the Copper Motor Rotor: Manufacturing Considerations and Motor Test Results"

Software tools have been developed, as part of education and technical assistance programs, to help end-users and service providers base repair/replace decision on detailed economics, including payback and life cycle costs, of both repair and replacement options. One of the most popular motor life cycle cost software tools employed to make a repair/replace decision is Motor Master, which is distributed free of charge by the U.S. Department of Energy (DOE). This tool is a data management application with which users can compare the cost of repair with the cost of replacement for industrial motors under any operating conditions and for any utility rate.[18]

3.3 SUMMARY OF REWIND/REPAIR PRACTICES IN SURVEYED COUNTRIES

This section describes the major findings of the survey on current repair techniques based on information[19] collected at repair shops during in-person interviews conducted by native-speaking experts in China, Japan, New Zealand, Vietnam and the United States. Participating shops were recruited based on their size (large, medium and small). A large-size shop was defined as one with more than 50 employees, a medium-size shop as a shop with 20 to 50 employees, and a small-size shop has fewer than 20. The questionnaire and the summary of answers on repair techniques are presented in Appendix III and Appendix IV, respectively. The detailed answers to the questionnaire will be used as input into the efficiency loss model developed as part of this mandate. Table 1 shows of number of shops by size surveyed in each country.

Table 1: Shops by Size Surveyed in Each Country

Size of Shop Surveyed	China	Japan	New Zealand	US	Vietnam
Number of Small Shops	4	7	3	3	4
Number of Medium Shops	4	2	7	3	2
Number of Large Shops	2	1	0	1	2
Total	**10**	**10**	**10**	**7**	**8**

3.3.1 Rewind/Repair Techniques in Five Surveyed Countries

This section analyzes rewind/repair techniques used by service shops in the five surveyed countries.

Winding removal and stator core testing

The survey findings suggest that shops use different methods to remove winding. None of the shops surveyed use chemical stripping, a method that has probably been phased out over time for Health, Safety and Environment reasons. Approximately 40 percent of shops in Vietnam remove windings

[18] http://www.copper.org/environment/sustainable-energy/electric-motors/case-studies/a6141/a6141.pdf (September 24, 2013)
[19] See Section II[19] of the survey form presented in Appendix III for information about repair techniques.

manually, which is the least technically advanced technique and likely results in higher efficiency losses in the repaired units. A far greater percentage of shops (approximately three quarters) in China use the “Mechanical stripping by cold process” method than in any other countries. One possible explanation for this difference is that the cold process method is significantly more labor intensive than other processes and may not be financially viable in countries where the wage of the workers is higher. In all countries surveyed, a larger percentage of medium-sized shops use burn out ovens compared with large-sized and small-sized shops. The use of a burn out oven is a standard practice among EASA member shops and also helps reduce the time to repair. Ideally, a winding removal procedure in a burn out oven must be followed by a stator core test. Surprisingly, fewer shops surveyed in the United States test stator cores compared with those in other countries, even though all shops in the United States use burn out ovens. All Chinese and Vietnamese shops reported testing stator cores before repair.

Measuring burn out oven temperature

This practice refers to process control. If the temperature in a burn out oven is not controlled, then there is a high probability that the stator core lamination insulation gets overheated and damaged. It is observed that slightly less than one third of small shops do not measure oven temperature; whereas, only few large and medium shops do not control oven temperature. It is likely that the cost of the controls and the awareness of the effects of high temperatures in the stator core during burn-out contribute to this observation.

Determining if stator lamination needs repair

As part of good quality motor rewind practices, shops examine stator lamination for evidence of damaged or missing components and repair any defects revealed during inspection. Testing the stator core with appropriate test equipment is associated with good practice, while performing a visual inspection is associated with bad practice in motor rewind/repair. Approximately two thirds of all shops visually inspect machines to determine if stator lamination needs repair. This is not surprising, as visual inspection is the first level check to look for obvious damage. A large majority (more than two thirds) of shops in all countries except China use this method along with other methods. Shops in the United States use the widest variety of methods while those in China use only a few methods. None of the shops surveyed in New Zealand use a commercial core loss tester. This is more likely to be a matter of awareness or local industry culture than technical capability. Shops are probably more focused on recurrent failures than on excessive core losses. Recurrent failures are connected with localized hot spots, and they are identified more easily with the core loop flux test, which only requires inexpensive test equipment. Three shops (one in New Zealand, one in the United States and one in Japan) use advanced equipment for testing. These shops rely on ‘thermal imaging’, ‘infra-red scanning’ and ‘sound inspection’ techniques, respectively, for motor inspection.

Thermal imaging or infrared scanning is used while performing the core flux loop test. The use of measurement tools such as these help decide whether a stator core with hot spots is acceptable or not. The use of “sound” or magnetic noise tests are used to indicate looseness of the stator core (not necessarily the presence of hot spots or insulation damage) and are seldom deployed.

Method to repair lamination damage

In case any defect has been detected in the iron core, and before proceeding with the rewind/repair, it is best practice to correct the defect by either: grinding and de-burring the lamination core plate; replacing removed laminations with equivalent material or applying the chemical inter-laminar re-insulation process or applying mica between the lamination. It is important to note that the existing material should be known by testing its chemical and physical properties.

All large shops surveyed reported repairing lamination damage, whereas approximately one fifth of small and medium shops reported that they do not generally repair lamination damage. The most popular method (about half of all shops) is to grind and separate the damaged lamination. The method does not involve removal of laminations and is the most cost-effective method. Grinding is the most popular way to remove ‘drag’ or ‘flash’ in the damaged area. None of the shops in Vietnam use the ‘grinding’ method, likely due to lack of awareness. Similarly, none of the shops surveyed in Japan reported replacing defective laminations, probably due to difficulty in obtaining replacement stampings. A far lower quantity of shops in Japan reported using the ‘remove laminations, stagger and re-stack the same or new laminations’ repair method as compared with shops in other countries. Although this method of restacking a stator core is the most reliable, it is the most labor-intensive. Shops in the United States 1) use the widest variety of methods and 2) always report repairing lamination damage. This is evidence of better repair practices among those shops. Finally, medium-sized shops use the widest variety of methods as compared with small and large shops.

Change in copper size

During a rewind procedure, it is best practice to ensure that the new copper-conductor size is identical to the original one. Also, it is possible to change the size by increasing the conductor cross-sectional area to enhance motor efficiency. None of the shops in China reported changing copper size as compared with more than half of shops in all the other countries combined. Quite probably, this is related to the local repair culture, where Chinese shops probably focus on exact duplication of winding which is a simple process without having to redesign the winding.

Replacement wedges

Magnetic wedges, if not designed and used correctly, can lead to reliability problems. Shops are likely to replace them with non-magnetic wedges to avoid recurrent failures. Also, there is a lack of awareness about the benefits of using magnetic slot wedges.

An approximately equal percentage of shops use magnetic and non-magnetic wedges to replace magnetic wedges. In China, the large and medium shops use non-magnetic wedges, while a majority of the small shops use magnetic wedges.

Repairing rotor windings

Rotor windings consist of rotor bars and short-circuiting rings. All shops in the United States replace damaged rotor windings, and it is the prevalent practice in other countries' shops (more than two-thirds reported replacing damaged rotor windings). Among the large shops, none of the Chinese shops reported following this practice but this may be due to the small sample interviewed. All medium sized shops reported replacing rotor winding. Approximately 15 percent of all shops replace the rotor outright when the rotor winding is damaged.

3.3.2 Availability of Tools and Equipment in Repair Shops

Use of certain tools and equipment allows electric motor repair shops to perform a high quality rewind/repair, thereby either maintaining or enhancing motor efficiency. Taken as such, the absence of the tools and equipment could be associated with bad repair practices.

Usage of tools

The survey considered some tools which are presented in the table below, along with the repair process they are associated with. Except a bearing oil bath, the absence of these tools in a repair shop is associated with bad practice rewind/repair. Bearing oil bath is an old tool; hence, its presence in a repair shop is associated with a bad practice.

Table 2: Tools Considered in the Survey

Repair Process	Tool
Rotor removal	Bearing/pulley pullers
	Single gantry crane
	Two gantry cranes
Record winding data	Micrometer screw gauge
Rewinding	Semi-automatic coil winding machine
	Crimping tool
Impregnation	Vacuum pressure impregnation (VPI) system
	Varnish dip tank (When VPI is not used)
Bearing assembly during reassembly	Bearing/pulley pullers
	Bearing induction heaters
	Bearing oil bath

Among all shops in the surveyed countries, bearing oil bath and VPI system are the least common tools followed by two gantry cranes, while micrometer gauges are the most common tool. It is further observed that U.S. shops possess the widest variety of tools, while Chinese shops possess the smallest variety of tools. The main trends observed are summarized as follows:

- Large majorities (80 and 100 percent respectively) of shops in China do not possess bearing/pulley pullers and two gantry cranes
- Not unexpectedly, all shops possess single gantry crane
- None of the Japanese shops possess crimping tool
- Semi-automatic coil winding machines are far more prevalent in large and medium shops than in small shops
- More than 90 percent of small shops do not possess a VPI system. To perform resin impregnation, a shop must ideally have either a varnish dip tank or a VPI system which is a very expensive piece of equipment. There are other methods of impregnation such as spray or pour methods, but these are not favorably compared with VPI or Varnish Dip methods as the VPI system allows much better deposition of varnish.

