Software Tool for Fast and Optimized Design of Three-Phase Stator Windings of Induction Motors

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Abstract

In this paper, an overview of the electric motor market and repair/rewinding services is presented, and the latest version of an innovative user-friendly software tool for (re)design of motor stator windings is described in detail. Its main advantages are pointed out and some application examples are presented. It can be used in technical courses on industrial motor maintenance/rewinding/repair (didactic purposes) and by the technicians and engineers dealing with motor rewinding/repair/design activities (professional purposes), being an excellent tool to, in a fast and accurate way, improve/optimize the original design of the motors. In the optimization process, it can be taking into account that, in general, handmade rewinding task has less design limitations/restrictions than those associated with automatic large-scale motor winding processes used by manufacturers. The unique automatic tool for simultaneous optimization of the coil pitch and number of turns provides the user with the best combined solution, which may allow improving the original winding design of motors of all efficiency classes, including IE4 class. If the automatic design features are used, this software tool reduces significantly the time associated with the required calculations to evaluate the impact of different design options. Moreover, it facilitates the stator winding technical information/data exchange and organization/standardization, promoting an easier and error-free data exchange between the professionals dealing with motor repair/rewinding tasks.

1. Introduction

World industrial electric motor market is moving toward IE4 and IE5 efficiency classes, and the European Union is strongly contributing to that trend (Fig. 1) [1-5]. New three-phase motor technologies are being developed and introduced in the market, such as line-start synchronous motors (Fig. 2) [2]. Nevertheless, the three-phase squirrel-cage induction motor (SCIM) still dominates the line-operated motor market for fixed-speed applications, being available from IE1 to IE4 classes.

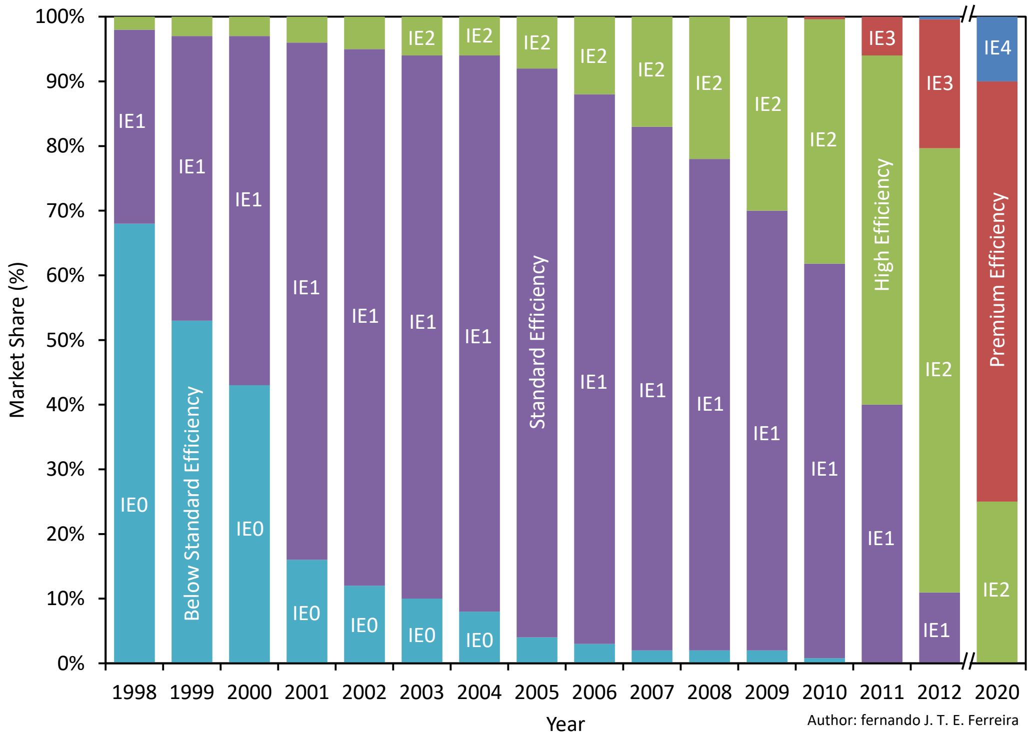


Fig. 1. Low-voltage motor market share evolution and 2020 forecast for E.U., 0.75-375 kW power range [1-5].

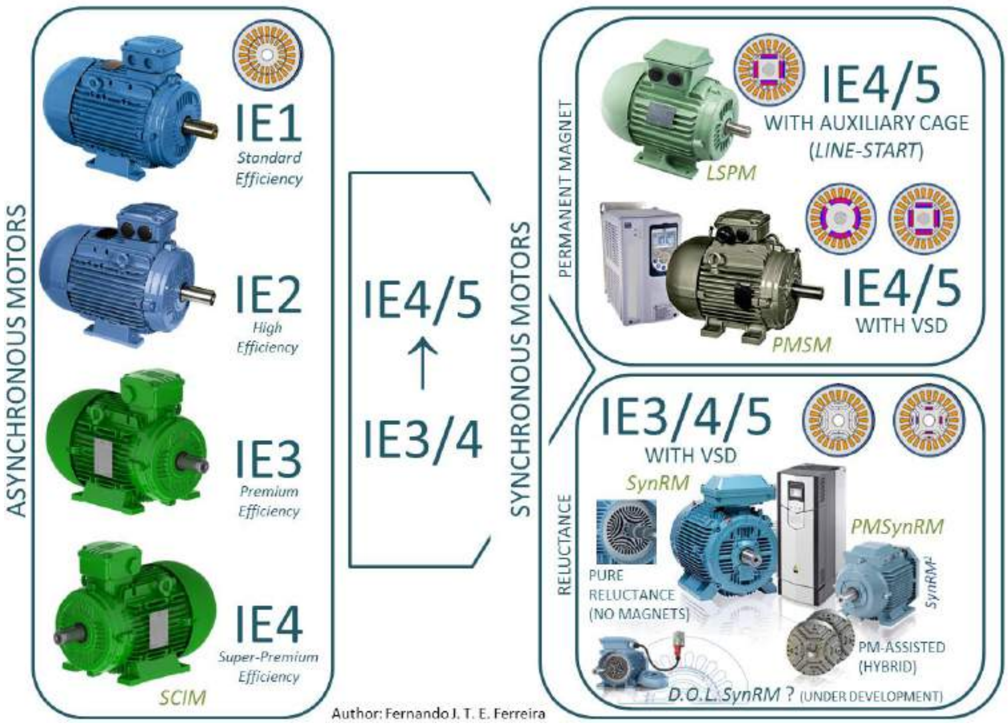


Fig. 2. Overview of the three-phase motor technologies available in the market and/or under development [6].

In Fig. 3, the percent nominal efficiency and the nominal efficiency gain in percentage points (p.p.) when moving to the higher efficiency class are shown. The lower the motor rated power is, the higher the efficiency gain will be.

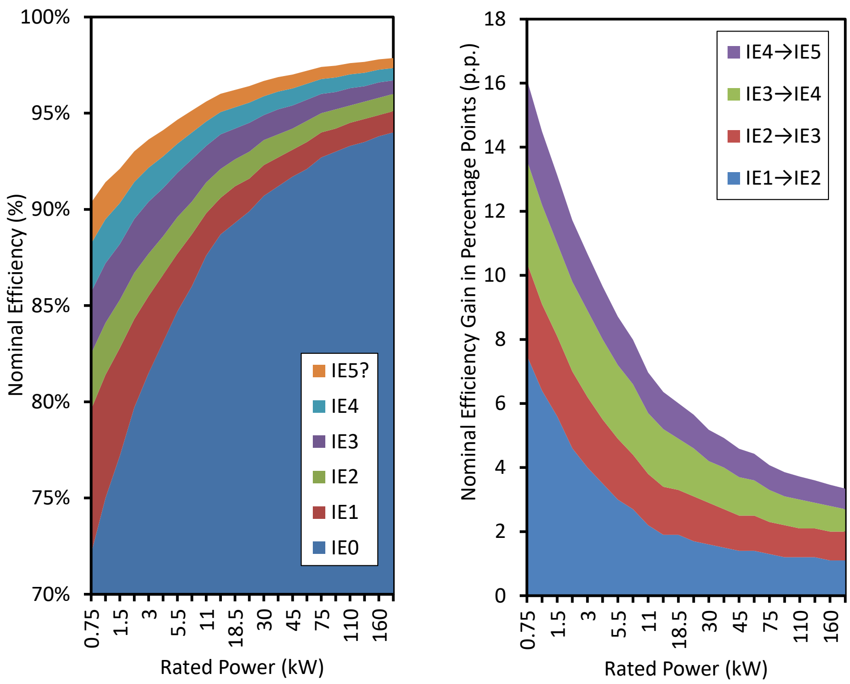


Fig. 3. Motor efficiency classes defined by IEC60034-30-1 standard for 4-pole, 50-Hz, single-speed motors in the 0.75-200 kW power range: (left) nominal efficiency limits; (right) nominal efficiency gain [2, 7, 8].

