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A Cost-Oriented Scheme for Reconstruction and Efficient Insulation of Medium- and High-Voltage Stator Coils

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Abstract:

In today's industrial world, it is indispensable to offer a correlated equilibrium between the reconstruction costs of damaged electric motors and desirable of performance characteristics so as to exploit available primary materials. This paper presents a cost-oriented scheme to choose an effective insulation method in reconstructing the medium- and high-voltage stator coils in both vacuum pressure impregnation and resin-rich methods. The insulations required in coil reconstruction include three sections: strand, group and main body insulation. These insulations have specific electrical characteristics and dimensions that limit their use in a specific part of the coil. On the other hand, sometimes of these insulations are not available or it is difficult to get them. Because of this, their prices are constantly changing, and it is very difficult to estimate the cost of materials relatively accurately. In this paper, various designs are produced by combining available insulation from each section. Then, mathematical models will be extracted to check the functional characteristics and costs of renovation materials in the plans. Ultimately, the best reconstruction design, changes in performance characteristics compared to insulations with different specifications is selected and the sensitivity of the cost of the designs to the cost of insulation materials and the effects caused by Remove group insulation is checked. For validation, the results associated with the reconstruction calculations of a damaged realistic 6-kV 535-kW electric motor are presented.

Keywords:

Medium- and high-voltage stator coils, reconstruction costs, performance characteristics, vacuum pressure impregnation, resin-rich.

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1. Introduction

1.1. Motivation

Nowadays, the use of the MV/HV electric induction motors is widely growing in various industrial fields due to its unique and attractive characteristics, such as good performance-to-price ratio, high reliability and easy start-up. (e.g., petrochemical and refinery industries, power plants, etc.) [1], [2]. In equipment-oriented organizations, a significant percentage of operational costs are related to maintenance and repair costs. This number is between 5 and 50 percent in different industries. By managing maintenance and repair costs, increasing profitability for the organization is achieved. The first step in this way is the correct method of calculating maintenance and repair costs. From a techno-economic point of view, although replacing faulty motors with new and efficient one's results in significant energy savings [3], however, since the procurement of these MV/HV electric motors faces many problems such as high prices, transportation difficulties, high time for construction process and international limits, etc.; therefore, replacing a new motor instead of a damaged motor is not economically justified. In addition to this, the maximum efficiency rarely occurs at full load and is in the range of 65% to 90% [4]. The Increase efficiency strategy of the large-scale electric motors can be also efficiently applied in the case of these equipment are properly monitored before damage and rewinding [4]. The issue was previously discussed in the research findings of reference [5] in such a way that only a limited number of electric motors operate continuously at full load. As a consequence, if efficiency calculation is conducted under actual load conditions, some possible modifications including changes in coil dimensions, insulation thickness, etc., can be applied when rewinding a damaged electric motor. In the process of reconstruction of MV/HV stator coils, it is necessary to choose the proper insulation of the strand, group and the main wall. Often, due to some limitations, it is not possible to provide original insulations, and available insulations must be used. This problem causes some changes in performance characteristics. On the other hand, the price of insulation is constantly changing due to economic instability in some countries. Choosing designs that have lower cost of reconstruction materials and have the least changes in the performance characteristics of the electric motor will greatly help the reconstruction companies of electric

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machines.

1.2. Research Background

The most prevalent faults in the MV/HV stators include phase-to-ground, phase-to-phase, and inter-turn short-circuits [6], [7], [8]. Further, extensive investigations conducted by authors of [9] indicate that approximately 36 to 45% of electric motor failures are attributed to stator and rotor winding. If inter-turn short-circuit of stator coils is not detected quickly, it can become a severe damage to the respective electric motor [10]. On the other hand, according to a five-year statistical analysis conducted in a prominent Iranian company in the realm of reconstruction of the MV/HV electric motors, it was found that most damages are associated with rotor-stator touch, inter-turn short-circuit, and phase-to-ground short-circuit within the stator windings. This issue is displayed in Fig. 1. It is well known that the life of a stator winding is limited most often by its electrical insulation and the end-of-life failure causes of stator windings are mainly associated with their insulation [11]. With that in mind, selection of reconstruction method and specifying insulation materials are counted as two significant factors within the reconstruction process of the MV/HV stator coils. It is noteworthy that, within this process, it may be necessary to replace the required insulation materials with available similar insulations due to different reasons such as (i) insufficient knowledge regarding the insulation characteristics used in genuine coils; (ii) long elapsed time from the electric motor construction; (iii) the upgrade of new insulation materials; and, (iv) the secrecy of the construction technology, or international trade bounds, etc. This issue may overshadow different electrical parameters and functional characteristics of the MV/HV electric motors. As a result, selecting well-suited construction methods of the MV/HV stator coils and insulation materials can bring about desirable design plans with minimum costs. Ref. [12] expresses approximately 60% of the overall losses, such as copper and core losses, occur in stator; and therefore, increasing the weight of the stator winding is recommended to diminish copper losses. As a technical result, the designed electric motors with an additional 25% copper demonstrate superior functionality. According to [13], current density distribution is a function of the height and thickness of conductors in slots.

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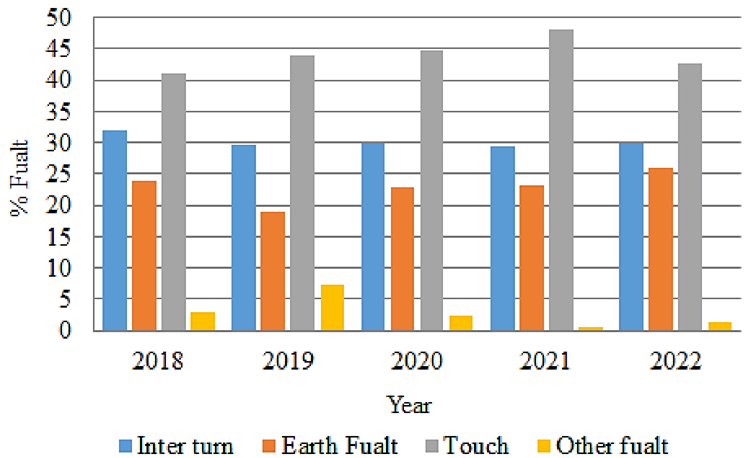

Fig. 1. Distribution of fault types in MV/HV electric motors.