With regards to shop size, large shops possess a wider variety of tools as compared with small and medium shops. Furthermore, it is observed that slightly lower than one third of the shops have none of the tools mentioned in the above table.

To conclude, it is interesting to observe the phasing-out of old methods for bearing heating (in oil baths) and the reliance on the newer induction heating methods. In fact, based on a review of literature and the knowledge of the study team, the old methods were used in the past and the survey has found a decrease in the prevalence of these old methods. This is certainly an indication of adoption of better repair practices by shops.

Usage of equipment

The survey also looked at the possession of a certain amounts of equipment in repair shops. The equipment presented in the table below is associated with good quality electric motor repair.

Table 3: Equipment considered in the survey

Repair Process	Equipment
Record winding data	Winding resistance meter
	Surge comparison tester
Rewinding	Surge comparison tester
	Winding resistance meter
	Insulation resistance checker <500V
	Insulation resistance checker >500V
	Hipot test kit (status voltage)
Stator core test	Thermo-graphic camera
	Test panel
	Watt meter
	Power analyzer

Since stator windings are most commonly 'replaced' during the repair of a motor, the winding resistance is a good and simple check to test for uniformity of the winding. It is observed that winding resistance meter is the most commonly used equipment while power analyzers and thermo graphic cameras are the least commonly used equipment. For example, in the United States it was observed that small shops tend not to use thermo graphic scanning. Usage of power analyzers was not reported as an important usage by the shops surveyed. Although one shop reported measuring efficiency, in general most of the shops did not consider that efficiency testing was a very important factor for their customers. The shops understand that efficiency is important, but what seemed to prevail in their customer expectation is that the horsepower output of the motor is maintained through the repair, and the speed of the turnaround of the motor repair/rewind. Those two factors dominated all other repair criteria including first cost. Other trends with regards to usage of equipment are presented as follows:

- Shops in the United States use the widest variety of equipment while those in China use the smallest variety of equipment.
- All shops surveyed in the United States and New Zealand possesses a "hipot" test kit and test panel respectively. One of the hypotheses to explain this observed practice is customer awareness of service processes and/or the standard expected of EASA member shops.

- A large majority of shops in China do not possess high voltage insulation resistance checkers[20] while none of the same shops possess surge comparison testers. This could be because high voltage machines do not form a significant part of the machines serviced in China.
- As expected, the large shops possess the widest variety of equipment, considered in the survey, as compared with small and medium shops.

4 PRESENTATION OF THE TECHNICAL AND ECONOMIC ANALYSIS MODEL

This section presents the technical and economic models that will be used to determine the energy efficiency potential associated with the introduction of best practices in motor repairs. The section also presents an example of an energy efficiency reduction calculation using this technical model. The results of the shop survey will feed this energy efficiency reduction model and will be used for the next phase of the study.

4.1 MODEL DESCRIPTION

The analysis of the repaired motor energy efficiency increase potential will be based on three different models. The first, the technical model, will determine the gain in efficiency associated with the introduction of best repair techniques for a single motor. The second model (repair cost and economic analysis model) will combine output from the first model with economic market data to determine the economic interest of different scenarios for the replacement versus repair of a single AC induction electrical motor. The third model (market potential) will use the results of the first two models and combine them with market data from the targeted countries, representing the quantity of motors that fail each year in different categories of motors. This model will multiply the results from single motors analysis to extrapolate them to the total market targeted.

The sub-sections below present a description of the models including the technical, the repair cost and economic analysis and the market potential model. A very brief description of the latter is made, as this model will be further developed in the next activity.

4.1.1 Technical Model – Algorithm to Evaluate the Efficiency Losses Associated with Each Repair Practice

This first component of the model estimates the increase of efficiency associated with the introduction of best repair practice and inversely, the reduction in efficiency if wrong repair practices are used. In

[20] It is worth mentioning that two types of insulation resistance checker exist. One has higher voltage ratings compared to the other. HiPot tester (not to be confused with IR checker) is mentioned separately in the survey.

order to build the model, a list of individual motor repair activities has been identified and classified. These individual repair activities have been established for the four most important repair situations considered in this study (rewinding only, rewinding with lamination repair, rotor repair and replacement). For instance, for motor rewinding without the lamination repair situation, the list of individual repair activities will include: first, the visual inspection; then, recording of rewinding data; followed by the removal of wiring and then the cleaning of the groove in the armature. The list goes on until the complete finalization of the repair activities associated with the repair situation. Each repair activity, part of the repair process, is associated with one or several types of loss that can be introduced by bad repair techniques during the repair process. Table 4 below shows the different repair activities that have been incorporated in this technical model of the electrical motor incremental losses caused by bad repair practices. They are presented according to the classification of sources of losses presented in Section 1.3 above.

Table 4: Source of Losses and Activities Associated with Part of the Repair Process

Activities	Stator Winding	Rotor Winding	Core	Friction and Windage	Stray
Rotor removal			x		x
Visual and internal inspection			x	x	x
Record winding data	x	x	x		
Core loss test			x		
Winding removal			x		x
Core cleaning			x		x
Rewinding	x	x	x		x
Impregnation	x				
Reassembly	x	x	x	x	x
Testing	x	x	x	x	x

For each of the individual steps in the motor repair activity, the model has an internal algorithm that links a maximum decrease in efficiency (compared to the nominal efficiency of the motor when it was new) to the activity, if the repair is not performed according to best practices. It is important to note that the decreases in efficiency associated with those activities are independent of one another and thus strictly additive.

The decrease in efficiency associated with each activity has been compiled from ABB research and development (R&D) laboratory's years of experience in motor repair techniques. During the initial model development, the calculation was made for individual motors using only two contexts: best practices and bad repair practices. During the refinement of the model, an additional functionality was added in such way that each repair activity can now be modulated from a fully "bad techniques" context to a fully “best practices” context. These repair technique characteristics will be used in the next phase of the project when the input to the technical losses model will be fed from weighted average value of the different input received from the repair shops that participated in the survey. For instance, if one third of the shops report using good practices for the removal of old windings, an activity that can cause an increase in the stray losses, the input to the model will be a value representing one third of the shops with best practices and two thirds with bad practices. The resulting averaged value inputted in the model will determine the efficiency loss associated with this repair activity for the market considered.

A weighting grid will be used to translate the answers from the shop survey into input representing the likeliness that each interviewed shop applies best practices for a given motor repair activity or not. The likelihood that a given shop applies best practices is deduced from the type of equipment it owns and specific questions asked about how its technicians perform some of the critical operations. This indirect approach was used to avoid potential bias that would have occurred if a more direct question like “do you apply the following best practices?” had been used instead.

For instance, Table 5 presents the survey questions and information that will be considered while determining whether the shop that filled the survey applies best practices for a rewinding operation or not. In some case, the simple lack of essential equipment will be a clear indication of the inability of the shop to perform a repair using the best recommended practices. Several data from the survey will thus be correlated to an evaluation of losses for a single repair activity using a series of weighted values associated with each question, equipment availability and testing performed. It is possible that a question is associated with several repair activities if the same equipment or testing procedure is used at different stages of the motor repair process.

Table 5: Relationship between the Survey Information and the Repair Activities

Questions	Rotor Removal	Internal Inspection	Record Winding Data	Core Loss Test	Winding Removal	Core Cleaning	Rewinding	Impregnation	Reassembly	Testing
What test equipment is used in the repair shop?										
E: Hipot test kit (status voltage)							x	x		x
E: Insulation resistance checker <500V							x	x		x
E: Insulation resistance checker >500V							x	x		x
E: Surge comparison tester			x				x			x
E: Test panel		x					x		x	x
E: Thermographic camera				x						
E: Winding resistance meter			x				x			x
How are windings removed?				x	x	x				
Is burn out oven temperature measured?					x					
Is copper size changed?			x				x			x
Is stator core tested?				x	x	x				
Method to determine if lamination needs repair?		x		x						x
What is the method to repair lamination damage				x						x
Which tools are used for the replacement of magnetic wedges?										
T: Semi-automatic coil winding machine							x			
T: Bearing induction heaters	x			x					x	
T: Bearing oil bath							x			
T: Bearing/pulley pullers							x			
T: Crimping tool							x			
T: Micrometer gauge			x				x			
T: Single gantry crane										
T: Two gantry cranes	x								x	
T: Varnish dip tank							x	x		
T: VPI system							x	x		

The efficiency decrease calculation module described above is the core component of the calculation model, and it needs as input a database of the survey answers from repair shops. Four iterations of this model will be done for each category of motors to generate the estimate of loss for four scenarios already mentioned earlier, namely: 1) motor replacement; 2) motor rewinding without lamination repair; 3) rewinding with lamination repair; and 4) rotor repair and replacement. The scenario on rotor replacement will build on findings of the motor repair modeling and simulation analysis by ICA. In a project completed at the end of 2012, the ICA built a theoretical model that allows calculating energy efficiency improvement of individual Chinese motors after rotor replacement from aluminum to copper. An analysis of this project's results was made to incorporate its findings into the modeling of rotor replacement options over a simple repair for motors with less than 50 kW, as the scope in terms of power rating of the current study is broader than that of ICA. The table below presents a comparison of the scopes of the ICA model and that of the current study.