Typically, it is assumed that SCIMs have a useful lifetime of 12 to 20 years. However, SCIMs older than 40 years can be easily found in the industrial sector (Fig. 4). On average, the motor load factor is 50-60%, but motors with a load factor lower than 20-30% are quite common in the industrial sector (Fig. 5).

Fig. 4. Data on SCIM actual age in the industrial sector, Switzerland, 2013 (4142 data points) [9].

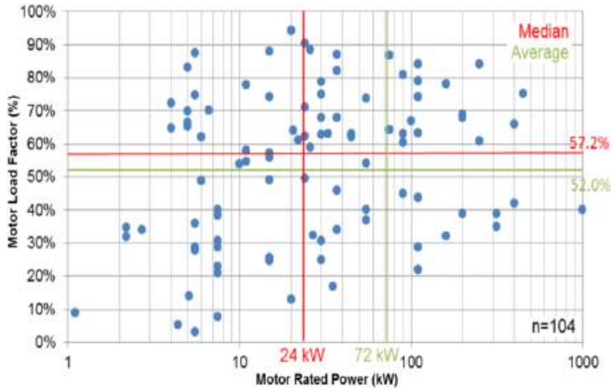


Fig. 5. Data on SCIM load factor in the industrial sector, 2013 (104 data points) [9].

Typically, SCIMs over 4 kW are rewound 2 to 4 times during their useful lifetime [10]. In most cases, a copy of the original winding configuration is made, which is the recommended option if (i) the motor is well sized to the actual maximum load over the entire operating cycle, (ii) the technical knowledge of the technicians performing the rewinding is limited, and/or (iii) the winding configuration has not been incorrectly changed in previous repair/rewinding services [10].

In Figs. 6 and 7, motor list prices from one of the largest motor manufacturers and the repair prices offered by a typical European repair shop, in EUR/kW, are presented. The most significant motor price jump occurs when changing from induction to permanent magnet motor technology. Typically, the repair price is independent of the motor class but depends on the pole number. Therefore, for 4-pole motors, the percent repair price varies from 20 to 40%, decreasing with the efficiency class due to the price increase (Fig. 8). The motor repair service cost is mainly related to the manpower, energy, cooper, resin and bearings cost. But, regarding the copper, in most cases repair shops attenuate the new cooper cost by selling the old used windings copper. This explains the independency of this cost on the motor efficiency class. For new IE3- or IE4-class motors, there is room for an increase in the repair price without losing the cost-effectiveness of the service. If the repair price is maintained, the repair services become more competitive as the motors move to higher efficiency classes. An interesting fact is that the repair cost as a percentage of the new motor price decreases from 2- to 4-pole SCIM because the repair price is the same for these two different models and the price of the new motor increases from 2- to 4-pole motors.

In Fig. 9, the average nominal efficiency and variation in respect to the immediately lower efficiency class can be seen for the 5.5-160 kW power range, 2- and 4-pole motors, using the datasheet efficiency values from a single motor manufacturer. The average nominal efficiency gain is between 1.3% and 2.0%.

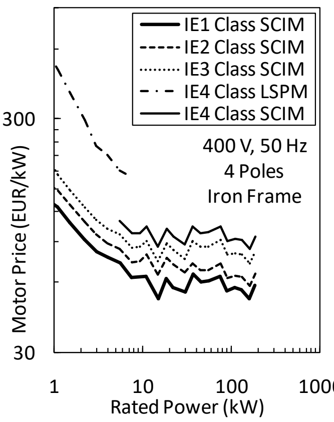


Fig. 6. List prices in EUR and EUR/kW for commercial motors of different efficiency classes (from the same manufacturer).

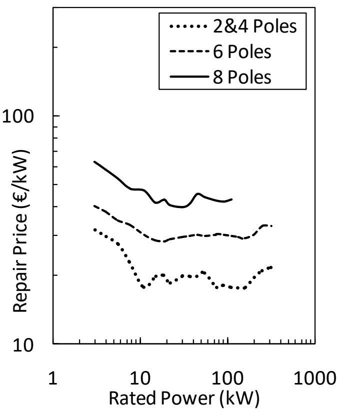
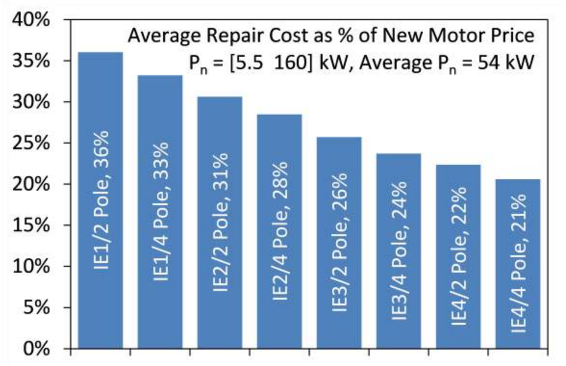


Fig. 7. SCIM repair prices per kW in a typical European repair shop including stator rewinding, standard bearing replacement, rotor dynamic calibration, painting and basic quality control tests.



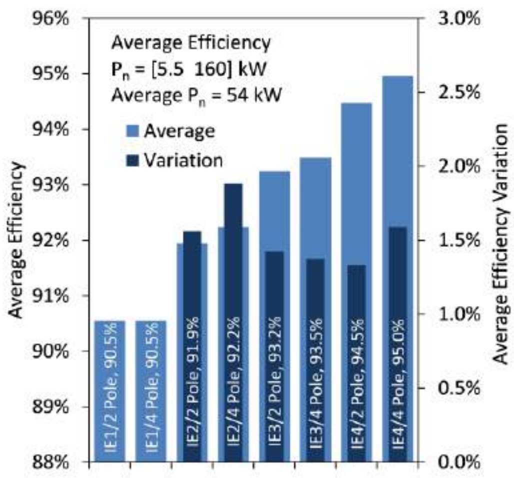
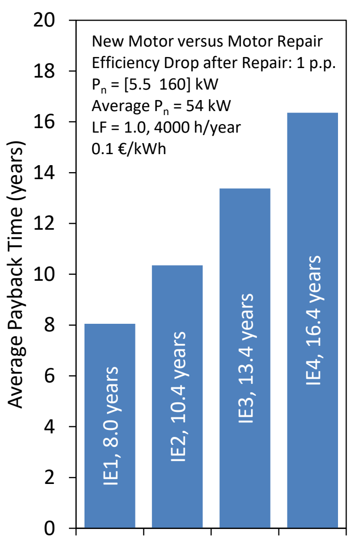


Fig. 8. Average repair cost as a percentage of new motor price.

Fig. 9. Average nominal efficiency and the percent efficiency increase in relation to the efficiency class immediately lower, for the 5.5-160 kW power range.

In Fig. 10, the average payback time for different scenarios is shown, for 4-pole IE1/2/3/4-class motors in the 5.5-160 kW power range, neglecting the possible operating point change (or speed change). Since the payback time to recover the extra cost of the new motor is higher than 3 years in most cases, the repair is an interesting low-cost option for all efficiency classes.

It should be referred that motor repair shops have two significant advantages. Firstly, they perform most of the work manually, not having the large-scale production equipment limitations, particularly concerning the stator winding insertion into the stator core slots, allowing the implementation of more complex winding configurations such as the short-pitched double-layer imbricated windings. Secondly, in most cases, they receive the motor with the damaged winding, having the opportunity to sell the copper for recycling. That is why, independently on the motor efficiency class, they can keep the price of the rewinding service more or less constant. Of course, in the case of the bearings, they should follow the manufacturer specifications and these components are typically more expensive in the premium and super-premium motors.



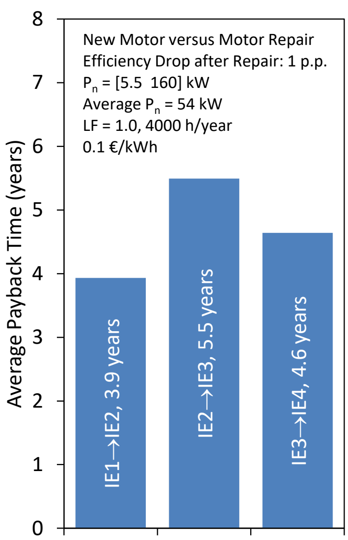


Fig. 10. New motor vs. motor repair average payback time for the 5.5-160 kW power range, considering: (left) the same motor efficiency class; (right) the new motor with a higher efficiency class.