Based on [14], the insulation systems of windings are considerably more intricate in MV/HV electric motors, with a paramount emphasis on insulation. Ref. [15] presents that the lifespan of the stator winding in the MV/HV electric motors is contingent upon the durability of the insulation employed in their coils. On the basis of this reference, during the coil reconstruction process, two principal methods are dominant. The first method is the resin-rich (RR) method, employing pre-impregnated resin tape, while the second one is the vacuum pressure impregnation (VPI) method, utilizing dry resin-impregnated tape through a vacuum and pressure process.

1.3. Novelty

According to the existing literature, this paper, aim to investigate the performance characteristics and material costs for coil reconstruction of the MV/HV electric motors by using both the VPI and RR methods and extracting cost estimation models. To do so, an induction motor with a power of 535 kW and a voltage level of 6 kV has been selected as a case study. Coil construction has been investigated by the VPI and RR methods. Considering that in the process of construction of the coil, the strand and the group of strands and the main wall of the coil must be insulated separately, so for each of the above parameters, different insulations from the products of ISOVOLTA great Company have been investigated. Assuming the limited availability of insulation types for rewinding an MV/HV stator, two types of insulation for the conductor, two types of insulation for the grouping and three types of insulation are taken into account for the insulation of the main wall. According to these choices, twelve proposed

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designs for the VPI and twelve designs for the RR will be presented. On the other hand, due to economic instability in some countries, the price of insulating materials is always fluctuating. In this paper, considering the range of price changes in one year and creating a price range for insulation, a large number of cost scenarios are defined for each design. The user can choose the best decision to choose the stator reconstruction method in accordance with the desired performance characteristics and the closest scenario to the price of insulation at any time. In fact, from a new point of view, providing the characteristics and coil reconstruction costs via different insulation materials, enable users to select one of the best proposed designs for the rewinding process in the MV/HV electric motors according to existing priorities.

1.4. Paper Organization

This paper is structured into six sections. Section II denotes the structure of the MV/HV stator coils. Section III represents the influence of insulation variations on coil reconstruction and outlines a cost model tailored explicitly for fabricating the MV/HV stator coils. Section IV serves as a case study to investigate a real damaged electric motor's performance and coil reconstruction cost and report a detailed analysis of the results. The concluding remarks are finally given in Section V and references in section VI.

2. Structure of the MV/HV Stator Coils

The most recently, insulation manufacturers produce their production technologies according to new insulations with lower thickness and higher insulation breakdown voltages. With this in mind, in the coil reconstruction process, reducing insulation thickness leads to an increased cross-sectional area of the conductors and giving rise to both reduced copper losses and enhanced electric motor efficiency. Ref. [16] Obviously demonstrates the feasibility of achieving up to a 10% increase in the cross-sectional area of conductors is available for 90% of the evaluated electric motors. This design enhances electric motor efficiency and facilitates the design and manufacturing of the E4-class motors. Insulation raw materials and manufacturing technology serve to categorize insulations into various thermal classes. Furthermore, the insulation breakdown voltage varies with different thicknesses. The IEC 60034-15 standard proposes that the breakdown voltage of total insulation materials employed for coil reconstruction must exceed the impulse test voltage [17]. Based on the above standard, this test is performed by applying a voltage equivalent to $3*U_n+1$ (kV) to the coil and stator body. The leakage current of the coil to the body should not be higher than the permissible value stated in the IEC 60034-15 standard. To ensure the quality of the construction or reconstruction of the coils, in addition to the impact test, other tests such as the insulation losses test, aging test and inter turn test are carried out. The point to be made here is that the method of performing all these tests is the same for the method of making VPI and RR. But the coil reconstruction method, the insulation employed in the reconstruction process and the quality of the insulation provide different results. In general, achieving this requirement necessitates the application of multiple layers of insulation. In practice, however, when determining the required insulation thickness of a coil, it is essential to consider the manufacturer's requirements in such a way that the combined thickness of conductor insulations, grouping, and main wall should exceed a specified value. In this respect, according to the empirical observations on reconstruction coils with a voltage level of 6 KV and recommendation of ISOVOLTA Company, a thickness of 1.6 mm is recommended. In fact, it is crucial to ensure that the total breakdown voltage of the insulation materials employed in a coil is equal to or greater than the coil withstand voltage. Fig. 2 illustrates the arrangement of insulation layers in the MV/HV coils. In the following, reconstruction of coil in RR and VPI methods are briefly explained.

2.1. VPI Coil Construction Method

To construction coil in VPI method, copper conductors are rolled and annealed to yield the desired cross-sectional area. Afterward, insulation taping is performed on the conductor's body. The number insulation layers are carefully designed with the aim of ensuring to fulfill the inter turn test breakdown voltage outlined in the IEEE 522-2004 standard. After the conductor insulation process, the coil is shaped to attain its final formation by special equipment. Next, the entire length of the coil is sequentially and continuously wrapped with specialized VPI-type insulating tapes to achieve the predetermined insulation thickness. After this, coils assembled in stator slots.

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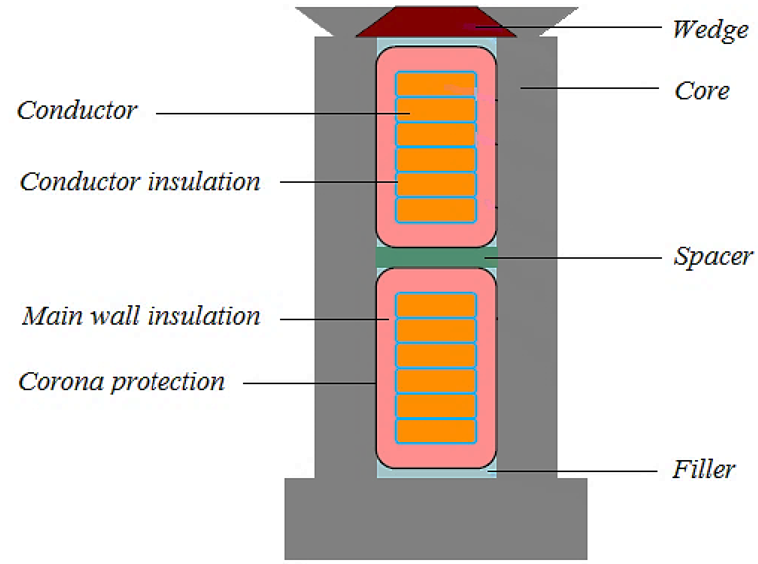

Fig. 2. The components of the MV/HV coils in slot [18].