Table 6: Comparison of ICA and the Study Model

Characteristics	ICA	Current Study
Motor category	Induction motor, squirrel-cage rotor (Y series, IE1 class)	Induction motor, squirrel-cage rotor
Type of enclosure	TEFC (Y Series)	Open Drip Proof (ODP) and Totally enclosed fan-cooled (TEFC)
Output (kW)	0.75 to 50	0.75 to 1,000
Frequency (Hz)	50	50 or 60
Voltage (V)	350	220 to 13,200 for 50 Hz or 13,800 for 60 Hz
Number of phase	3	3
Number of poles	2,4 and 6	2 to 12

The results of the ICA simulation, which are also used for this model, are presented in Appendix IV to this report. The main finding is that replacing aluminum rotors with copper ones can improve motor efficiency, changing from IE1 to IE2.[21] The simulation found that the efficiency of some motors can even change from IE1 to IE3.[22]

Up to eight categories of motors will be used for the analysis based on the results of the market study. As shown in Table 7, the criteria to determine the boundaries of each category of motors will be based on range of power rating and number of poles.

[21] For three-phase motors, IE1, IE2 and IE3 are efficiency classes defined by the international standards IEC 60034-30:2008
[22] ICA simulation results were kindly provided by Daniel Liang

Table 7: Motor Characteristics

Characteristic	Category Considered	Observation
Size	Less than 50 kW Between 51 kW and 200 kW Between 201 kW and 300 kW More than 300 kW	This categorization was defined by taking into account the relationship between motor size and the usual voltage associated. Normally, motors rated less than 50 kW are low-voltage motors. In countries such as Vietnam and China, it is possible to have medium- or high-voltage motors rated from 200 kW.
Number of poles	4 or fewer poles More than 4 poles	Generally, motor construction can be divided into 2 categories: 4 poles or fewer and more than 4 poles. There is a difference in energy efficiency from repair techniques for those two categories of motors. Motors with more than 4 poles generally have a much lower efficiency than those with 4 or fewer poles. On the other hand, the reliability of motors having more than 4 poles is higher than those having 4 or fewer poles.

Taking into account the different categories considered in the table above, there will be 8 combinations (4 x 2) for each scenario.

The result, which is the percentage decrease in efficiency of a given motor under specific repair conditions representing bad practices, is used as input for the second model, an economic analysis, which is described as follows.

4.1.2 Repair Cost and Economic Analysis Model

This model compares the financial impact of repairing a motor by looking at 3 scenarios (namely, motor rewinding without lamination repair; rewinding with lamination repair; and rotor repair and replacement) with the one involving motor replacement. The outputs of the analysis include motor repair cost or replacement cost, as well as energy savings resulting from the application of best practices to repair the motor. The net present value and the return on investment of improved repair practices are calculated.

This analysis requires certain parameters as basic inputs: motor specifications and operating conditions (type of duty, average load percentage, variable or fixed load operation). The analysis also needs other reference data, such as electricity prices in each country, inflation of electricity costs and costs of various types of repair or replacement options.

In addition to the parameters above, the economic model uses other inputs, such as the efficiency reduction resulting from the application of best practices to repair the motor in countries.

The analysis has also incorporated the following additional variables to increase the precision of the results:

Time between rewinding operations: When comparing the life cycle costs between a repair option and an option of replacing with a new motor, it is important to consider the average time between two rewinds. In fact, the model factors in the costs for multiple rewinding procedures if the average time between two rewinds is lower than the life duration of a brand-new motor.

Cost of motor base modification: For motor replacement by a new unit options, the economic model also considers the adaptation cost (baseplate adjustment/coupling/cable terminations), which is an element often overlooked when a motor owner considers whether to repair or replace a motor.

Reliability factor: The reliability factor is often overlooked when comparison is made between motors repair and replacement by a new motor. On one hand, in cases with poor repair techniques, damage by stampings may occur, but it will not result in significant losses in efficiency. On the other hand, it will increase the risk of failure as the hot spot will burn the insulation and result in shortage of motor winding. So if the reliability factor is not considered in the analysis of traditional repair techniques, quite often they appear to be more cost-effective on paper than replacement by a new motor. For example, the type of enclosure is an important parameter for the analysis, from the point of view of reliability. In fact, in countries with high humidity, e.g. Vietnam, the ODP type will have more problems. ODP motors are less popular because of airborne contaminants, especially dust. It will be important to know the percentage of motors with TEFC or ODP design in the targeted countries.

The results from the calculation for individual motors will be used as input to determine market potential in energy savings for the covered countries.

4.1.3 Market Potential Model

This model will build on the two models described above to integrate the market data about volume of failed motors by categories with the objective to evaluate the global potential for introducing better repair practices in the market. This model will be presented in the upcoming task 3 report.

4.2 APPLICATION OF THE TECHNICAL ALGORITHM TO DETERMINE THE DECREASE IN ENERGY EFFICIENCY

The technical model described in Section 4.1.1 is applied to a motor based on its rating, number of poles (speed) and frequency. The technical model objective is to weight each repair activities presented in Table 4 above and to determine how it contributes to a reduction of motor efficiency compared to a best practices scenario.

Table 8 presents an example of the maximum efficiency losses that can be incurred by an AC induction motor of less than 50 kW and up to four poles in the case of a rewinding without lamination repair. In this example, the motor losses in percentage increase by 16.8 percent in a worst case scenario. The comparison is made against the best repair practices, meaning that if the repair was carried out using recommended best practices, the actual loss increase of 16.8% would be avoided. This loss percentage increase should be applied to the nominal energy losses of the new motor of lower than 50 kW. For instance, if a motor specification mentions 92 percent efficiency that translates to 8 percent energy losses, the maximum losses after a repair using bad practices will be 8% x 1.168 or 9.3 percent. In a country, the average loss in efficiency will be lower than the theoretical maximum as most of the shops use techniques that fall between the best and worse practices. The answer to the shop survey will be used to determine the resulting average efficiency drop in each targeted market. In Table 8, the item “a” is the distribution of the nominal losses (motor specification) between the different categories. For instance, if a given motor has an 8 percent loss (or 92 percent efficiency), then the stator winding losses will be 33 percent of the 8 percent, or 2.64 percent.

The item “b” represents the maximum increase in losses that can be expected if bad repair practices are applied by a repair shops. In the example given in Table 8, we can expect a 15 percent increase in the stator losses, 10 percent for the rotor losses and so on. The multiplication of “a” and “b” provides a direct indication of the maximum increase of losses for each category which results in the maximum of 16.8 percent increase in losses.

The “repair activities” portion of the table then distributes the maximum increase in losses for each category amongst the individual repair activities. For instance, a wrong procedure for recording winding data can lead to 0.3 x 5% or 1.5 percent of the 5.0 percent maximum overall loss increase associated with stator losses.

Table 8: Partial Application of the Technical Model to a 50 kW Motor with up to 4 Poles[23]

	Item/ Formula	Stator Loss	Rotor Loss	Core Loss	Friction and Windage Loss	Stray Loss	Total (%)
Percent of total loss	a	33	20	20	15	12	100
Maximum impact on loss as a result of rewinding without lamination repair (% of above)	b	15	10	30	10	20	-
Maximum overall loss increase (%)	a x b	5.0	2.0	6.0	1.5	2.4	16.85
Repair activities[24]							
Rotor removal	-	-	-	0.04	-	0.10	0.48[25]
Visual and internal inspection	-	-	-	0.10	0.20	0.05	1.02
Record winding data	-	0.30	0.30	0.12		-	2.81
Core loss test	-	-	-	0.25	-	-	1.50
Winding removal	-	-	-	0.16	-	0.60	2.40
Core cleaning	-	-	-	0.17	-	0.10	1.26
Rewinding	-	0.40	0.20	0.06	-	0.05	2.86
Impregnation	-	0.15	-	-	-	-	0.74
Reassembly	-	0.05	0.20	0.03	0.70	0.05	2.00
Testing	-	0.10	0.30	0.07	0.10	0.05	1.79
Total		**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**16.85**

For each category of motor considered in the study (4 different sizes, namely under 50 kW (67 hp), 51 to 200 kW (68 to 268 hp), 202 to 375 kW (269 to 502 hp), above 375 kW (Above 502 hp), 2 speeds (4 poles and fewer and 6 poles and more), 2 frequencies (50 Hz or 60 Hz), the percentage of total loss (item “a” in Table 8) distribution will be different. However, the matrix that split the energy loss increases amongst the different repair activities may be similar. As indicated in Section 4.1.1, the total loss increase fraction for a repair activity from the table above is further adjusted according to the shop survey answers to represent the average repair process followed in each economy targeted.

[23] Source of data: ABB Research and Development laboratory.
[24] Each line indicates to which extent each activity in the repair process contributes to the increase of each type of loss in the case of rewinding without lamination repair of a 50 kW AC induction motor.
[25] This total indicates to which extent the rotor removal process contributes to the increase of all loss types. It is obtained as follows: 0.48 is 0.04*6.0 + 0.10*2.4. The same calculation methodology is used to arrive at a total for the other process activities.

CONCLUSION

After reviewing the main sources of motor inefficiency and identifying the various types of failures that occur in an electric motor, the study provided a detailed review of the existing poor and best practices in the motor repair industry of five surveyed countries. Also, a technical and economic analysis model was developed for comparing repair techniques with replacement scenarios for motors and providing estimates of the differences in achieved efficiency between the scenarios and the associated costs for replacement or repair. The main findings include:

› Energy losses that occur in an AC induction motor, whether new or repaired are the determining factor in motor efficiency. These losses are classified in five main categories: (i) stator copper loss; (ii) rotor copper loss; (iii) iron loss; (iv) friction and windage loss and (v) stray loss. Motor losses are affected by repair practices; in fact, poor practices may increase losses and, therefore, reduce the energy efficiency of a repaired motor;

› While poor practices in motor repair exist, several motor repair industry specifications and quality assurance programs have established recommended best practices that summarize years of experience from the electric motor repair industry. Among all these specifications and quality assurance programs, the EASA specifications and the GMI program developed by the GMPG prescribe best practices that could ensure the maintenance of motor efficiency during the repair process.