There are several customized aspects that can be specified to the motor manufacturer when potential operating issues can be predicted. However, most of the motor operation problems are identified after buying, during installation, running and after failure. Examples of problems identified after the motor failure are bearing current activity, unbalanced winding overheating or single-phasing, voltage surges/transients and partial-discharge occurrence. During the repair service, the motor can be upgraded and/or equipped with extra components to increase its reliability and efficiency.

For VSD-fed motors, examples of possible improvements during motor repair/rewinding are:

- Installation of a partial faraday shield in the slot openings to reduce the electrostatic coupling between the windings and the rotor;
- Installation of shaft-ground brushes to deviate common-mode currents form the bearings;
- Reinforcement of the winding insulation in the first coil(s) of each phase, including the use of inverter grade magnetic/enameled wire with extra layers and special enamel compounds;
- Upgrade of the insulation system class to accommodate the additional harmonic losses due to the PWM voltage supply;
- Redesign of the stator winding for star connection at rated voltage to avoid homopolar circulating currents in the delta loop.

For line-operated SCIMs, examples of possible improvements during motor repair/rewinding are:

- Reduction of the average length of the end-windings (or coil heads), which does not contribute for the torque production, only contributing the increase of the stator Joule losses, stator winding resistance, leakage reactance and amount of copper used;
- Increase of the slot fill factor, leading to the reduction of the winding resistance and Joule losses, as well as to the improvement of the heat dissipation;
- Potting of the winding heads with thermal conductive polymers/resins to improve heat dissipation. At full-load, a decrease of 22% in the average coil temperature can be obtained or, alternatively, an increase of 16% is possible in the output power at original nominal temperature;
- Replacement of the conventional general purpose bidirectional fans with more efficient unidirectional fans if the motor operates in a single direction (which is typical in fan and pumps);
- Replacement of the existing bearings by low-friction bearings (20 to 30% lower friction losses);
- Upgrade of the insulation system class to extend motor winding lifetime.

Since the largest loss share is associated with the Joule losses in the stator winding (Fig. 11), the improvement of the stator winding by means of an optimized redesign is an excellent opportunity for the motor user to benefit from a significant efficiency gain in the motor when a repair/rewinding service is required, taking advantage from the fact that, in general, handmade rewinding task has less design limitation/restrictions than those associated with automatic large-scale motor winding processes used by manufacturers. The optimizations can involve shortening the winding head length, increasing the slot fill factor, reducing the space harmonic content of the magnetomotive force (MMF), and/or adapting the fundamental flux to the motor actual load. The latter possibility (optimized rewinding [11, 12]), may allow converting a strongly oversized IE1-class SCIM into a well-sized IE5-class SCIM, as shown in Fig. 12, and, at the same time, improving significantly the power factor.

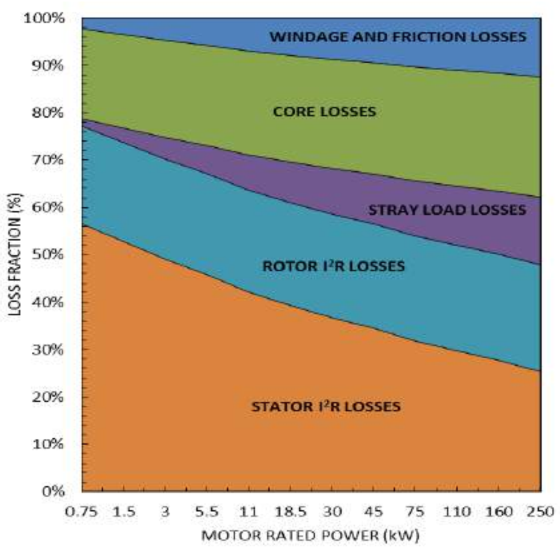


Fig. 11. Typical SCIM loss fraction as a function of the motor rated power [13].

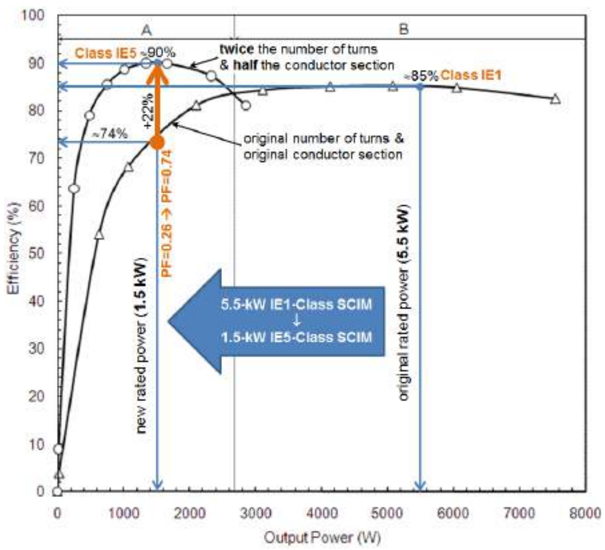


Fig. 12. Converting a strongly oversized IE1-class SCIM into a well-sized IE5-class SCIM, by means of adapting the fundamental magnetizing flux.

2. Software for Motor Winding Design

In order to facilitate the (re)design process of the motor stator windings and to help repairers/rewinders improving the motor efficiency, a software tool was developed in 2004, named BobiSoft [14]. This software tool is very easy to use and integrates a unique computing algorithm that simplifies the original winding improvement or change process (Fig. 13). It helps the user to quickly, easily and accurately design an optimized motor winding, computing key stator winding parameters such as MMF space harmonics and total distortion, wire length, copper weight, electric resistance, Joule losses, magnetic flux, current density, slot fill factor, etc.

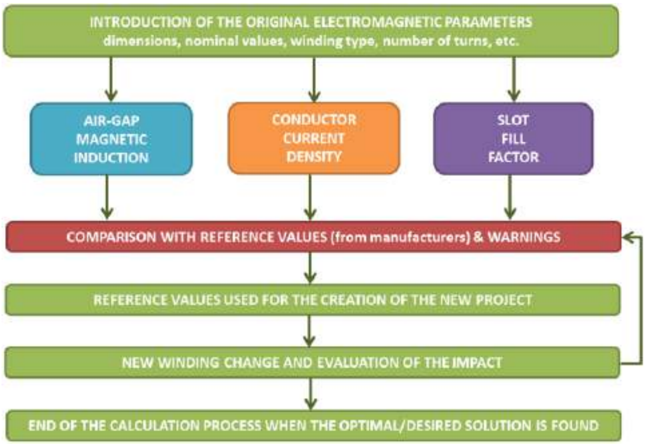


Fig. 13. Computing algorithm to improve or change the original winding design.

Basically, the user has to fill-up the original mechanical and electrical parameters of the motor (Fig. 14 and 15) and, after that, it will be able to change the original winding and check for the improvements in the Joule losses and spatial harmonic distortion of the air-gap MMF. After concluding the new design, the user can print the graphical (circular and planar) or numerical schemes of the coils (Fig. 16 and 17), which can then be printed out and used to help positioning correctly the coils in the stator. Key electrical and magnetic data is computed and presented immediately for both the original and new windings (Fig. 18). A section for additional information on the rewinding/repair service is also offered, in which some quality control information and photos can be saved (Fig. 19).

Design procedures that take hours can be done within a few minutes. Moreover, there is a section for the core loss test that performs all the required calculations. Each project/design can be saved as a separate file (*.bob), which can be attached to e-mails, facilitating the stator winding technical information/data exchange and organization/standardization, promoting an easier and error-free data exchange between the professionals dealing with motor repair/rewinding tasks. The automatic reports are an excellent way to show to the clients of repair shops what was actually done in the service and to demonstrate the quality of the provided service.

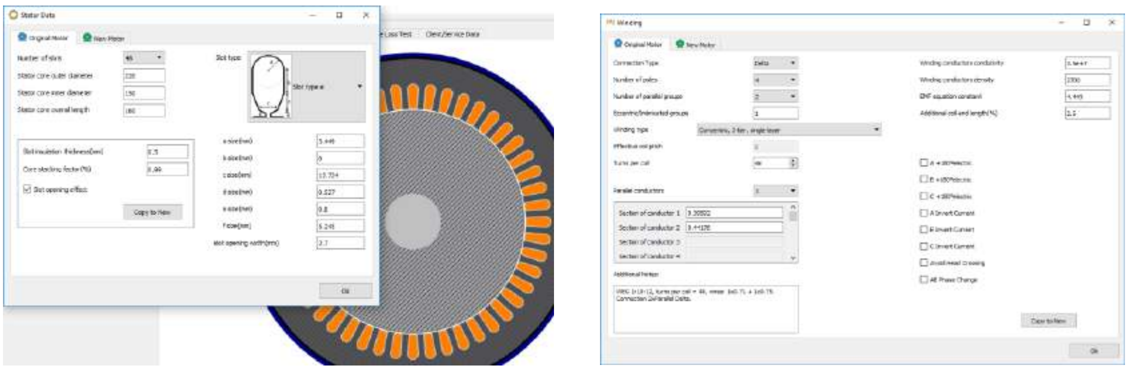


Fig. 14. Section to insert the stator data of the original and new motor/winding.