Then the entire stator assembly necessitates preheating, with the specific duration and temperature dependent on the insulation thickness and component dimensions. The stator is transferred to a vacuum chamber, where hot resin is pumped into an evacuated tank. Following this stage, the resin is injected into the coil by applying air pressure within the chamber for a specified period. Subsequently, the stator is removed from the vacuum tank and transferred to a furnace for resin curing. With this regard, the resin-coated stator is placed inside a furnace with a specified temperature. In this regard, temperature, vacuum pressure, and time may vary depending on the resin type and insulation, as determined by the manufacturer's requirements. Advantages of the VPI method are included: (i) fast Installation; and, (ii) readily available higher class. Disadvantages of the VPI method are also included: (i) difficult to repair, (ii) hard and brittle resin, (iii) difficult to maintain the VPI process, (iv) require to stator rotation during curing; and, (v) require to a large enough VPI vessel.

2.2. RR Coil Construction Method

The conductor is initially enveloped with a predetermined number of insulation layers using suitable insulating tape virtually the same as the VPI method. Next, the insulated conductor undergoes coiling via a coil winding machine. Following this step, coil arms are prepared for the insulation process. the arms undergo an initial insulation process followed by hot pressing. The hot-pressing process entails placing

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the coil arms within adjustable steel molds. These molds are equipped with the predetermined heating elements that facilitate generating necessary heat, allowing for adjustable heat and time parameters. Oil jacks integrated into the lateral and upper mold surfaces enable the simultaneous application of heat and pressure. As the manufacturers' requirements stipulated, the temperature and pressure levels depend on the insulation employed. Afterwards, a tape of thread and glass bandage are applied to wrap the coil front end. The coil is shaped by an automated forming machine; and then, the superficial of its arm is coated with conducting paint so as to reach a constant potential surface. In practice, the designers' recommendations allow employing conducting tape, as an alternative to conducting paint, with careful consideration of their respective thicknesses in the final coil dimensions. To mitigate the corona effect, the bending area of the arm and the coil front end can be also covered with either semi-conductive paint or tape. Advantages of the RR are included: (i) winding in site, (ii) testing at every stage, (iii) high quality impregnation, (iv) fully cured and void free, (v) high dielectric properties, (vi) easier for partial repairs, (vi) on-site insulation; and (vii) improved end-winding bracing systems. Disadvantages of the RR are also included: (i) being two pieces of arm insulation and overhang, (ii) generally has merely insulation class F; and, (iii) requirement expert man with higher competency. Fig. 3 illustrates comparison of the VPI and RR processes [19].

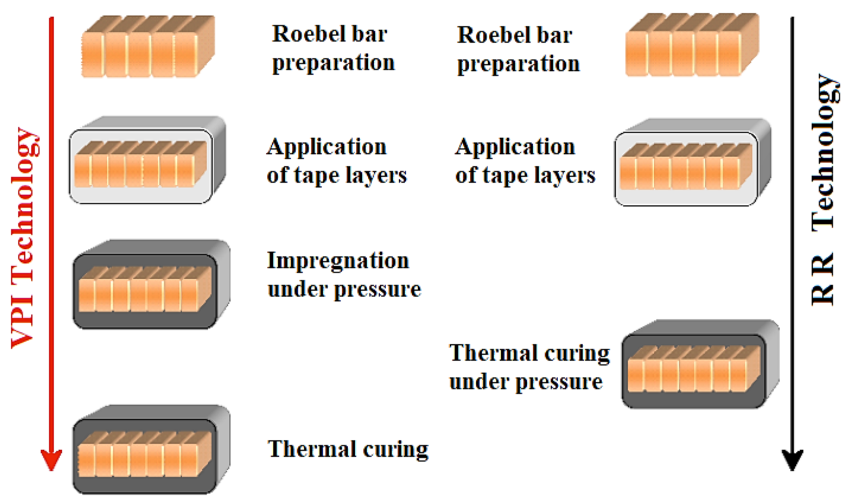

Fig. 3: Comparison of the VPI and RR processes.

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3. Insulation of Coil

By changing the material and thickness of the insulations, some functional characteristics change, and others remain unchanged. Nevertheless, coil production costs usually vary remarkably, especially for the modernization of high and medium voltage stators and the choice of coil production methods. This aspect requires considerable attention; and hence, current study examines the effects of such changes from two perspectives: performance characteristics and cost analysis.

3.1. Performance Characteristics

To examine the influence of insulations with varying specifications on the coil reconstruction process and their consequential impact on electric motor performance characteristics, it is effective to derive the equivalent circuit parameters (See Fig.4). In this figure, R_1 is stator resistance per phase, x_1 is stator leakage reactance per phase, x_m is magnetic resistance, R_2 is rotor resistance and x_2 is rotor leakage reactance per phase transfer to stator. Further, to precisely obtain the equivalent circuit parameters of an electric motor, it is crucial to have comprehensive knowledge of the structural details of the stator and rotor, as well as the coil placement within the stator slots. Calculation of equivalent circuit parameters is presented in the books of electric machine design, which are avoided in this paper [20] [21]. How to place the coil in the stator slot and the rotor bar placement in the rotor slot are depicted in Fig. 5. Computing the stator leakage reactance accurately and sensitivity of the leakage reactance caused by the insulation characteristics change is presented in the equations 1 to 15. (All dimensions of the given parameters are in millimeters).