› Shops in Japan and New Zealand come very close to those in the United States in terms of repair practices. Any marked difference in usage of tools or equipment and practices between U.S. shops and shops in Japan and New Zealand could be a result of cultural differences and attitudes towards motor repair.

› China, however, displayed an interesting array of contrasts among its surveyed shops. While some Chinese shops seemed to use old technology, some others used modern technology, which was a pattern that differed from what was observed in other countries. It was expected that the survey results would suggest the existence of best practices in rewind/repair in shops in the industrialized countries surveyed, rather than in those in emerging economies like China or developing countries like Vietnam. But, findings of the survey suggest a more balanced reality. Indeed, it appears that Vietnamese and Chinese shops, in general, were also well equipped and followed good practices, though there was still room for improvement which can result in increased efficiency of the repaired units.

› Practices also vary according to shop size. It is observed that large shops are well equipped and possess a wider variety of tools as compared with small and medium ones. With a few exceptions, large shops also appear to follow better repair practices as compared with small and medium shops.

- Repair shops do suggest that their customers replace a failed motor if repair alternatives appear to be uneconomical. However, the repair/replace decision is handled differently by service shops, depending on their capabilities. Some shops settle on a fixed power rating (kW or hp) above which they prefer repairing a failed motor instead of suggesting a replacement option to their clients. Other variables such as the availability/quick delivery of the replacement motor, the number of times the failed motor has already been repaired, and the replacement motor's efficiency are also considered. Other shops base their decision on detailed economics, including payback and life cycle costs, of both repair and replacement options.
- The model developed under task 1 of the study consists of three models: the technical model, the repair cost and economic analysis model, and the market potential model. It is important to note that the third model (market potential) will be further refined in the third phase of the study. However, at the second phase, the technical model and the repair cost and economic analysis model will be used based on survey responses from repair shops as key data input to, first, evaluate the energy efficiency losses associated with repair practices and, second, compare life cycle costs for different repair and replacement scenarios for all the covered countries.

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13. Tom Bishop at http://ecmweb.com/motors/repair-guidelines-motors-generators, as of June 22, 2011.

Websites

1. Copper Development Association at http://www.copper.org/applications/electrical/energy/casestudy/a6141/a6141.html
2. Electric Motor Rebuilding on SKF website at http://www.skf.com/group/index.html?contentId=687952

APPENDIX I
METHODOLOGY AND SCOPE OF THE STUDY

METHODOLOGY

The ultimate objective of this study is to create awareness among policy makers and standard and labeling regulators regarding the energy saving potential of motor rewinding and repair procedures. This section presents the task 1 methodology which goal is to analyze current best practices in motor rewinding and evaluating the technical and economic interest of applying those practices in APEC economies. The following activities were carried out to achieve the goal mentioned above.

- Selection of the countries to be covered by the study. The project scope of work mandated that the study cover at least the six following countries: Australia, China, Japan, New Zealand, South Korea and the United States. Two additional countries in Southeast Asia were selected based on the international experience of the study team—Indonesia and Vietnam. Indonesia is representative of a large Southeast Asia market while Vietnam is more representative of a smaller size country. Therefore, it was deemed interesting to compare the repair practices to countries of variable size, with different levels of service industries. The final country list was approved by CLASP and its partners including the APEC Expert Group of Energy Efficiency and Conservation (EGEE&E), the China National Institute of Standardization (CNIS) and the International Copper Association (ICA), during the formal project kick-off meeting.
- Identification and selection of stakeholders to be interviewed in each of the surveyed countries. This activity, with input from CLASP, resulted in the identification of more than 80 stakeholders (government ministries and agencies involved in electric motor programs, motor vendors, and motor repair shops) to be interviewed by written survey for data collection purposes.
- Selection of size and type of motor to be covered by the study, with input from CLASP and its partners. This activity resulted in the definition of the project scope which is presented in detail in the section below.
- Collection of information in the surveyed countries to estimate the energy efficiency improvement potential related to available technical solutions through the adoption of rewinding and repair best practices. Besides the experience of the study team leader in motor repair practices, data collection was based on various sources. First, the study team conducted field research in the eight countries through a series of surveys. For that purpose, the team developed survey forms which were tailored for each stakeholder in order to solicit specific information. Second, the study team conducted a literature review to identify motor repair techniques that are currently at commercialization stage and that can be offered by the repair shops with a reasonable level of adaptation. Also, the literature review was used to collect data such as hours of operation as well as the price of electricity according to jurisdiction and market.

› Last, data were also taken from the results of the International Copper Association (ICA) prototype testing and motor repair modeling and simulation analysis. In fact, in parallel to this study, the ICA built a model to simulate energy efficiency improvement of motors by changing aluminium rotors for copper ones. The development of the model only focused on Chinese motors. The ICA model included a limited range of products compared to the model that was developed for the current study. It was used as an interesting source of benchmark data for the efficiency input data that was considered.

TYPE AND SIZE OF MOTORS INCLUDED IN THE STUDY

Electric motors are classified according to the type of power supply (AC or DC, single or three phases) and other characteristics related to the design and construction. The main categories are summarized in Figure 3 below:

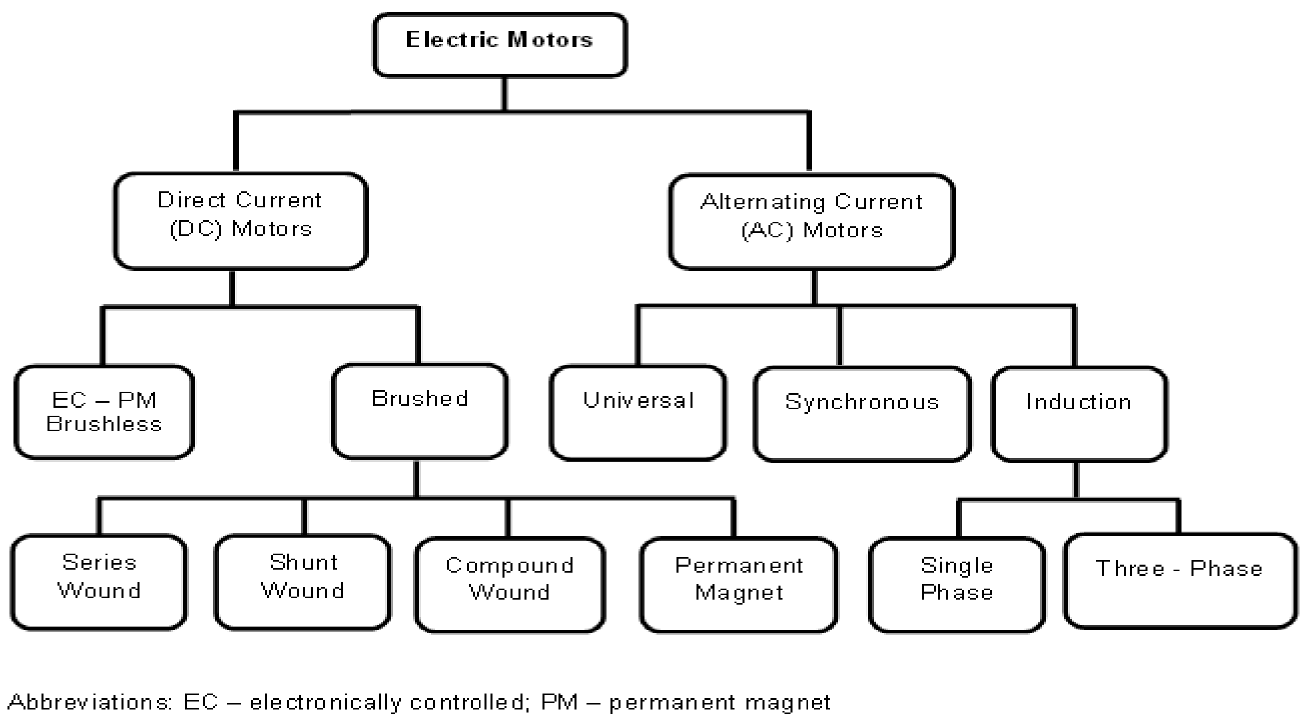

Figure 3: Electric Motor Categories[26]

AC induction motors largely dominate the electric motor market in terms of sales and stock installed. These motors have become popular because they are reliable and have a low cost compared to DC, synchronous and universal ones.

[26] Adapted from International Energy Agency (IEA) at http://www.iea.org/papers/2011/EE_for_ElectricSystems.pdf, p.20

DC motors are less prevalent than AC motors. The general application of these motors is variable speed operation and they perform well in terms of energy efficiency at low speed and high torque. Hence, energy saving features have already been taken into account in their design. They represent a less homogeneous group, as there are several sub-categories related to their operating principles and construction details. The market trend shows a decline in this motor category as advances in electronics and design of AC motors enable manufacturers to produce AC units that have the same torque and speed characteristics at a much lower cost. This category is thus of low interest for the present study.