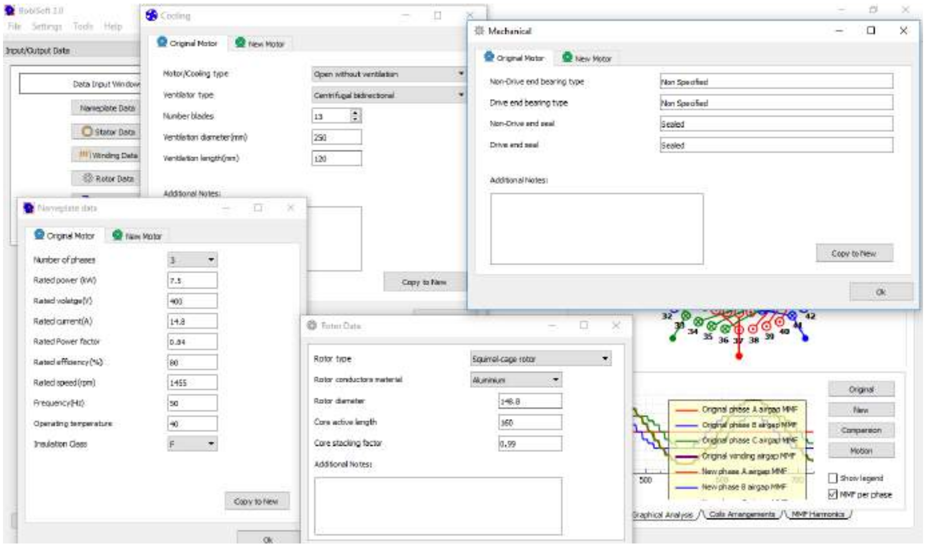


Fig. 15. Section to insert nameplate and mechanical data of the original and new motor.

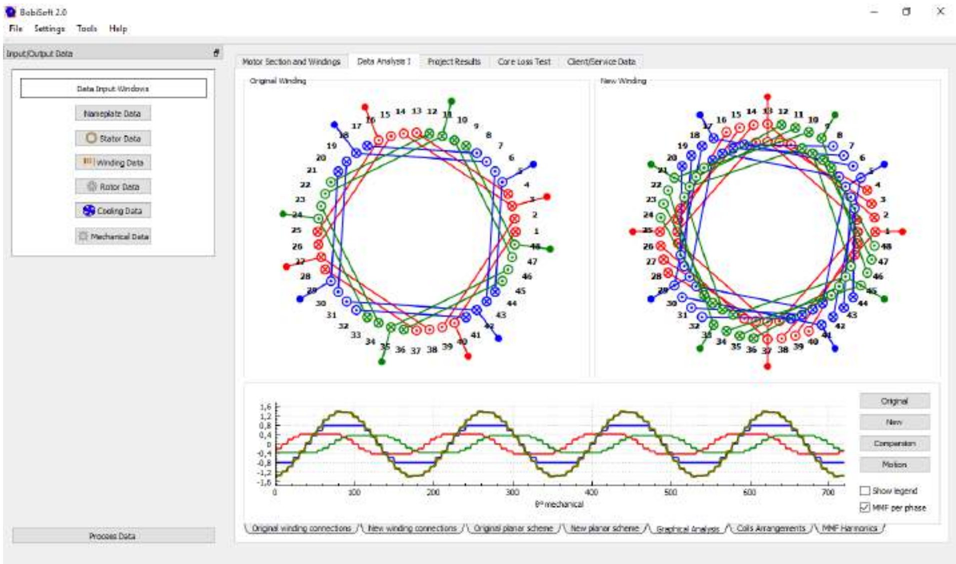


Fig. 16. Circular representation of the windings and of the MMF waveform.

BobiSoft 2.0 can handle windings for stator cores with up to 180 slots and offers 9 different automatically-generated winding types (Fig. 20), 6 single-layer and 3 double-layer windings, as well as fully-editable single- and double-layer windings, where the user is able to define the position and number of turns of each coil in each phase. It also allows designing two-phase windings for single-phase motors, as well as converting three-phase to two-phase windings and vice-versa.

This new version of BobiSoft offers extra and improved functionalities, namely, new and simpler user interface, 2D graphical representation of the stator core section, improved winding schemes/diagrams (circular scheme has the orientation of the coil and planar scheme has the number of winding parallel groups along with their connection to the motor terminals and the heads are fully represented), improved design of the MMF in the airgap and free winding editor (where the user can customize the winding design, with variable number of turns per coil; fractional windings can also be implemented).

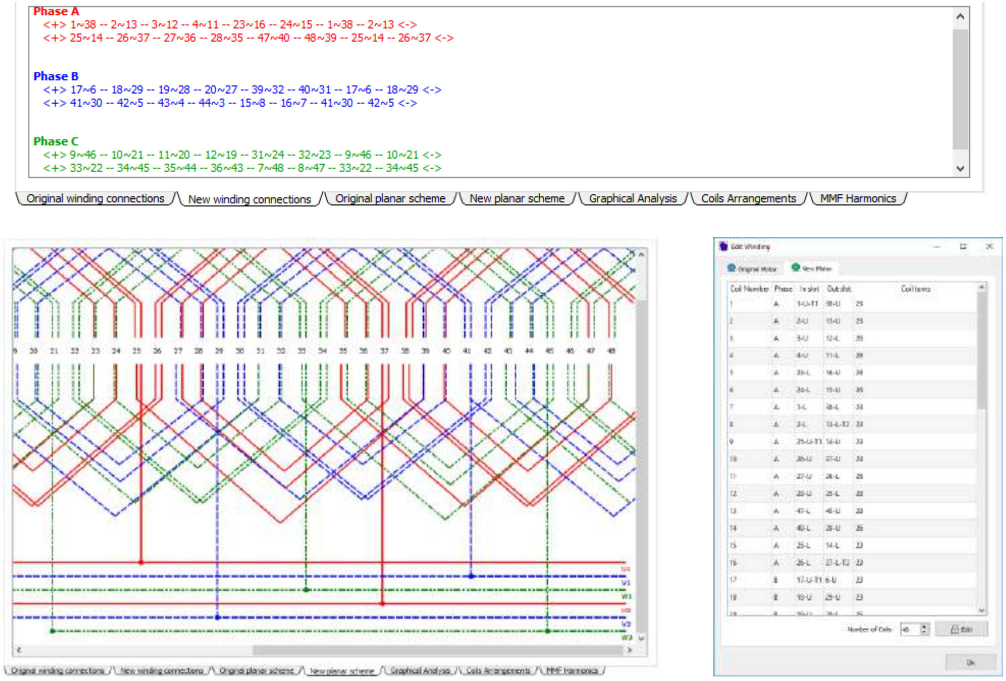


Fig. 17. Numerical and planar representation of the windings and coils.

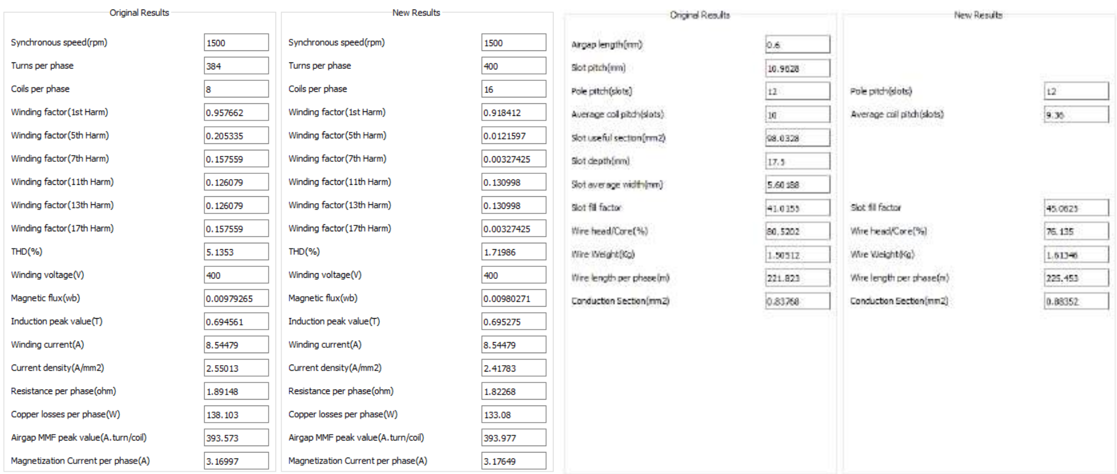


Fig. 18. Display of the computed data associated with the original and new winding.