$$p_1 = \frac{2h_1}{3w_{ss}} \tag{1}$$

$$p_2 = \frac{h_2}{4w_{ss}} \tag{2}$$

$$p_3 = \frac{h_3}{w_{ss}} \tag{3}$$

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$$p_4 = \frac{2h_4}{w_2 + w_{ss}} \tag{4}$$

$$p_5 = \frac{h_5}{w_2} \tag{5}$$

where p_1 is leakage flux factor at coil height, p_2 is leakage flux factor between coils, p_3 is leakage flux factor for filler under edge, p_4 is leakage flux factor for edge and p_5 is leakage flux factor for gap up edge.

$$p_{ec} = 0.34\left(\frac{q}{L}\right).\left(L_{ec} - \left(0.64\beta.\left(\frac{\pi D}{p}\right)\right)\right) \tag{6}$$

where p_{ec} is leakage flux factor overhang, q is slot per phase per pole, L is length of stator, L_{ec} is length of overhang, β is step shortening factor, D is inner diameter of stator, P is number of poles.

$$p_{zg} = \left(\frac{(5g.k_c)/w_2}{5+((4g.k_c)/w_2)}\right).\left(\frac{3\beta+1}{4}\right) \tag{7}$$

$$p_s = p_1 + p_2 + p_3 + p_4 + p_5 + p_{ec} + p_{zg} \tag{8}$$

where p_{zg} is leakage flux factor zigzag, g is gap length, k_c is carter factor and p_s is total leakage flux factor.

$$x_1 = \frac{24\pi.f.n_{ph}^2.L.k_{stac}.p_s}{q.p} \tag{9}$$

where f is frequency, n_{ph} is number of turns per phase, k_{stac} is stacking factor.

$$p_{11} = \frac{d_{sr}}{3w_{sr}} \tag{10}$$

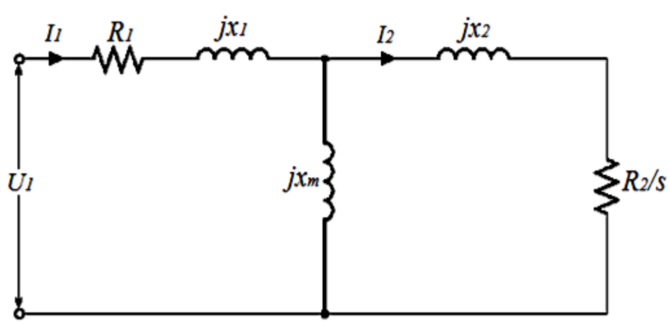

Fig. 4. Equivalent circuit of induction motor.

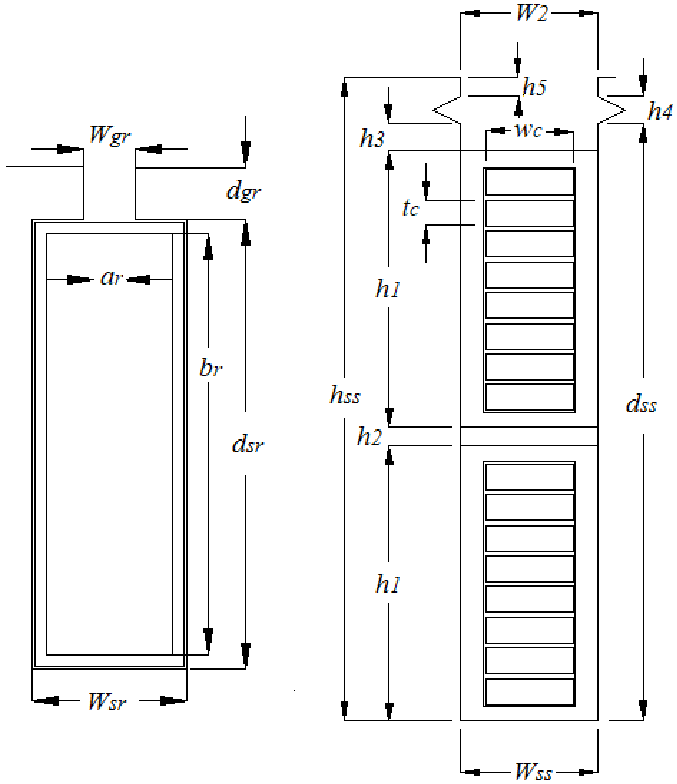

Fig. 5. Rotor slot and stator slot.

$$p_{55} = \frac{d_{gr}}{w_{gr}} \tag{11}$$

$$p_r = p_{11} + p_{55} \tag{12}$$

where p_{11} is leakage flux factor for rotor bar, p_{55} is leakage flux factor for gap up rotor bar and p_r is leakage flux factor of rotor.

$$x_{sr} = \frac{24\pi.f.\mu.L.(n_{ph}.k_w)^2.s_s.p_r}{s_r^2} \tag{13}$$

$$x_{le} = \frac{24(n_{ph}.k_w)^2.(\pi.f.L_{ec})}{sin(\pi.p / s_r)} \tag{14}$$

$$x_2 = x_{sr} + x_{le} \tag{15}$$

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where x_{sr} is leakage reactance of rotor slot, x_{le} is leakage reactance of rotor end ring, k_w is winding factor, S_s is number of stator slot and S_r is number of rotor slot.

3.2. Reconstruction Costs

During coil construction, insulation prices far surpass that of the consumed copper. As a consequence, any variations in the insulation quantity give rise to the corresponding cost changes. Additionally, selecting a coil reconstruction method influences the incurred costs. Thus, this current study separately scrutinizes and models the costs, as follows:

- Cost of copper: The weight of the copper in the stator coils can be determined by calculating the weight of a single coil and multiplying it by the total number of coils used. Field research on rewinding MV/HV stator coils reveal that approximately 3% of the overall coil weight should be allocated for the weight of terminals and stator bridges. Around 2% of the weight should be also considered for copper waste. The total cost of copper can be, then, obtained using Equations (16) and (17).

$$w_{cu} = 1.05(L_{mt}.a_{cu}.\gamma_{cu}.n_{coil}).T_{coil} \tag{16}$$

$$co_{cut} = co_{cu}.w_{cu} \tag{17}$$

  where, w_{cu} is weight of copper, L_{mt} is average length of coil, a_{cu} is surface conductor per phase, γ_{cu} is specific gravity of copper, n_{coil} is number of turns per coil, T_{coil} is total stator coils, co_{cu} is price of copper per kg and co_{cut} is total price of copper.