Synchronous electric motors are more expensive to produce than induction ones and thus are used only when some of their characteristics are essential for an application. One of their advantages is a constant speed even under high load (whereas AC induction motors will have some slippage). They can also run at power factors to improve the overall power factor of an industrial facility. Their efficiencies are higher than those of induction motors with equal power rating. Their size is generally higher than 500 kW and what was considered for the power range of this study.

Universal AC motors are used less and do not represent a large potential for EE. These motors can operate on AC and DC power, and they have advantages only in specific applications. A study realized in 2006 in Europe showed that this category of motor was only 4 percent of the integral AC[27] motor market[28]. Furthermore, they are often used in small power applications incorporated in household appliances that are already regulated for minimum efficiency standards. There is thus little interest to consider this category of motor in the present study.

Therefore, based on an analysis of the main segments of electric motors for which the main conclusions are outlined above, this study will principally focus on AC induction motors which represent the largest share of the market. The table below presents the characteristics of AC induction motors selected to define the scope for the study.

[27] Even if universal motor can work on DC and AC, they are usually included in the AC category for statistical purposes.
[28] Aníbal T. de Almeida, 2007, "Electric Motors: Preliminary Technical Analysis", Presentation at AP6 Workshop, Beijing, June 10, 2007, available at http://www.asiapacificpartnership.org/pdf/BATF/electric_motors_workshop/Motors%20WS-Electric%20Motors-almeida.pdf

Table 9: AC Induction Motor Range Covered by the Study

Characteristics	Range	Observation
Type of enclosure	Open drip proof (ODP) and Totally enclosed fan cooled (TEFC)	Both are widely used and are included in the study.
Output (kW)	0.75 to 1000	The study focuses on medium size (0.75 to 375 kW) and large size motors (> 375 kW). However the upper size practical limit considered for this study will be 1000 kW, specifically from a repair perspective. The lower limit is mainly from a replacement perspective and we expect that the threshold where the decision to replace failed motors is prevalent will be within the 0.75 kW to 80 kW range so we will capture this decision point by using 0.75 kW as the lower limit for the study. The scope does not cover smaller size motors (< 0.75)
Frequency (Hz)	50 or 60	It is the typical range available on the market. The scope will also include variable frequency drives.
Voltage (V)	220 to 13,200 (50 Hz) or 208 to 13,800 (60 Hz)	A wide range is necessary to capture the complexity of motors design at different voltages.
Number of phase	3	Unlike 3 phase motors, single phase motors are quite small and are replaced rather than repaired. Therefore the number of single phase motors rewound is very small and does not represent a significant potential.
Number of poles	2 to 12	In general, the number of poles for motors varies between 2 and 12. This is the typical range covered for similar studies.

APPENDIX II
SUMMARY OF EXISTING POOR PRACTICES AND THEIR IMPACTS ON MOTOR LOSSES[29]

Repair Process	Poor Practice	Impact on Motor Efficiency	Copper Loss	Core (Iron) Loss	Stray Loss	Mechanical Loss
Dismantling the Motor						
Terminal box position, layout, connections	Overlook bad joining practice, or lead or lug sizes	Increased copper loss	x			
Rotor axial position	Overlook axially displaced rotor	Increased bearing forces, stray loss and magnetizing current	x		x	x
Rotor removal	Allow the rotor to scrape the stator core	Stator core hot spots and increased losses in the stator core		x		
Internal inspection	Overlook core surface damage, magnetic wedge damage	Persistence or increase of core and stray loss		x	x	
Mechanical damage	Overlook misalignment	Increased frictional loss				x
Winding Removal						
Old winding	Wrong wire size or parallels or turns or pitch or end connection length or wrong winding connection	Increased stator copper loss, increased iron loss (less turns), negative sequence if unequal turns	x	x	x	
Core loss test	Wrong procedures for core loss test, improperly applied acceptance norms	Acceptance of faulty core could lead to increased core (iron) loss		x		
Cutting coil extensions non connection side	Cutting very close to stator could result in core damage	Increased core (iron) losses		x		
Removal of insulation and varnish on top of windings	Improper burn out temperature can cause damage to insulation between stator laminations	Increased core (iron) losses		x		
Removal of old windings	Failing to ensure that the end teeth splay outwards	Increased stray losses			x	

[29] The two types of copper losses are presented in a single column here to avoid repetition.

Repair Process	Poor Practice	Impact on Motor Efficiency	Copper Loss	Core (Iron) Loss	Stray Loss	Mechanical Loss
Core						
Cleaning the core	Overuse of abrasive blasting with sand or such materials can lead to shorting of the laminations. Use of files and grinders to remove insulations as they smear lamination surfaces.	Shorting of laminations can cause increase in core loss and stray losses		x	x	
End of the core	Hammer ends with excessive force could lead to shorting of end core stampings. Instead, use soft hammer and thrust minimum force	Increased core/stray loss		x	x	
Air gap surface of core	Hammering the core	Smeared laminations lead to increased core losses.		x		
Rewinding						
Rewinding the motor	End turns more than the original winding length, cross-sectional area less than original, inadequate slot fill, wrong connections, wrong turns	Higher copper loss in the stator winding, higher stray and iron loss	x	x	x	
Stator core test	No test or improper test	Unrepaired core could lead to higher iron loss		x		
Slot fill	Replacement of magnetic slot wedges with glass laminate wedges	Increased stray loss and increased no-load current	x		x	
Reassembly of the motor						
Bearing lubrication	Excess greasing	Increased frictional losses				x
Thrust washers	Wrong installation	Increased frictional losses				x
Fans and air baffles	Wrong fan placement decreases cooling	Cooling is affected by fan position, which could lead to an increase in winding temperatures, thereby increasing stator copper losses.	x			
Impregnation						
Impregnation	Wrong impregnation	Increased winding temperature and losses	x			

APPENDIX III EASA AND GREEN MOTORS PRACTICES GROUP (GMPG) RECOMMENDED BEST PRACTICES FOR THE REWIND/REPAIR OF ELECTRIC MOTORS

ANSI/EASA AR 100-2010: Recommended Practice for the Repair of Rotating Electrical Apparatus

Initially developed in 2006 by the EASA, this standard was revised and published in 2010 by the American National Standards Institute (ANSI) as the AR 100-2010.[30] Most of the best practices for maintaining motor efficiency included in AR 100-2010 were identified during a thorough study[31] conducted in 2003 by the EASA and the Association of Electrical and Mechanical Trades (AEMT). These best practices for mechanical repair, rewinding, and testing help electric motor service centers maintain or enhance the energy efficiency and reliability of electric motors (AC and DC) as well as generators. This section of Appendix III strictly focuses on EASA recommended best practices in AC motors rewind and repair.

General practices

Upon receipt of a motor, the electric motor repair shops should ensure that the electric motor has a nameplate. The information from the nameplate should be recorded, and mechanical measurements of a motor's characteristics are mandated both before and after repair/rewind. Review of nameplate data helps shops ensure that the motor is suited for its application and that the motor's original characteristics are maintained after rewind or repair. Also, shops inspect and test the motor to confirm its condition and obtain the information and data necessary to perform a failure investigation before any work is carried out. This helps identify the root causes of failures and adequate actions with regard to its operation and maintenance that can help avoid a recurrence.

Mechanical repair

Electric motor repair shops examine motor shafts, bearings and frame as well as bearings housings for defects such as cracks and breaks which are repaired according to manufacturers' specifications. Shops also examine stator and rotor laminations for evidence of hot spots or damaged or missing components. These shops make sure that the rotor is of proper fit on the shaft, sleeve or spider on which the lamination stack is assembled. It is important to check that the outer diameter of the rotor[32]

[30] See "ANSI/EASA AR 100-2010: Recommended Practice for the Repair of Rotating Electrical Apparatus" at http://www.easa.com/sites/default/files/AR100-2010_1010-2.pdf
[31] EASA/AEMT, 2003, "*The effect of Repair/Rewinding on Motor Efficiency*"
The EASA/AEMT study consists of Part 1 and 2. Part 1 provides detailed information about testing motor efficiency and demonstrates that motor efficiency can be maintained provided repairers use best practices outlined in part 2.
[32] It is also important to check the balancing of the rotor, which is part of standard repair practice. Checking of concentricity is often not done.

laminations is true and concentric with the bearing journals, while the bore of the stator laminations is true and concentric with the rabbet (spigot) diameter of the frame.

Rewinding

Rewinding is one of the most important aspects to ensure that efficiency of the motor is kept optimal after the repair process. According to the AR 100-2010, a good practice rewind begins with careful inspection of core laminations and thermal protectors or sensors. Inspection of core laminations requires core testing, which is conducted before burnout and after winding removal. Repair shops compare results of the tests (before burnout and after winding removal) to detect any increase in losses, which should be investigated. Damaged laminations should be repaired or replaced. Thermal protectors or sensors are also checked for any electrical and physical defects. The following six activities describe in details the best practices related to the actual rewinding:

Winding data

To maintain or enhance the energy efficiency and reliability of electric motors, the standard highly recommends that a new winding have the exact electrical characteristics of the original one. Therefore, repair shops should record and check the accuracy of the "as found" winding data before it is destroyed. Furthermore, during the new winding installation, shops should make sure that coil overhang is not longer than the originals and that cross-sectional area of conductors are at least equal to the original manufacturer's specifications. These good practices help maintain or reduce winding resistance and associated losses, thereby maintaining or improving winding life and energy efficiency.