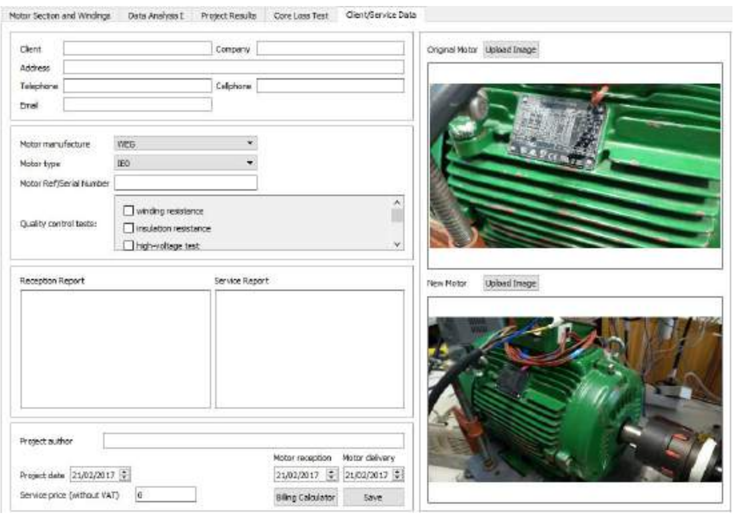


Fig. 19. Section to insert additional information photos associated with the repair/rewinding service.

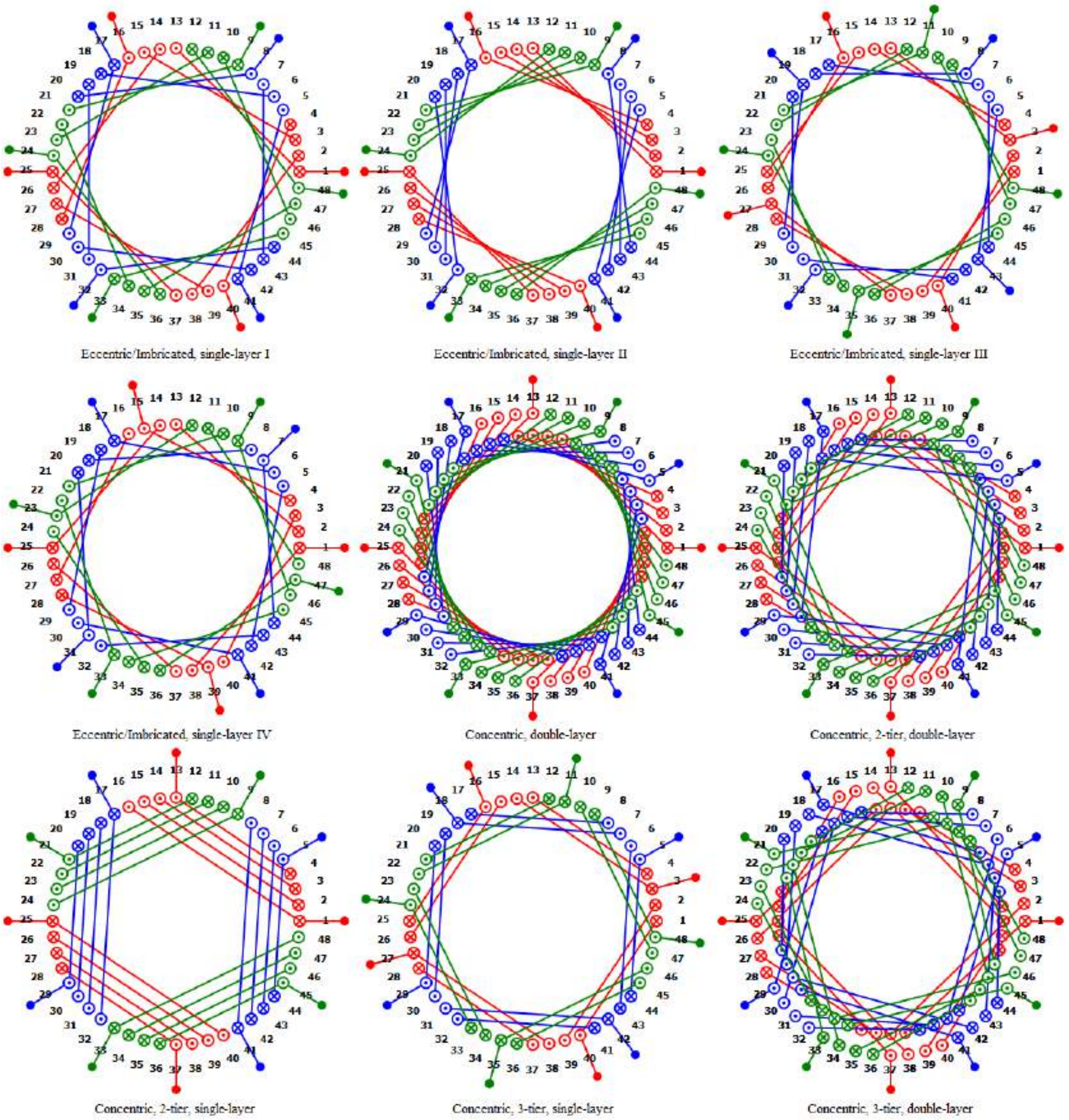


Fig. 20. The nine different automatic winding configurations available in BobiSoft.

An innovative and very useful feature of BobiSoft 2.0 is the automatic winding optimization tool (Fig. 21) to determine separately or simultaneously (combined solution) the best coil pitch in double-layer windings and the best number of turns of each coil in concentric windings, maintaining, if desired, the product of the fundamental winding factor by the total phase turns constant (in order to avoid changing the fundamental flux and, thus, the electromagnetic torque developed by the motor). In the case of double-layer imbricated/eccentric windings, only the coil pitch is optimized (it is assumed the same number of turns for all coils). Basically, the software evaluates all the eligible combinations (using advanced parallel processing techniques) and identifies the one minimizing the total space harmonic distortion of the MMF. As far as the authors know, this is the only software in the market offering this feature/tool.

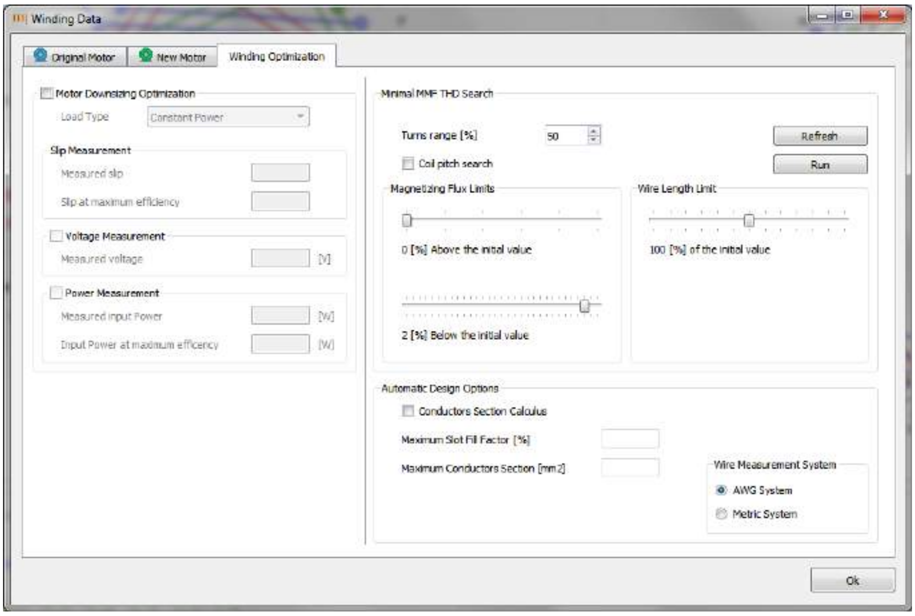
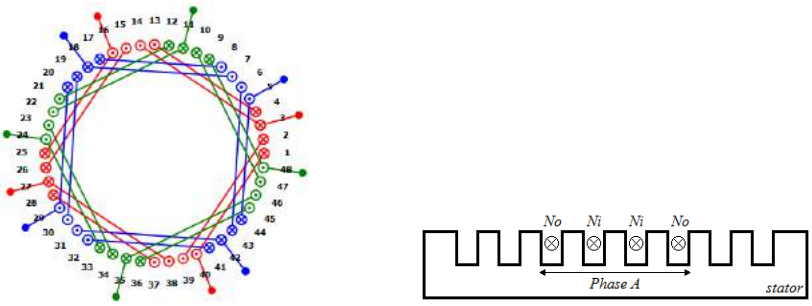


Fig. 21. Winding optimization window of BobiSoft.

