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Virtual and Physical Prototyping in the Development of an Axial Flux Induction Motor

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***Abstract*—This study presents a methodology that combines virtual and physical prototyping, exploiting the advantages of both approaches. It gives a flexible solution for the development process of innovative design, alternating between numerical simulations over virtual prototypes and experimental testing of manufactured physical prototypes. Presented sequence of steps covers the starting point of examination of existing practices, finishing with ready-for-manufacturing technical documentation. The application of the methodology is demonstrated by a process of axial flux induction motor design development. The innovative design development is presented in detail and corresponds to the proposed methodology. It includes description of concept elaboration, virtual prototyping cycle (aiming to optimize output parameters), detailed design development (with manufacturing constraints analysis), testing and validation, to reach an improved design solution. Thus, two major contributions are obtained: the specific consequence of applying both types of prototyping is demonstrated, together with detailed description of an innovative design of electrical motor, with application in automotive industry.**

***Keywords*— Axial flux induction motor, Electric machines, Physical prototyping, Virtual prototyping**

I. Introduction

The meaning of word "prototype" could be defined as an early sample, model, or release of a product built to test a concept or process [1]. Prototypes are widely used in design and engineering to perfect items and processes before implementing them on a large scale. Prototyping, as an activity, is an integral step of product development process (PDP) [2]. Generally, two types of prototyping are used – virtual (VP) and physical (PP). Virtual prototyping utilizes computer models, referred also as digital mock-ups, to simulate the behavior and performance of a product. This type of prototyping is very attractive in the early stages of design, where changes can be made quickly and there is no opportunity to prepare certain physical prototype [3]. The virtual prototyping has several advantages:

- Cost effectiveness: there is no need of manufacturing components and using materials.
- Time effectiveness: any modifications can be implemented in real-time, allowing for faster iterations and quicker time-to-market.
- Flexibility: any changes could be performed, without the constraints of physical limitations.
- Concurrent engineering: virtual environments facilitate collaboration among team members, regardless of their geographical locations.

Respectively, the physical prototyping has its advantages:

- Direct interaction: PP allows obtaining immediate overview of the usability and functionality of examined product.
- Accuracy: the physical prototypes are more exact as they represent real-world performance.
- Validity: this is related to the direct implementation in work environment condition, where certain thesis could be checked with high confidence [4].

The new PDP makes use of both virtual and physical prototypes that play a vital role in the process. There is also a potential need to use them both simultaneously. The most obvious common area is in the early stages of product development, namely conceptualization [5]. Also, the advanced technologies allow for creating a real prototype based on a digital model of a mechanical system in quite a short time [6].The processes of virtual and physical prototyping complement each other and allow for creating more advanced structures, providing maximum opportunities for consideration of the design requirements [7].

The combination of both types of prototyping could be performed in many ways, depending on the sequence of their application and their internal connections, [8]. This approach could be used also for optimization of design parameters, where the physical testing is used for validation [9], [10]. Some studies are performed already, directed to development of combined, hybrid, approach which involves both virtual and physical prototyping [11], [12]. Nevertheless, the specifics of the development process of each type of product sometimes require specific approach.

Presented study aims to demonstrate a developed hybrid methodology for electrical motors design by the example of the PDP of axial flux induction motor (AFIM) with cage rotor. It alternates both virtual and physical prototyping to reach a product that meets specific technical requirements.

II. Methodology

The developed methodology is step based and its general overview is presented in Fig.1. Each step is described briefly as follows:

- *S1: State-of-the-art study:* Proposed methodology initiates with a thorough study of existing solutions and patents, implemented in similar products. This step is oriented to the review and analysis of analogous or close to the developed solutions of axial induction motors. The aim is to determine the achieved operating parameters for the considered structures, their advantages and disadvantages. Identification of potential problems in the development of an innovative design of an axial induction motor with a cage rotor is also carried out, as well as the methods of their solution.
- *S2: Conceptual design development:* The concept should use the previously made analyzes of the

existing solutions, according to the determined necessary working parameters, as well as the specifics of components' manufacturing technology. This step is basic for the entire process as it predefines many of further design parameters. It finishes with general scheme of the developed product and a preliminary principal model.