Stripping of windings

Motor repair shops, which follow AR 100-2010 good practices, remove defective and/or damaged windings in a way that the laminations or any other components are not damaged. This is done by placing the stator in a temperature-controlled oven, with a water suppression system, to avoid degrading of the interlaminar insulation and distorting any other part. During this process, core slots are kept clean and free of sharp edges or particles.

Insulation system

It is best practice to ensure that the insulation system, materials and methods of application are equal to or better than that used by the original manufacturer. It is important that all components of the insulation system are compatible with each other with respect to electrical, mechanical and thermal characteristics. According to Bishop[33], the "better than" option is normally achievable, because service centers typically use Class H systems (180°C) for random windings and Class F systems (155°C) for form coil windings. Most original manufacturers use either Class F (155°C) or class B (130°C) random windings and class B (130°C) form coil windings.

[33] Tom Bishop at http://ecmweb.com/motors/repair-guidelines-motors-generators, as of June 22, 2011

Rewind procedure and slot fill

The best practice related to rewind process is to ensure that the new winding has the same electrical, thermal and mechanical characteristics as the original one. This means that the new winding uses the same conductors (wire cross-sectional area) or better material, the same number of turns per coil and the same coil dimensions as the original. However, it is possible to enhance electric motor efficiency by increasing the wire cross-sectional area to increase conductivity and reduce losses. Another way is to reduce the average length of coil turns in order to reduce resistance and losses[34].

It is best to ensure that wedges for stators, armatures and rotors have adequate mechanical strength and thermal rating to withstand normal operation of the electric motor. Therefore, magnetic wedges are replaced with equivalent magnetic wedges, which have to fit tightly in the slots.

Winding impregnation

At this point, repair shops preheat windings of rewound motors and treat as well as cure these windings by applying varnish/resin with sufficient thermal rating to withstand the normal operation of the motor. Preheating is done to remove residual moisture/solvents that might be present in the windings. If preheating is not done before impregnation, moisture/solvents are likely to be trapped within the insulation.

Shops make sure that the treatment is compatible with the entire insulation system and suitable for the environment in which the motor is to operate.

In addition to EASA best recommended practices described above, the Green Motors Practices Group (GMPG) initiated a program to address elements of energy efficiency retention when electric motors are repaired, as part of its efforts to promote good motor management practices.

Rewind/Repair Processes for Electric Motor Efficiency Retention –GMPG

The GMPG issued a specification which covers correct ways to rewind/repair low- and medium-voltage random-wound and form-coil AC induction motors without reducing their efficiency.[35] Members (service centers) of the GMPG commit to rewind/repair motors according to the specification, which details minimum requirements for repair and overhaul of such machines. Service centers rewind/repair electric motors by following practices presented in the table below:

[34] Ibid
[35] GMPG, 2012, “Rewind/Repair Processes for Electric Motor Efficiency Retention”, Electric Motor Repairing Specification 2012

Initial Inspection and Disassembly

Initial inspection

Upon receipt of an electric motor by a service shop, repairers inspect to record in detail each motor's as-received condition and configuration. The inspection includes testing and digital imaging. These inspection and tests are done to discover any type of defect within the motor. In the event of a defect in the motor, service shops give a detailed description of the defect to the motor's owner or his (her) designated representative.

Disassembly

At this point, the service shop: (i) performs match-mark to identify external and internal component configuration for correct reassembly; (ii) performs an insulation resistance test of insulated stationary and rotating components; (iii) identifies and locates needed equivalent replacement components; and (iv) stores the disassembled motor protected and isolated from unrelated components.

Winding Removal

Winding data

Service centers precisely record winding data (wire dimensions and size, the number of turns as well as cross-sectional area) in order to reproduce the winding original configuration. For motors with more than two poles, replacing a concentric configuration with a lap winding configuration is preferred when appropriate, and permissible if: (i) the replacement does not affect the winding's magnetic flux densities, harmonic content, or current densities by more than 2 percent, and (ii) the replacement reduces current density (increases wire cross-sectional area per ampere). In the event that the motor repair shop does not change the winding configuration, the original total cross-sectional area of a turn, the turns per coil, the span and the connection of the coils are maintained. Where practicable, a motor repairer can reduce end-turn extensions, but not increase them.

Core loss

Service centers, part of the GMPG initiative, conduct core loss tests before and after stripping and iron repair, thereafter comparing both results to check for damaged inter-laminar insulation. At this point, repairers carry out a temperature check for hot spots and overall core heating. Hot spots should not exceed 15°C above the ambient temperature after 15 min. In case the hot spot is less than 15°C, the losses after stripping should not be more than 4 W per pound, and not more than 20 percent higher than the pre-strip losses.

Burn out

Motor repairers strip the winding clean by placing it in a controlled temperature burnout oven where (i) the part temperature is monitored by a fixed location sensing probe attached to the upper half of the stator bore, and (ii) the calibrated temperature is limited by means of fuel control and supplementary (water spray) cooling to 370°C (700°F).

Winding Extraction

Repairers extract the winding while avoiding lamination damage due to coil cutoff, coil extraction, or splaying of teeth.

Core Preparation

Iron damage

Before proceeding with the repair, it is recommended that iron damage and significant frame damage, plus any defects revealed by the core loss tests, be corrected according to an appropriate method of repair selected among the four methods described below.

- Grinding: Limited grinding and de-burring of the lamination core plate is recommended if dimensional integrity of the slots and bore remains unchanged and lamination insulation integrity is maintained;
- Removal of laminations: If individual laminations are removed, it is highly recommended to replace them with an equivalent material. This is possible, provided that the repair shop knows about the material by actually analyzing the existing material;
- Motor repairers can restack part or all of the assembly with the same number of de-burred, undamaged laminations if they have the same material composition, dimensions, and inter-laminar characteristics as the original core plate assembly;
- Chemical inter-laminar re-insulation process: This method is permitted in case core-plate integrity remains uncompromised and core loss tests results remain within the parameters indicated above;
- Mica between lamination: This method is used in case the lamination assembly dimensions remain unchanged.

Winding

Insulation system

This system is created in such a way that it is equal to or better than the insulation classification temperature rating of the original system installed by the manufacturer.

Conductor and conductor cross-sectional area

Under the green motor initiative, it is best practice to rewind a motor with conductors and conductor cross-sectional area that are equal or greater than the area (of total conductor per turn) and conductivity of the original materials supplied by the manufacturers.

Stator coil extension

It is best to ensure that the coil overhang is not greater than the original extension from the core plate, thereby avoiding an increase of I^2 R losses. Repairers also make sure that coil-to-coil connections are equal or greater than the conductivity of the winding conductors and nameplate insulation class rating.

Impregnation

This method includes preheating, treatment and curing of stator with materials suitable to the operating temperature and environment in which the equipment is to operate, or per the machine owner's requirements, whichever is more stringent.

Rotor Test and Repair

Service centers conduct testing for damaged bars and end rings, whether the motor rotor is suspected or not suspected of damage. The test consists in applying a stable single-phase voltage to the stator of the assembled motor while a slowly-rotated shaft makes at least one revolution. If the test reveals an electrical or mechanical defect with the rotor or if the stator winding is defective, repairers conduct one or more additional tests, such as the growler[36] test, current analysis or vibration analysis of a loaded motor, physical examination, ultrasonic or magnetic impression examination of the bars and end rings and core loss tests (axial current through shaft). Thereafter, appropriate actions are taken for rotor repair. It is best practice to repair a rotor by re-barring and/or replacing rotor bars and end rings with the same materials used in the original design.

Shaft and Bearing Fits

Service centers repair shaft and end-bracket bearing housings by building up the metal and machining to size concentric and parallel to component original manufactured machined surfaces. Best repair methods consist of welding, plating and sleeving. It is highly recommended to use wear-resistant high-strength epoxy products designed for use on bearing housings. At this point, repairers make sure that they do not use general epoxies or other compounds, or to knurl and/or peen to lock or seat bearings.

[36] Growler is a testing instrument consisting of an open-end transform that induce an AC current in a motor armature to detect shorted turns.

APPENDIX IV
SURVEY FORM FOR REPAIR SHOPS

TO THE INTERVIEWER

On behalf of the Asia-Pacific Economic Cooperation (APEC) Expert Group on Energy Efficiency and Conservation, Econoler is performing a market study on the potential for energy savings related to repair and preventive maintenance of installed motors. The objective of this survey is to collect information that will be used as inputs for a model developed to determine the energy efficiency potential that could be realized in a given market through electric motor repair best practices. Please make sure the respondent knows that the information he will provide will be kept confidential and will only be used to provide aggregated statistics as input to the analytical work.

From the perspective of the model, Sections I, II, III and V are crucial, and the interviewer must make sure that the respondent provides answers to questions in these sections. Section IV is important too for the survey, however, as it draws a lot on the practical experience of the respondent, we are not expecting precise figures but an estimate based on his or her expertise in the field of motor repair. In case you realise that the responses to the questions in Section IV are vague and not useful, please use the fallback questionnaire presented in Appendix I to this survey form. The questionnaire is meant to get the respondent's sense about the national electric motor repair market. Please make sure that the respondent provides reasons to support his or her responses.

Instruction: When filling out this electronic form, use the *tab* key to move around within the form.