3. Application Examples

In this section, some stator winding optimization examples are presented.

As a base case, the typical stator winding configuration used by one of the largest motor manufacturers in three-phase, 400-V, 7.5-kW, 4-pole SCIMs of classes IE1, IE2, IE3 and IE4, is considered. The 48-slot, concentric, single-layer stator winding of these motors only differs in the phase turns and section of the conductors. The respective winding configuration generated with BobiSoft is shown in Fig. 22a.



(a) (b)

Fig. 22. Concentric, single-layer, 3-tier, stator winding configuration (original): (a) circular scheme; (b) identification of inner and outer coils.

In single-layer windings, the spatial harmonic distortion of the magneto-motive force (MMF) is significantly affected by the number of stator slots per pole. In general, the lower the number of slots per pole is, the higher the MMF harmonic distortion will be. In this type of winding, the coil pitch cannot be shortened. Hence, the only possibility to improve the MMF spatial distribution is by means of changing the number of turns of each coil individually.

Since the original winding has 4 slots or coil sides per pole, there are four degrees of freedom to modify the MMF waveform. However, if the odd symmetry of the MMF waveform is to be maintained, there are only two degrees of freedom. Thus, the two coil sides of a pole can be combined in pairs in respect to their distance from the pole center, as represented in Fig. 22b, namely, two inner coil sides (denoted by N_i) and, two outer coil sides (denoted by N_o). For example, considering one pole of *Phase A*, coils 1-40 and 4-13 are the outer coils and coils 2-39 and 3-14 are be the inner coils.

Considering that the fundamental per-phase magnetic flux is to be kept equal to the one produced by the original winding and the fundamental winding factor does not change significantly, the total number of phase turns has to be equal to that of the original winding. As a result, adding 1 turn in the outer coils implies subtracting 1 turn in the inner coils. Applying this design strategy iteratively, the best coil turn combination can be found. In Fig. 23, the evolution of the MMF space harmonics and total harmonic distortion (THD) as a function of the turn difference is shown. The original winding has 48 turns per coil, which is the base case (turn difference equal to zero). As it can be seen, it is not possible to reduce simultaneously all harmonics with this strategy. The spatial THD is minimized for a turn difference of 3.

The fundamental winding factor slightly decreases with the crescent number of turns in outer coils (for the minimum spatial THD point, it decreases less than 0.5% in relation to the original case). Therefore, when the best combination is found, an adjustment of the total number of turns per phase in order to have the original magnetic flux may be required. This is an example that demonstrates how single-layer concentric windings can be improved just by properly adjusting the number of turns of each coil, following a simple rule, i.e., iterative symmetrical turn number change.

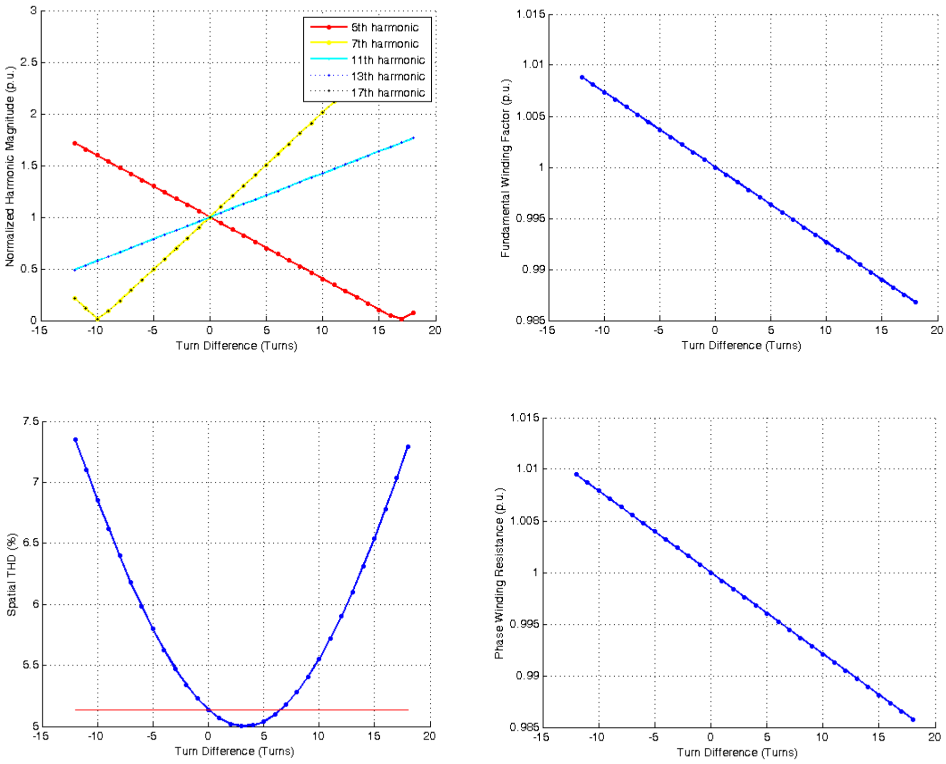
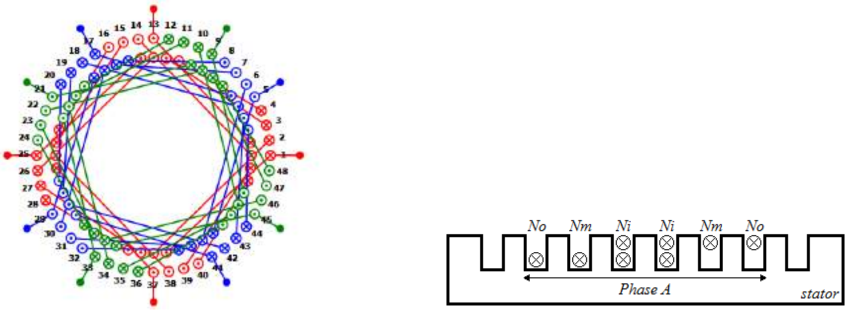


Fig. 23. MMF space harmonics (normalized in relation to the fundamental) and THD as a function of the turn difference, for a 48-slot, 48-turn/coil, concentric, single-layer winding.

It should be noted that the reduction of the 5th spatial harmonic (negative sequence) of the MMF contributes to the reduction of the rotor harmonic losses. The reduction of the 7th spatial harmonic (positive sequence) is important to attenuate the respective perturbation in the accelerating torque for a slip between 1.0 and 0.8.

In the case of double-layer windings, both the coil pitch and the number of turns per coil can be changed (Fig. 24a). In this type of windings, there is an optimal coil pitch which minimizes the spatial THD of the MMF. In Table I, the MMF space harmonic content for different coil pitches is presented. A coil pitch of 10 slots minimizes the MMF space harmonic content, although there is a small decrease of the fundamental winding factor (–3.4%), which can be compensated by adding a few more turns to the winding in order to ensure a fundamental magnetic flux as close as possible to original. From this point, it is possible to reduce even more the spatial THD of the MMF by also properly changing the number of turns of every single coil of this winding, as it was done for the single-layer winding case. In this case, the outer coil sides (with N_o turns) and inner coil sides (with N_i turns) are adapted (Fig. 24b). N_m is kept constant (equal to the original). The effect of these two strategies combined is presented in Fig. 25. Similarly to the result obtained for the single-layer case, the fundamental term of the MMF is slightly reduced when the turn difference increases, so to keep the magnetic flux as much equal as possible to the one of the original winding, the total number of turns may have to be properly adapted.



(a) (b)

Fig. 24. Concentric, double-layer, 3-tier, stator winding configuration: (a) circular scheme; (b) identification of inner and outer coils.

Table I
Fundamental and harmonic winding factors for different coil pitches.