- Cost of Insulation: Estimating the relatively accurate cost of insulation for coil reconstruction requires calculating the required length of each insulation. The tolerable voltage of insulation is specified by the manufacturing company according to its thickness and material. According to IEC 60034-15 and IEEE 522-2004 standards, the maximum voltage that the total insulation of each strand must withstand is determined. Therefore, to overcome this voltage, the number of insulating layers must be increased. The minimum of insulation layers of each strand is 2 layers.

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Also, in order to determine the number of insulation layers of main wall, according to IEC 60034-1:2017 standard, the maximum voltage that the main wall insulation must withstand is first determined. then considering the electrical characteristics of the insulation, the number of insulation layers of main wall is calculated. In some manufacturing companies, in addition to the mentioned standard, due to the mechanical strength of the coil, they require that the total thickness of the coil insulation is greater than a certain value, which should be considered. The length of conductor and group insulations and the main wall is calculated from simple mathematical equations according to the dimensional characteristics of the coil and insulations, which of presentation have been avoided. Finally, according to equations 18-21 by calculating the insulation length of the strand and group and main wall for all the stator coils and asking for its price, the required insulation cost is calculated. It should be noted that the estimation of insulation of the main wall in the RR method is different for arm and overhang insulation and is calculated separately.

$$VPI : co_i = L_{tc}.c_{cpm} + L_{tg}.c_{gpm} + L_{tsv}.c_{spm} \tag{18}$$

where, co_i is Price of insulation a coil, c_{cpm} is Price of conductor insulation per meter, c_{gpm} is Price of group insulation per meter, c_{spm} is Price of main wall insulation per meter, L_{tc} is Total length of insulating tape of strand, L_{tg} is Total length of insulating tape of group, L_{tsv} is Total length of insulating tape of main wall coil.

$$RR : co_i = L_{tc}.c_{cpm} + L_{tg}.c_{gpm} + L_{tbr}.c_{bpm} + L_{tor}.c_{opm} \tag{19}$$

where c_{bpm} is Price of arm insulation per meter, c_{opm} is Price of overhang insulation per meter, L_{tbr} is Total length of insulating tape of arm, L_{tor} is Total length of insulating tape of overhang.

$$co_{it} = 1.05.T_{coil}.co_i \tag{20}$$

$$co_t = co_{cut} + co_{it} \tag{21}$$

where co_{it} is total price of insulation, co_{t} is total price of material, T_{coil} is total stator coils.

4. Case Study

The current study examines the performance characteristics and costs of coil reconstruction with respect to available insulation. The case study is an asynchronous squirrel cage induction motor with the nameplate specifications listed in Table 1, which is used in the rolling line of steel factory. The dimensional parameters of the stator and rotor according to Fig. 5 are also presented in Table 2. This electric motor needs a complete reconstruction of the coil due to the ring connection in one phase. Fig. 6 shows the stator changing the coil. In both RR and VPI methods, the proposed insulations for conductors and grouping are of two different types of insulation and the main wall insulation is used of three other types of insulation. The number of designs created based on the above insulations is 12, and these proposals are reviewed with single and double strands. In practice, Insulations required in stator coil reconstruction, selected from the ISOVOLTA Company's available products [22]. Table 3 provides some of technical characteristics of consumed insulations and their price. Tables 4 and 5 show the proposed designs of the RR method and VPI method, respectively. Next, using common design calculations for induction motors, equivalent circuit parameters were determined for each design and some performance characteristics such as efficiency, starting current, torque and power factor were compared. Also, changes of price of insulations have been specified in a period of one year. In order to generate a wide range of material cost information over a one-year period, each price change was expanded to 4 parts and the total production scenarios to 65,536. Also, to compare the cost of insulation materials, the minimum, maximum and average cost of all scenarios are shown in Fig.7. Figs. 8 and 9 show the stator resistance, stator reactance and efficiency changes in the proposed designs. Also, the cost of materials was calculated according to the fluctuation of insulation prices, and the designs were compared in different conditions. To calculate costs, the prices of insulations were sourced from online sales websites, and there is a marginal probability of price variations. However, given that the analysis relies on comparing designs, any negligible price variations can be disregarded. Ref. [23] is given an instance online source of

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procuring insulation prices. By comparing the price of each insulation in the cost of materials, the price of main wall insulation and group insulation respectively have the greatest and least impact in estimating the cost of materials in the reconstruction of the coil (Fig. 10). Among 12 designs presented in table 4 with double-stranded, the highest abundance occurred in design number 5 with 22.6% and the lowest frequency in design number 2 with 0.5% (Fig. 11). Also, by removing group's insulation in both VPI and RR methods, the cost of insulation materials is reduced between 19.7% and 29%, and the total cost of materials is reduced between 5.7% and 9% (Fig.12).

Table 1. Rated values of the study machine.

535 kw	6000 V	50 Hz
PF 0.85	64 A	985 RPM
Duty S1	IP 54	Class F

Table 2. Dimensions of the study machine.

Item	**Value**	**Unit**	**Item**	**Value**	**Unit**
D	705	mm	g	1.5	mm
L	660	mm	s_r	86	---
s_s	72	---	d_{sr}	60	mm
h_{ss}	70	mm	w_{sr}	6	mm
w_{ss}	15	mm	d_{gr}	5	mm
w_2	15	mm	w_{gr}	3	mm
t_c	9.50	mm	a_r	25	mm
w_c	2.80	mm	b_r	60	mm
n_{coil}	8	-	Cage	Al	-
R_1	0.34	ohm	h_3	1	mm
h_1	31.5	mm	h_4	3	mm
h_2	1	mm	h_5	2	mm

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Fig. 6: Study machine.