Important Note: Should you have any questions, please contact:

Kevo Luc Tossou, chargé de Projet/Project Manager / **Email : ltossou@econoler.com**

I. INFORMATION ON FAILURE MODES

A. Based on your experience please estimate the percentage (%) of motors received in your service shop associated with each type of failure for each category of motor indicated in the table below. **Note: Motors that have only bearing failures should not be included in the percentage. Total percentage for each column could be more than 100% if some motors have both stator and rotor failures.**

Types of failure	Motors under 50 kW (67 hp)	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
Stator winding failures with lamination damage	%	%	%	%
Stator winding failures without lamination damage	%	%	%	%
Rotor failures	%	%	%	%

II. INFORMATION REPAIR TECHNIQUES

A. Do you test the stator core?

☐ Yes ☐ No

A. How do you remove the windings from a failed stator?

1. ☐ Burn-out oven
2. ☐ Mechanical Stripping by using heating with an open flame
3. ☐ Mechanical stripping by cold process
4. ☐ Chemical Stripping
5. ☐ Other (please specify)

B. If you chose "burn-out oven," is the part temperature measured during the burn-out process?

☐ Yes ☐ No

C. How do you determine if the stator lamination needs repair?

1. ☐ Core test the stator using commercial core loss tester
2. ☐ Core test the stator using loop test
3. ☐ Visual inspection
4. ☐ Any other (please specify)

D. Which method(s) do you use for lamination repair?

1. ☐ Grind and separate the damaged section
2. ☐ Remove laminations, stagger and re-stack the same or new laminations
3. ☐ Grinding
4. ☐ Replace the defective laminations
5. ☐ Chemical etching (Specify chemical
6. ☐ Other (describe)
7. ☐ Generally, we do not repair lamination damage

E. Which tools are commonly used in your repair shop? Check all that apply:

1. ☐ Micrometer gauges
2. ☐ Bearing/pulley pullers
3. ☐ Bearing induction heaters
4. ☐ Bearing oil bath
5. ☐ Varnish dip tank
6. ☐ Semi-automatic coil winding machines
7. ☐ Single gantry crane
8. ☐ Two gantry cranes
9. ☐ VPI system
10. ☐ Crimping tools

F. What test equipment is used in the repair shop?

1. ☐ Insulation resistance checker 500 V
2. ☐ Insulation resistance checker > 500 V
3. ☐ Hipot tester (state voltage and AC or DC)
4. ☐ Winding resistance meter
5. ☐ Surge comparison tester
6. ☐ Test panel
7. ☐ Watt meters
8. ☐ Power analyzer
9. ☐ Thermo-graphic camera

G. When rewinding AC motors, do you change the copper size from the original size?

☐ Yes ☐ No

Yes—if so, do you increase or decrease the size and why?

H. When rewinding an AC motor with magnetic slot wedges, what replacement wedges are used?

☐ Magnetic ☐ Non-magnetic

I. How are cage rotor windings repaired?

☐ Winding replaced ☐ Rotor replaced

J. Are damaged rotor cores repaired?

☐ Yes ☐ No

Yes— If so, please specify how:

III. REPAIR/REPLACEMENT DECISION

I. REPAIR/REPLACEMENT DECISION

A. Do you suggest customers a replacement motor option if the repair alternative appears to be uneconomical?

☐ Yes ☐ No

B. Which of the following criteria do you use to advise your client whether to repair or rewind a failed motor versus replacing that motor?

10. ☐ Power rating in kW
11. ☐ Availability/quick delivery of a replacement motor
12. ☐ Cost of rewinding versus cost of replacement
13. ☐ The number of times the motor has been repaired
14. ☐ Replacement motor efficiency
15. ☐ Other, please specify:

C. What is the typical minimum motor kW size for rewinding, i.e. above what size is a repair typically performed instead of a replacement?

Answer:

D. Do you use any software tool to make a repair/replace decision? If yes, please name them.

Answer:

E. What repair standards, guidelines, procedures or specifications, if any, are followed by your service center for repair or rewind of AC induction motors?

Answer:

IV. GENERAL INFORMATION ABOUT THE CURRENT SITUATION

Note: This section draws a lot on the practical experience of the respondent. We are not expecting precise figures but more estimate base on expert in the field of motors repair.

A. Based on your experience, please estimate the percentage distribution by size of AC induction motors that you receive for repair at your shop. Note: Consider only motors that have a rotor or a stator failure. Do not include motors that have only bearing failure.

Motors under 50 kW (67 hp)	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
%	%	%	%

B. Based on your experience, out of the AC induction motors that you receive at your shop, please estimate the percentage of motors that are rewound versus replaced. Note: consider only motors that have a rotor or a stator failure. Do not include motors that have only bearing failure.

Motors under 50 kW (67 hp)	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
%	%	%	%

C. Based on your experience, please estimate what percentage of AC induction motors that you receive for repair at your shop are in each age range, according to the power categories presented in the table below. **Note: Each column should add up to 100%.**

Average age range	Motors under 50 kW (67 hp)	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
Less than 5 years	%	%	%	%
Between 5 and 10 years	%	%	%	%
Between 10 and 20 years	%	%	%	%
Older than 20 years	%	%	%	%

D. Based on your experience please tell us: after how many years on average are the following categories of AC induction motors, which you receive at your shop, are replaced or discarded versus repaired? This is equivalent to the total life duration of the average motors in each category.

Motors under 50 kW (67 hp)	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
Year (s)	Year (s)	Year (s)	Year (s)

E. Based on your experience, please tell us what is the average number of years between rewind for the following categories of AC induction motors at your shop. The answer to Question D divided by the answer to the present question should give the average number of time a motor is rewound during its life time before being discarded.

Motors under 50 kW (67 hp) Year	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
Year (s)	Year (s)	Year (s)	Year (s)

F. Based on your experience, please estimate how old an AC induction motor of each category has to be, on average, for you to recommend replacing it instead of repairing it.

Motors under 50 kW (67 hp) Year	Motors rated 51 kW to 200 kW (68 hp to 268 hp) Year	Motors rated 201 kW to 375 kW (269 hp to 502 hp) Year	Motors above 375 kW (502 hp) Year
Year (s)	Year (s)	Year (s)	Year (s)

G. Based on your experience, please estimate what percentage of the AC induction motors that you repair at your shop are of Totally Enclosed Fan-Cooled (TEFC) design for each category in the table below. Note: This is to get the fraction of TEFC motors versus Open Drip Proof (ODP).

Motors under 50 kW (67 hp)	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
%	%	%	%

H. Based on your experience, please estimate the percentage of AC induction motors that you repair/rewind at your shop that have four (4) poles and fewer, and six (6) poles and more, for each of the motor categories indicated in the table below. **Note: Each column should add up to 100%.**

Number of poles	Motors under 50 kW (67 hp)	Motors rated 51 kW to 200 kW (68 hp to 268 hp)	Motors rated 201 kW to 375 kW (269 hp to 502 hp)	Motors above 375 kW (502 hp)
Four (4) poles and fewer	%	%	%	%
Six (6) poles and more	%	%	%	%

V. REPAIR SHOP PROFILE

A. How long has the repair shop been in business?

Answer:

B. How many workers are employed at this electric motor repair facility?

Answer:

C. How many motors are received at this electric motor repair facility in a year? Note: Including motors received with Bearing failures and motors with winding or lamination failure.

Answer:

D. Is the repair shop affiliated with a manufacturer ☐ or independent? ☐

E. Is the repair shop ISO 9001?

Answer:

Thank you very much for your time and co-operation. Your answers will be treated in strict confidence. Your name(s) will not be mentioned in the report neither shops specific information. As said at the beginning of the interview, only aggregated results of this study will be used to inform policy makers on the energy efficiency potential resulting from the adoption of the best practices in electric motor rewinding and repair. Please kindly provide us with your contact details below.

IDENTIFICATION

Name of repair shop:

Address:

City

Country

Zip or postal code:

Phone number or email address: - - or - -
@ .

Contact name and title:

Interviewer's name:
Interviewer's comment about the interview:

APPENDIX V RESULTS OF SECTION II OF THE SURVEY

This Appendix presents the results of section II on rewind/repair techniques at surveyed electric motor repair facilities in five APEC member countries (China, Japan, New Zealand, the United States and Vietnam).

Questions	Response	Options	Number of Responses				
			China (Number of Shops interviewed:10)	Japan (Number of Shops interviewed: 10)	New Zealand (Number of Shops interviewed:10)	US (Number of Shops interviewed: 7)	Vietnam (Number of Shops interviewed:8)
Do you test the stator core?	No		0	3	3	3	0
How do you remove the windings from a failed stator?							
	Yes	Burn-out oven	6	2	7	7	3
	Yes	Mechanical stripping by using heating with an open flame	1	9	3	4	3
	Yes	Mechanical Stripping by cold process	7	2	3	1	0
	Yes	Chemical Stripping	0	0	0	0	0
	Yes	Other (please specify)	0	0	0	0	4
If you chose "burn-out oven," is the part temperature measured during the burn-out process?	No		2	0	3	1	0
How do you determine if the stator lamination needs repair?							
	Yes	Test the stator core using commercial core loss tester	3	1	0	4	2
	Yes	Core test the stator using loop test	6	5	8	2	1
	Yes	Visual inspection	2	9	7	5	7
	Yes	Any other (please specify)	0	1	2	2	0
Which method(s) do you use for lamination repair?							
	Yes	Grind and separate the damaged section	4	5	5	5	4
	Yes	Remove laminations, stagger and re-stack the same or new laminations	5	1	6	4	2
	Yes	Grinding	5	6	4	4	0