Coil pitch (in slots)	12	11	10	9	8
k_{W1}	0.95766	0.94947	0.92503	0.88476	0.82936
k_{W5}	0.20534	0.16290	0.05314	0.07858	0.17783
k_{W7}	0.15756	0.09592	0.04078	0.14557	0.13645
k_{W11}	0.12608	0.01646	0.12178	0.04825	0.10914

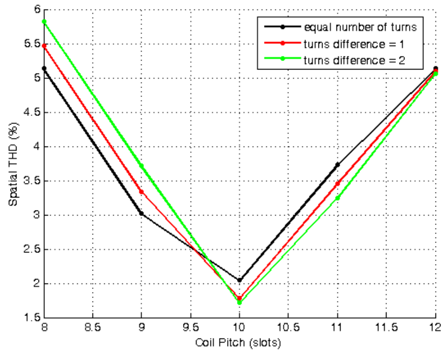


Fig. 25. MMF spatial THD as a function of the coil pitch for a 48-slot, 48-turn/coil, eccentric, double-layer winding.

Two additional winding optimization examples, using two different strategies, are analyzed next.

In first place, the winding of a commercial IE1-class, 4-pole SCIM has been optimized, being the results presented in Table II.

Considering Fig. 26 as reference, the coil distribution for Case 2 is N_0=13 turns, N_1=25 turns, N_2=36 turns and N_3=22 turns. In Fig. 27, the MMF waveforms for the Cases 0 and 2 are presented, evidencing the much better waveform of the MMF spatial distribution of the optimized winding. The spatial THD decreased from 8.046% to 5.909%. The coil position and number of turns of the optimized winding are presented in Fig. 28.

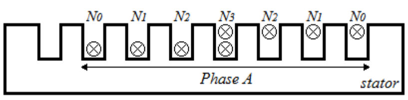


Fig. 26. Coil side distribution in the optimized double-layer winding.

Table II
Optimization of the Original Stator Winding of an IE1-Class SCIM.

Case	**0**	**1**	**2**
	Original Winding	Coil Pitch Optimization	Coil Pitch & Turns Optimization
Winding Type	Concentric, Single-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier
Average Coil Pitch (slots)	10.0	9.50	9.40
Slot Fill Factor (%)	41.02	42.72	41.02 [(1)]
Head to Slot Wire Ratio (%)	80.52	77.09	76.38
Wire Weight (kg)	1.51	1.54	1.47
Wire Length (m/phase)	221.82	226.68	216.74
Conduction Section (mm^2)	0.396+0.442	0.396+0.442	0.396+0.442
Wire Resistance per phase (Ω)	1.891	1.933	1.848
Turns per phase	384	400	384
$\mathbf{k_{w1}}$	0.95766	0.92503	0.91267
$\mathbf{k_{w5}}$	0.20534	0.05315	0.00494
$\mathbf{k_{w7}}$	0.15756	0.04078	0.00234
$\mathbf{k_{w11}}$	0.12608	0.12178	0.00328
$\mathbf{k_{w13}}$	0.12608	0.12178	0.00328
$\mathbf{k_{w17}}$	0.15756	0.04078	0.00234
THD (%)	8.046	6.291	5.909
Magnetic Flux (Wb)	0.00979	0.00973	0.01027
Current Density (A/mm^2)	2.55	2.55	2.55
Winding Joule Losses (W/phase) [(2)]	138.1	141.1	134.9
Airgap MMF Peak Value (A.turn/coil)	393.6	391.2	413.0

[(1)] Highest fill factor higher than the original. Some slots have lower slot fill factor.
[(2)] Considering the nominal current.

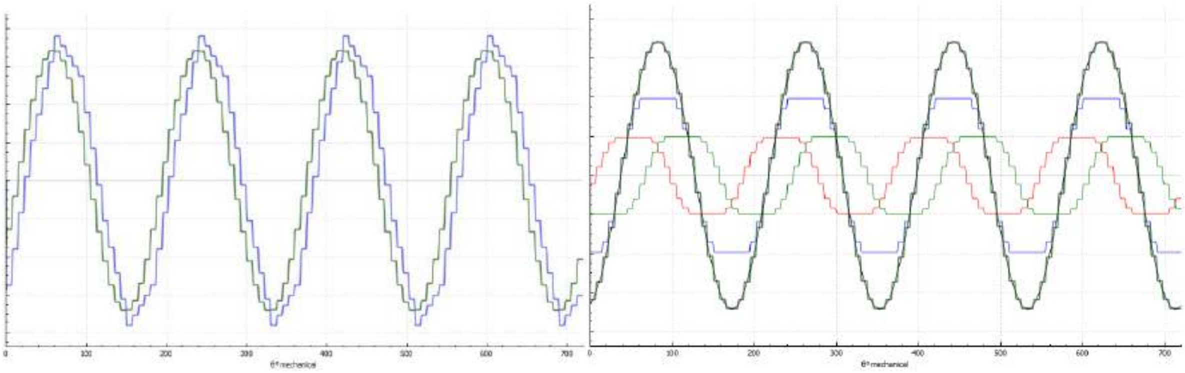


Fig. 27. MMF waveform: (left) comparison between original (in blue color) and new (in green color) winding; (right) new winding pulsating fields.

Coil Number	Phase	In slot	Out slot	Coil turns
1	A	1-U-T1	37-L	22
2	A	2-U	12-L	36
3	A	3-U	11-L	25
4	A	4-U	10-L	13
5	A	22-L	16-U	13
6	A	23-L	15-U	25
7	A	48-L	38-U	36
8	A	1-L	13-L-T2	22
9	A	25-U-T1	37-U	22
10	A	26-U	36-L	36
11	A	27-U	35-L	25
12	A	28-U	34-L	13
13	A	46-L	40-U	13
14	A	47-L	39-U	25
15	A	24-L	14-U	36

Coil Number	Phase	In slot	Out slot	Coil turns
16	A	25-L	13-U-T2	22
17	B	17-U-T1	5-L	22
18	B	18-U	28-L	36
19	B	19-U	27-L	25
20	B	20-U	26-L	13
21	B	38-L	32-U	13
22	B	39-L	31-U	25
23	B	16-L	6-U	36
24	B	17-L	29-L-T2	22
25	B	41-U-T1	5-U	22
26	B	42-U	4-L	36
27	B	43-U	3-L	25
28	B	44-U	2-L	13
29	B	14-L	8-U	13
30	B	15-L	7-U	25

Fig. 28. Position and number of turns of the coils of the new optimized winding.

In second place, the winding of a commercial IE4-class, 4-pole SCIM has been optimized, being the results presented in Table III. It should be referred that the simultaneous optimization of both coil pitch and number of turns is performed automatically by BobiSoft in a few seconds.

Considering Fig. 26 as reference, the coil distribution for Cases 2 and 3 is N_0=7 turns, N_1=13 turns, N_2=18 turns and N_3=11 turns. The only difference between Cases 2 and 3 is the conduction section, which has a direct impact in the slot fill factor and winding resistance.

The optimization strategy used in Cases 2 and 3 leads to a lower head to slot copper ratio, which is an advantage.

In Fig. 29, the MMF waveforms for the Cases 0 and 3 are presented, evidencing the much better waveform of the MMF spatial distribution of the optimized winding. The spatial THD decreased from 8.046% to 5.916%. The coil position and number of turns of the optimized windings (Cases 2 and 3) are presented in Fig. 30.

In Fig. 31, the approximate electromagnetic torque curve for the IE4-class SCIM, considering the effect of 5th- and 7th-order space harmonics of MMF, is presented for Cases 0 and 3.

The obtained results, either for the IE1- or IE4-class motor windings may lead to an increase of the motor efficiency particularly due to the reduction of the space harmonics and its influence on the rotor losses. A further reduction in the stator Joule losses may be obtained if the coil heads are shortened by means of reducing its average distance to the stator core.

Table III
Optimization of the Original Stator Winding of an IE4-Class SCIM.

Case	**0**	**1**	**2**	**3**
	Original Winding	Coil Pitch Optimization	Coil Pitch & Turns Optimization	Coil Pitch & Turns Optimization
Winding Type	Concentric, Single-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier	Concentric, Double-Layer, 3-Tier
Average Coil Pitch (slots)	10.0	9.50	9.34	9.34
Slot Fill Factor (%)	47.17	53.33	55.99 (1)	49.18 (1)
Head to Slot Wire Ratio (%)	66.09	63.75	63.03	63.03
Wire Weight (kg)	6.94	7.73	8.08	7.10
Wire Length (m/phase)	128.35	143.05	134.2	134.2
Conduction Section (mm^2)	4x0.5027	4x0.5027	4x0.5027+1x0.2299	3x0.5027+2x0.2299
Wire Resistance per phase (Ω)	1.071	1.194	1.005	1.144
Turns per phase	**184**	**208**	**196**	**196**
k_{w1}	0.95766	0.92503	0.91010	0.91010
k_{w5}	0.20534	0.05315	0.01121	0.01121
k_{w7}	0.15756	0.04078	0.00067	0.00067
k_{w11}	0.12608	0.12178	0.00159	0.00159
k_{w13}	0.12608	0.12178	0.00159	0.00159
k_{w17}	0.15756	0.04078	0.00067	0.00067
THD (%)	8.046	6.291	5.914	5.914
Magnetic Flux (Wb)	**0.0102**	**0.0094**	**0.0101**	**0.0101**
Current Density (A/mm^2)	4.135	4.135	3.711	4.225
Winding Joule Losses (W/phase) (2)	74.0	82.5	69.5	79.1
Airgap MMF Peak Value (A.turn/coil)	336.7	308.4	440.7	332.6

(1) Highest fill factor higher than the original. Some slots have lower slot fill factor.
(2) Considering the nominal current.