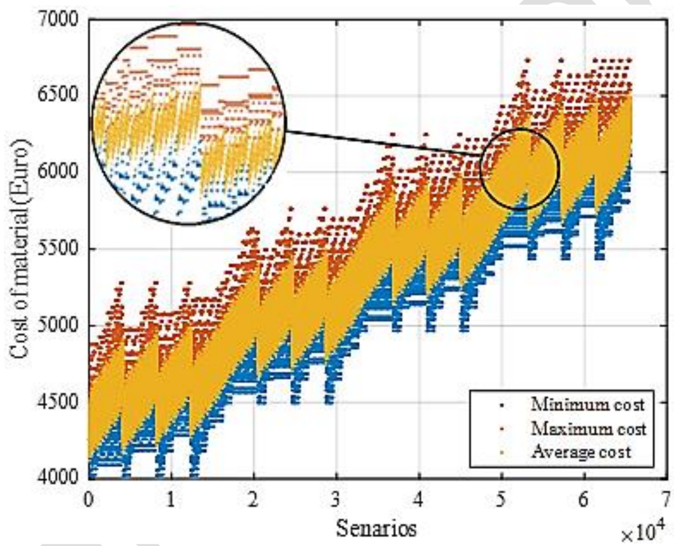

Fig. 7: Minimum, maximum and average cost of 65536 scenarios.

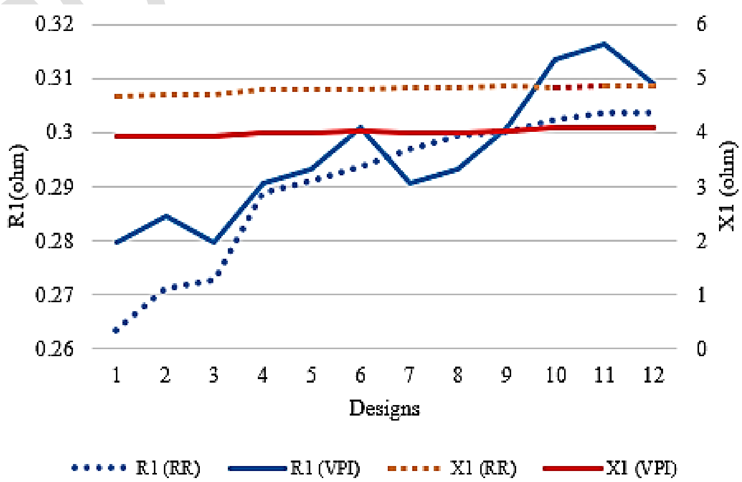

Fig. 8: R1, X1 at the RR & VPI.

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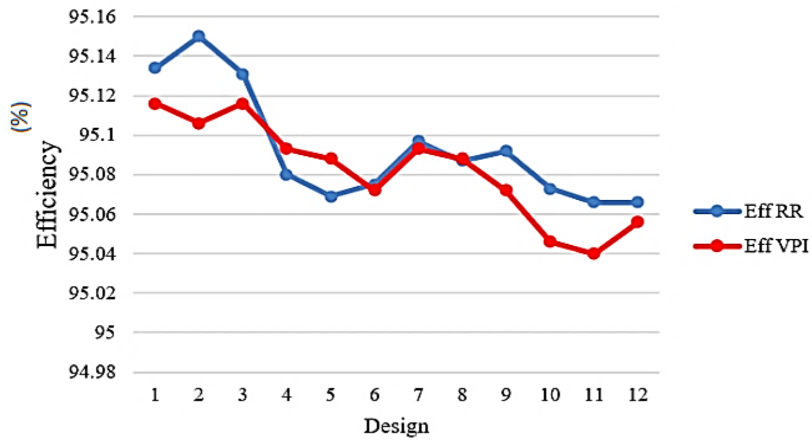

Fig. 9: Efficiency at RR & VPI.

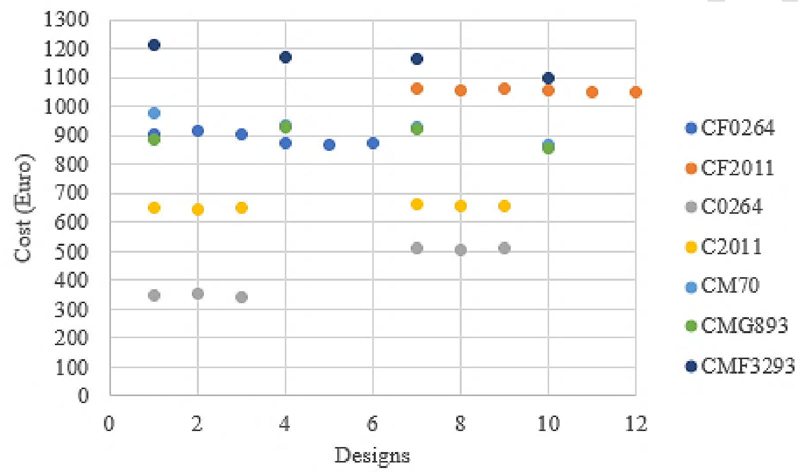

Fig. 10: Price any insulation in total cost.

According to Fig.13 in all proposed designs using the same consumed copper weight, the coil reconstruction material cost in the VPI method surpasses that of the RR method.

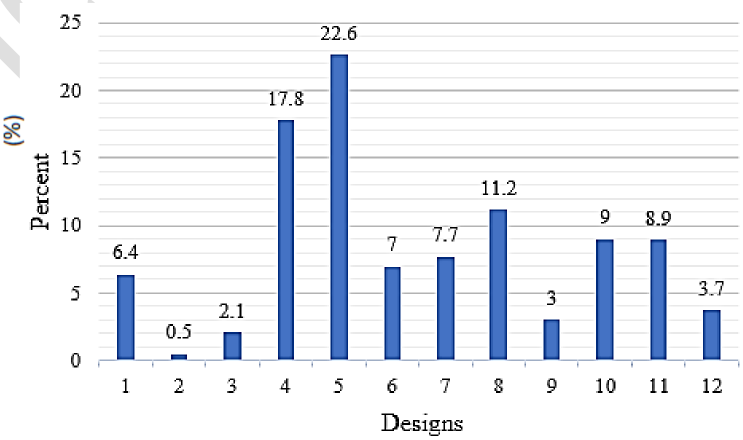

Fig. 11. Percentage of designs of double strand RR method.