	Yes	Replace the defective laminations	3	0	1	4	4
	Yes	Chemical etching (Specify chemical	0	0	1	1	0
	Yes	Other (describe)	0	1	1	0	1
	Yes	Generally, we do not repair lamination damage	3	2	2	0	3
Which tools are commonly used in your repair shop? Check all that apply							
T: Micrometer gauges	No		1	0	0	0	2
T: Bearing/pulley pullers	No		8	0	0	0	0
T: Bearing induction heaters	No		0	1	0	1	6
T: Bearing oil bath	No		10	7	10	6	2
T: Varnish dip tank	No		10	3	1	0	2
T: Semi-automatic coil winding machines	No		2	4	1	1	1
T: Single gantry crane	No		3	3	3	4	2
T: Two gantry cranes	No		10	6	3	0	4
T: VPI system	No		7	7	9	4	6
T: Crimping tool	No		2	10	0	0	4
What test equipment is used in the repair shop?							
E: Hipot test kit (status voltage)	No		2	4	4	0	1
E: Insulation resistance checker <500V	No		3	2	1	1	0
E: Insulation resistance checker >500V	No		9	0	0	0	3
E: Surge comparison tester	No		10	6	5	2	4
E: Test panel	No		2	3	0	2	3
E: Thermo-graphic camera	No		10	9	6	3	7
E: Winding resistance meter	No		0	0	1	0	1
When rewinding AC motors, do you change the copper size from the original size?	Yes		0	7	6	4	2
if so, do you increase or decrease the size and why?	Decrease		0	0	0	0	0
When rewinding an AC motor with magnetic slot wedges, what replacement wedges are used?	No		7	2	0	4	5
How are cage rotor windings repaired? (Replaced or repaired)	Winding replaced		7	7	8	7	6
Are damaged rotor cores repaired?	No		10	4	5	3	4

APPENDIX VI
RESULTS OF ICA SIMULATION

Refurbished Y-Series induction motor efficiency by rotor replacement

Type	Power/kW	Voltage/V	Efficiency (%)				Power Factor		Starting Current		Starting Torque		Max Torque	
			Original efficiency (0.5% stray load loss)	IE2 standard	Efficiency after change rotor	Efficiency after change rotor (0.5% stray load loss)	Original Motor	Refurnished motor	Original Motor	Refurnished motor	Original Motor	Refurnished motor	Original Motor	Refurnished motor
Y801-2	0.75	220	75.0%	77.4%	80.64%	81.85%	0.8	0.9	6.8	5.9	2.3	1.9	2.3	2.7
Y802-2	1.1	220	76.2%	79.6%	81.83%	83.08%	0.8	0.9	7.3	6.0	2.3	2.0	2.3	2.5
Y801-4	0.55	220	71.0%	77.5%	77.47%	78.26%	0.8	0.8	6.5	5.1	2.2	2.1	2.2	2.6
Y802-4	0.75	220	73.0%	79.6%	79.02%	79.85%	0.8	0.8	6.6	5.3	2.3	2.3	2.3	2.6
Y90S-2	1.5	220	78.5%	81.3%	82.39%	83.68%	0.8	0.9	7.6	6.7	2.3	2.1	2.3	2.8
Y90L-2	2.2	220	81.0%	83.2%	83.61%	84.95%	0.9	0.9	7.8	6.7	2.3	2.2	2.3	2.6
Y90S-4	1.1	220	76.2%	81.4%	80.51%	81.38%	0.8	0.8	6.8	5.9	2.3	2.4	2.3	2.6
Y90L-4	1.5	220	78.5%	82.8%	81.76%	82.67%	0.8	0.8	6.8	5.9	2.2	2.4	2.2	2.4
Y90S-6	0.75	220	69.0%	75.9%	76.74%	77.21%	0.7	0.7	5.9	4.6	2.0	2.1	2.1	2.8
Y90L-6	1.1	220	72.0%	78.1%	77.40%	77.89%	0.7	0.7	5.9	4.5	2.0	2.1	2.1	2.6
Y100L-2	3	220	82.6%	84.6%	85.67%	86.71%	0.9	0.9	7.8	7.5	2.2	2.3	2.2	3.2
Y100L1-4	2.2	220	81.0%	84.3%	83.80%	84.77%	0.8	0.8	7.4	6.2	2.3	2.1	2.3	2.8
Y100L2-4	3	220	82.6%	85.5%	85.39%	86.42%	0.8	0.8	7.4	7.1	2.2	2.5	2.3	3.1
Y100L-6	1.5	220	76.0%	79.8%	80.81%	81.37%	0.7	0.7	5.5	5.5	2.0	2.4	2.1	2.7
Y112M-2	4	380	84.2%	85.8%	86.78%	87.85%	0.9	0.9	8.3	7.0	2.3	2.1	2.3	3.3
Y112M-4	4	380	84.2%	86.6%	87.06%	88.13%	0.8	0.8	7.5	7.4	2.3	2.6	2.3	3.1
Y112M-6	2.2	220	79.0%	81.8%	83.08%	83.66%	0.7	0.7	6.2	5.6	2.1	2.3	2.1	2.7
Y132S1-2	5.5	380	85.7%	87.0%	88.28%	89.22%	0.9	0.9	8.3	7.5	2.2	1.7	2.3	3.1
Y132S2-2	7.5	380	87.0%	88.1%	89.17%	90.15%	0.9	0.9	8.3	7.4	2.0	1.7	2.3	2.9
Y132S-4	5.5	380	85.7%	87.7%	88.46%	89.41%	0.8	0.8	7.4	6.6	2.0	2.0	2.3	2.7
Y132M-4	7.5	380	87.0%	88.7%	89.43%	90.42%	0.8	0.9	7.4	7.1	2.0	2.1	2.3	2.7
Y132S-6	3	220	81.0%	83.3%	85.51%	86.17%	0.7	0.8	6.8	6.6	2.0	2.0	2.1	2.7
Y132M1-6	4	380	82.0%	84.6%	86.52%	87.20%	0.7	0.8	6.8	6.7	2.0	2.1	2.1	2.6
Y132M2-6	5.5	380	84.0%	86.0%	87.74%	88.43%	0.8	0.8	6.8	6.5	2.0	2.0	2.1	2.4
Y160M1-2	11	380	88.4%	89.4%	89.65%	90.38%	0.9	0.9	7.9	7.2	2.2	2.0	2.3	3.0

Type	Power/kW	Voltage/V	Efficiency (%)				Power Factor		Starting Current		Starting Torque		Max Torque	
			Original efficiency (0.5% stray load loss)	IE2 standard	Efficiency after change rotor	Efficiency after change rotor (0.5% stray load loss)	Original Motor	Refurnished motor	Original Motor	Refurnished motor	Original Motor	Refurnished motor	Original Motor	Refurnished motor
Y160M2-2	15	380	89.4%	90.3%	90.66%	91.40%	0.9	0.9	7.9	7.1	2.2	2.1	2.3	2.8
Y160L-2	18.5	380	90.0%	90.9%	91.46%	92.22%	0.9	0.9	8.1	7.3	2.2	2.3	2.3	2.8
Y160M-4	11	380	88.4%	89.8%	90.57%	91.31%	0.8	0.9	7.5	6.8	2.2	2.1	2.3	2.5
Y160L-4	15	380	89.4%	90.6%	91.28%	92.03%	0.8	0.9	7.5	7.1	2.2	2.3	2.3	2.4
Y160M-6	7.5	380	86.0%	87.2%	88.92%	89.64%	0.8	0.8	6.7	6.3	2.1	2.3	2.1	2.4
Y160L-6	11	380	87.5%	88.7%	89.93%	90.67%	0.8	0.8	6.9	6.5	2.1	2.5	2.1	2.3
Y180M-2	22	380	90.5%	91.3%	90.88%	91.67%	0.9	0.9	8.1	6.6	2.2	2.4	2.3	3.3
Y2-180M-2	22	380	90.5%	91.3%	90.61%	91.39%	0.9	0.9	8.1	7.3	2.2	2.2	2.3	3.2
Y180M-4	18.5	380	90.0%	91.3%	91.56%	92.37%	0.9	0.9	8.1	7.2	2.2	2.4	2.3	3.3
Y180L-4	22	380	90.5%	91.6%	92.02%	92.83%	0.9	0.9	7.8	7.2	2.2	2.4	2.3	3.3
Y180L-6	15	380	89.0%	89.7%	90.27%	91.03%	0.8	0.8	7.2	6.8	2.0	2.8	2.1	2.9
Y200L1-2	30	380	91.4%	92.0%	91.98%	92.53%	0.9	0.9	7.5	6.6	2.0	2.2	2.3	3.2
Y200L2-2	37	380	92.0%	92.5%	92.65%	93.22%	0.9	0.9	7.5	6.7	2.0	2.3	2.3	3.2
Y2-200L1-2	30	380	91.4%	92.0%	91.72%	92.27%	0.9	0.9	7.5	7.6	2.0	2.2	2.3	3.1
Y2-200L2-2	37	380	92.0%	92.5%	92.33%	92.89%	0.9	0.9	7.5	7.4	2.0	2.2	2.3	2.9
Y200L-4	30	380	91.4%	92.3%	92.89%	93.46%	0.9	0.9	7.2	7.0	2.2	2.3	2.3	3.1
Y200L1-6	18.5	380	90.0%	90.4%	91.07%	91.61%	0.8	0.8	7.2	7.0	2.1	2.5	2.1	2.7
Y200L2-6	22	380	90.0%	90.9%	91.46%	92.01%	0.8	0.8	7.5	6.9	2.1	2.5	2.1	2.7

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