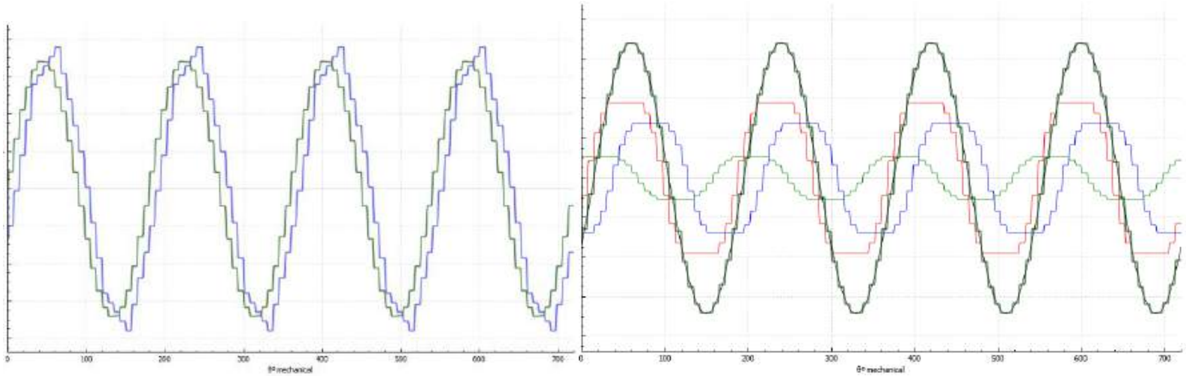
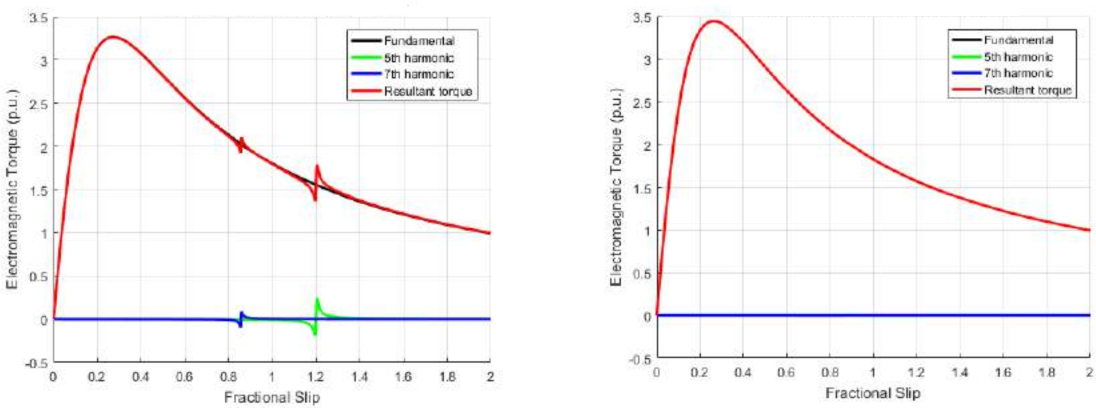


Fig. 29. MMF waveform for the IE4-class motor winding: (left) comparison between original (blue trace) and new optimized winding (green trace; Case 3); (right) new optimized winding (Case 3) pulsating phase MMF.

Coil Number	Phase	In slot	Out slot	Coil turns
1	A	1-U-T1	37-L	11
2	A	2-U	12-L	18
3	A	3-U	11-L	13
4	A	4-U	10-L	7
5	A	22-L	16-U	7
6	A	23-L	15-U	13
7	A	48-L	38-U	18
8	A	1-L	13-L	11
9	A	25-U	37-U	11
10	A	26-U	36-L	18
11	A	27-U	35-L	13
12	A	28-U	34-L	7
13	A	46-L	40-U	7
14	A	47-L	39-U	13
15	A	24-L	14-U	18
16	A	25-L	13-U-T2	11
17	B	17-U-T1	5-L	11
18	B	18-U	28-L	18
19	B	19-U	27-L	13
20	B	20-U	26-L	7
21	B	38-L	32-U	7
22	B	39-L	31-U	13
23	B	16-L	6-U	18
24	B	17-L	29-L	11
25	B	41-U	5-U	11
26	B	42-U	4-L	18

Coil Number	Phase	In slot	Out slot	Coil turns
23	B	16-L	6-U	18
24	B	17-L	29-L	11
25	B	41-U	5-U	11
26	B	42-U	4-L	18
27	B	43-U	3-L	13
28	B	44-U	2-L	7
29	B	14-L	8-U	7
30	B	15-L	7-U	13
31	B	40-L	30-U	18
32	B	41-L	29-U-T2	11
33	C	9-U-T1	45-L	11
34	C	10-U	20-L	18
35	C	11-U	19-L	13
36	C	12-U	18-L	7
37	C	30-L	24-U	7
38	C	31-L	23-U	13
39	C	8-L	46-U	18
40	C	9-L	21-L	11
41	C	33-U	45-U	11
42	C	34-U	44-L	18
43	C	35-U	43-L	13
44	C	36-U	42-L	7
45	C	6-L	48-U	7
46	C	7-L	47-U	13
47	C	32-L	22-U	18
48	C	33-L	21-U-T2	11

Fig. 30. Position and number of turns of the coils of the new optimized winding (Cases 2 and 3).



(a) (b)

Fig. 31. Approximate motor electromagnetic torque curve considering the 5^{th}- and 7^{th}-order space harmonics of MMF: (a) original single-layer winding (Case 0); (b) optimized double-layer winding (Case 3).

4. Conclusions

The presented software tool allows to (re)design and evaluate the performance of complex stator winding configurations in a fast and accurate way (less than 10 minutes, if an automatic winding configuration is used).

The unique tool for simultaneous optimization of the coil pitch and number of turns provided in the latest version of BobiSoft, can be used to minimize the spatial THD of the air-gap MMF in single- or double-layer concentric windings, for a given fundamental magnetizing flux, offering the opportunity to improve the motor performance during rewinding.

The examples provided with the winding designs of commercial motors of classes IE1 and IE4, clearly demonstrate that even very well designed winding can be slightly improved with this optimizing tool, by searching the best coil pitch and number of turns.

The user can also use this software to downsize the motor in order to increase its efficiency and power factor (optimized rewinding), as well as to evaluate the impact in the stator winding Joule losses and check the feasibility of reducing the coil head length and by increasing the conduction section.

The stator winding design improvement may lead to motor efficiency gains of up to 4% and a much better MMF waveform. In the cases where the motor is strongly oversized, which are quite common, if the stator winding is adapted to the actual motor load, efficiency gains up to 15% may be obtained.

The presented software tool allows saving and exchanging with other users the key technical information of the winding design through an editable electronic file. It also helps organizing in a standard format the technical information associated with each rewinding service. Moreover, technical reports can be generated automatically.

BobiSoft can be used in repair shops, industrial maintenance departments/companies and motor manufacturers for professional purposes and in electrical engineering schools/universities for teaching/training purposes.

In the case of the motor rewinding shops, it may help gross errors in the winding redesign, since automatic alert messages are generated if the typical/recommended values of key parameters, such as current density, induction/flux and/or slot fill factor, are exceed. Moreover, the automatic tool to optimize simultaneously the coil pitch and number of turns allows improving the performance of the motor even if the nominal torque, number of poles, frequency and voltage are to be maintained.

The motor market is moving to premium and super-premium motors, which are inherently more expensive. Since, in general, SCIMs over 4 kW are rewound 2 to 4 times during their useful lifetime, and the repair/rewinding cost is not likely to increase, the percent price in relation to the new motors is nowadays lower and, therefore, such services become more competitive and represent a way to maintain or even increase significantly the motor efficiency by means of an optimized winding redesign. BobiSoft is an excellent software tool for that purpose, requiring only basic knowledge on electric machines to be used effectively.

5. Acknowledgments

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