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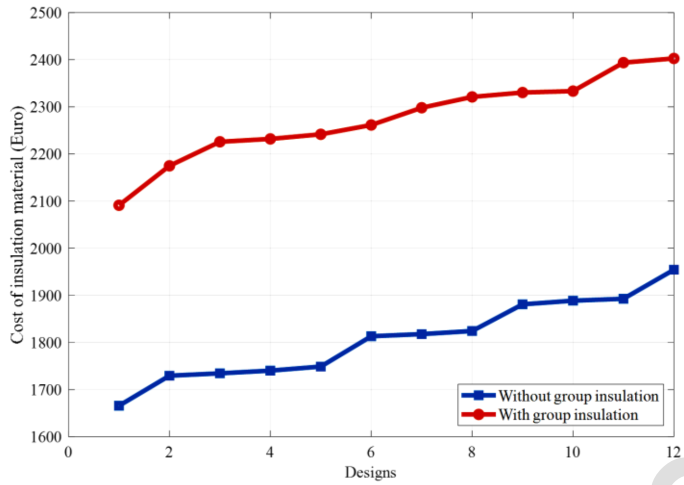

Fig. 12. Effect of deleting group insulation in cost of insulation materials at double strand RR method.

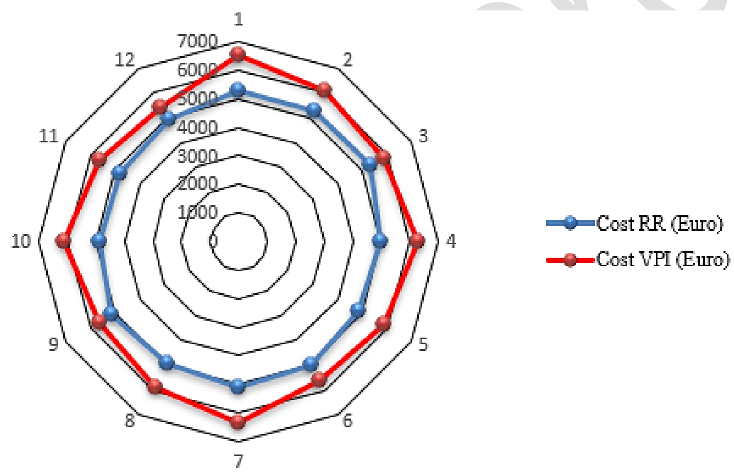

Fig. 13. Cost of material at RR & VPI.

Cost estimation of the MV/HV stator winding can bring about increase of components such as useful life of equipment, efficiency, continuous working time of equipment and profitability of production. On the other hand, reducing maintenance costs and reducing ancillary costs such as insurance, tax and energy costs are also estimated as other cost components. Any change in the type and specifications of the insulators in different scenarios gives rise to a change in the cross section of the conductor, and ultimately causes a change in the weight of copper consumed. Figs. 14 and 15 demonstrate the sensitivity efficiency-weight and cost-weight.

5. Conclusions

This paper studied coil reconstruction with methods RR and VPI, using single-strand and two-strand conductors in a MV/HV induction machine.

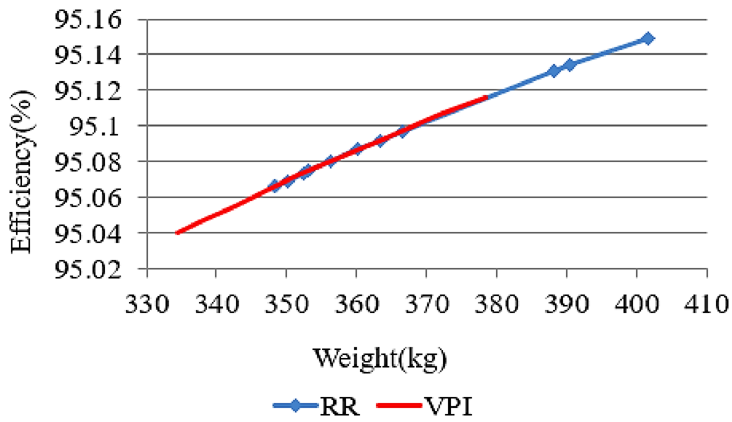

Fig. 14. Sensitivity Efficiency-weight.

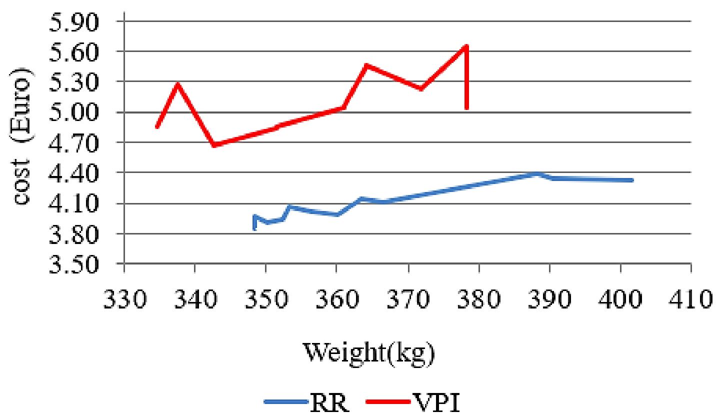

Fig.15. Sensitivity Cost-weight.

Due to various constraints, determination and access to the original insulations is often unattainable during the process. Consequently, utilizing available alternative insulations becomes necessary. By improving the technology of produce insulation, decreases their thickness and increases their insulation voltage. Considering the insignificant effect of increasing the insulation thickness on electrical parameters such as efficiency, power factor and torque, the use of available insulation does not cause concern in the motor performance. Meanwhile, due to the availability of these insulations, the cost of insulating materials for reconstruction of coils is greatly reduced. The results of the analysis can be expressed, as follows.

- The price of the insulation of the main wall and group insulation has the highest and lowest impact, respectively, on the estimation of the cost of materials in the reconstruction of the coil.
- The ratio of the highest to the lowest material cost is estimated at 1.07.

- Taking into consideration the insulation required of the conductor to pass the surge voltage, removing the group insulation does not have any adverse effect on the performance of the coil.
- In all proposed designs using the same consumed copper weight, the coil reconstruction material cost in the VPI method surpasses that of the RR method.
- Also, considering that the insulation of the main wall has the largest volume used in the process of coil reconstruction, it is necessary to consider the amount required for storage in the coil reconstruction workshops.

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Table 3. Specifications of some insulation materials.

Insulation Type	Symbol	Local of use	Thickness (mm)	Width (mm)	Break voltage (KV)	Price per meter (Euro)	Price change range in one year (Euro)
Conductofol0264	CF0264	Conductor ins.-VPI - RR	0.06	15	5	0.12	0.1~ 0.15
Coductofol2011	CF2011	Conductor ins.-VPI - RR	0.09	15	4	0.13	0.1~ 0.18
Coductofol2159	CF2159	Conductor ins. - VPI	0.1	15	7	0.14	0.09~ 0.2
Conductofol0264	CF0264	Group ins. -VPI-RR	0.06	15	5	0.12	0.1~ 0.15
Coductofol2011	CF2011	Group ins. -VPI- RR	0.09	15	4	0.13	0.1~ 0.18
Coductofol2159	CF2159	Group ins. - VPI	0.1	15	7	0.14	0.09~ 0.2
Calmica70	CM70	Main wall ins. - RR	0.16	18	5	0.11	0.08~ 0.13
Calmicaglas0893	CMG893	Main wall ins. - RR	0.18	18	8.1	0.12	0.1~ 0.14
Calmicafab3293	CMF3293	Main wall ins. - RR	0.15	18	5	0.12	0.09~ 0.15
Profab3290	PF3290	Main wall ins. -VPI	0.12	18	1.5	0.15	0.09~0.16
Probond0410	PB0410	Main wall ins. -VPI	0.15	18	1.5	0.16	0.12~ 0.18
Profol0546	PF0546	Main wall ins. -VPI	0.17	18	5	0.25	0.22~ 0.29

Table 4. Selected designs of the RR method with single and double strands.

Conductor ins.	Group ins.	Main wall ins.	Z_c =1						Z_c =2					
			No.	τc	τg	τs	$w_{c\max}$ (mm)	$t_{c\max}$ (mm)	No.	τc	τg	τs	$w_{c\max}$ (mm)	$t_{c\max}$ (mm)
CF0264	CF0264	CM70	1	2	2	13	10.08	2.915	1	2	2	13	5.04	2.915
CF0264	CF0264	CMG893	2	2	2	11	10.28	2.94	2	2	2	11	5.14	2.94
CF0264	CF0264	CMF3293	3	2	2	14	10.04	2.91	3	2	2	14	5.02	2.91
CF0264	CF2011	CM70	4	2	3	12	10.1	2.655	4	2	3	12	5.05	2.655
CF0264	CF2011	CMG893	5	2	3	11	9.98	2.64	5	2	3	11	4.99	2.64
CF0264	CF2011	CMF3293	6	2	3	13	10.04	2.6475	6	2	3	13	5.02	2.6475
CF2011	CF0264	CM70	7	2	3	12	10.16	2.715	7	2	3	12	5.08	2.715
CF2011	CF0264	CMG893	8	2	3	11	10.04	2.7	8	2	3	11	5.02	2.7
CF2011	CF0264	CMF3293	9	2	3	13	10.1	2.7075	9	2	3	13	5.05	2.7075
CF2011	CF2011	CM70	10	2	3	11	10.3	2.575	10	2	3	11	5.15	2.575
CF2011	CF2011	CMG893	11	2	3	10	10.22	2.565	11	2	3	10	5.11	2.565
CF2011	CF2011	CMF3293	12	2	3	12	10.22	2.565	12	2	3	12	5.11	2.565

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Table 5. Selected designs of the VPI method with single and double strands.

Conductor ins.	Group ins.	Main wall ins.	Z_c =1						Z_c =2					
			No.	τc	τg	τs	$w_{c\max}$ (mm)	$t_{c\max}$ (mm)	No.	τc	τg	τs	$w_{c\max}$ (mm)	$t_{c\max}$ (mm)
CF0264	CF0264	PF3290	1	2	2	17	9.86	2.8875	1	2	2	17	4.93	2.8875
CF0264	CF0264	PB0410	2	2	2	14	9.74	2.8725	2	2	2	14	4.87	2.8725
CF0264	CF0264	PF0546	3	2	2	12	9.86	2.8875	3	2	2	12	4.93	2.8875
CF0264	CF2159	PF3290	4	2	2	16	9.94	2.7575	4	2	2	16	4.97	2.7575
CF0264	CF2159	PB0410	5	2	2	13	9.88	2.75	5	2	2	13	4.94	2.75
CF0264	CF2159	PF0546	6	2	2	12	9.7	2.7275	6	2	2	12	4.85	2.7275
CF2159	CF0264	PF3290	7	2	2	16	9.94	2.7575	7	2	2	16	4.97	2.7575
CF2159	CF0264	PB0410	8	2	2	13	9.88	2.75	8	2	2	13	4.94	2.75
CF2159	CF0264	PF0546	9	2	2	12	9.7	2.7275	9	2	2	12	4.85	2.7275
CF2159	CF2159	PF3290	10	2	2	16	9.78	2.5975	10	2	2	16	4.89	2.5975
CF2159	CF2159	PB0410	11	2	2	13	9.72	2.59	11	2	2	13	4.86	2.59
CF2159	CF2159	PF0546	12	2	2	11	9.88	2.61	12	2	2	11	4.94	2.61