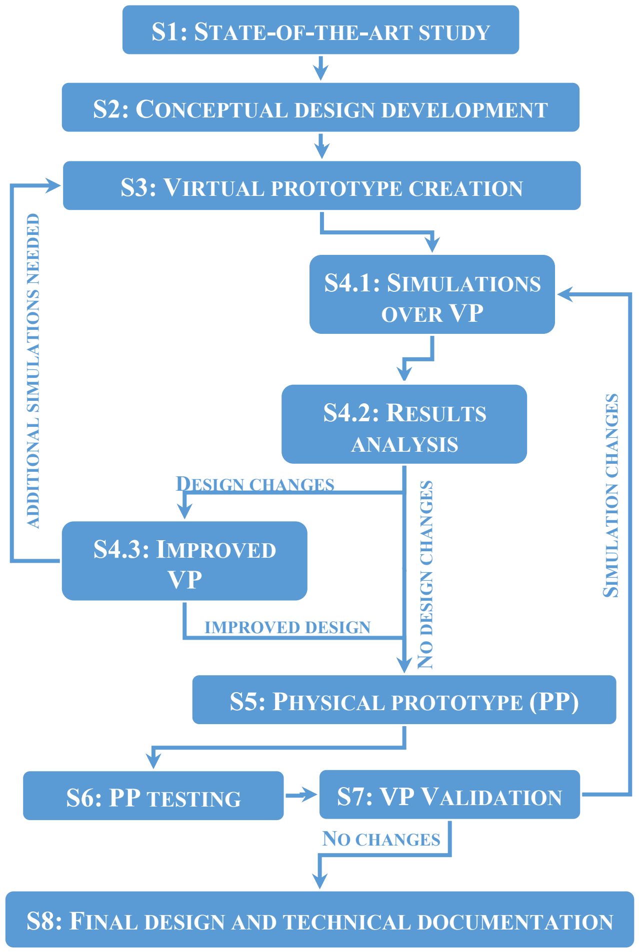

Fig. 1. Functional scheme of developed methodology.

- *S3:Virtual prototype creation:* in this step, a detailed virtual prototype is created based on the concept developed in the previous work package. The created object will be used when performing activities from the next steps. The virtual prototype contains detailed information about all components of the construction, including the initial values of some parameters. This CAD model could be used for many purposes further, as it is seen by the diagram in Fig.1.
- *S4: Virtual prototyping:* this is a complex step and could be used for an extensive design optimization through simulations [13], [14]. It is presented by three separate sub-steps:
  - *S4.1: Simulations over VP:* one or more simulations are performed to study work parameters and overall behavior of developed product. Common practice is to use available commercial software for numerical simulations.
  - *S4.2: Results analysis:* this sub-step uses the results from all simulations to review examined design and to provide sufficient information for a decision for model improvement. If the results correspond to requested technical specification, then could be proceeded to next step. In opposite, additional sub step is needed.
  - *S4.3: Improved virtual prototype:* design modifications take place in this sub-step that are consequent from conclusions, formed in S4.2. Further, the process could continue to physical prototyping, or, entire S3 could be re-run, if an additional assessment of performed changes is needed.
- *S5: Physical prototype (PP):* next, the manufacturing of the prototype is done. Any additional test equipment could be also included, depending on the specifics of planned tests.
- *S6: Physical prototype testing:* includes various tests to determine work parameters values of examined product. This step finishes with analysis of obtained results and final comments and conclusions.
- *S7: Virtual prototype validation:* the test results could be used for validation of the virtual prototype. If significant differences are indicated, the virtual prototyping step could be re-run.
- *S8: Final design and technical documentation:* this is the last step that summarizes all information for product design, obtained in the PDP. Direct result is a ready for manufacturing product.

The developed and presented methodology is applied to an innovative product under development – an axial flux induction motor (AFIM) with cage rotor. Obtained results are discussed in the next chapter.

III. Application and Results

Electric motors have been in the process of dynamic development in recent years, mainly determined by the development of their application in the automotive industry, as well as in the automation of various processes, including lifting and transport equipment and elevators. Electric motor development and research to find the most suitable motor for electric vehicles is a continuous process that is actively continued by numerous researchers and engineers around the world [15], [16]. On the other hand, electric motor designs can be divided into two types: radial motors and axial motors. In radial motors, the magnetic flux flows radially through the stator, air gap and rotor, while the magnetic flux in axial motors flows in the direction of their axis [17]. Compared to radial, axial electric motors can provide higher electromagnetic torque [18]. When looking for a direct drive option, axial electric motors have more advantages than radial electric motors. For example, axial electric motors have balanced attraction forces, a better heat dissipation configuration, and more options for adjusting the air gap. Axial permanent magnet motors have high efficiency and wide applicability. They have a very good torque to weight ratio [19].

The development of axial flux induction motor is started by performing a state-of-the-art study, as it is defined in the proposed methodology.

A. S1: State-of-the-art study

The review of existing design solutions mainly shows that this type of electric motors is under active development. Their main advantage is the absence of magnets, which significantly reduces their cost. It is this advantage that is the reason for the active research and applied work related to the development of this type of motors. A patent purity and prior art survey of caged Rotor axial induction motors was conducted. Possible solutions were analyzed and initial conclusions were drawn and next steps were formed. Possible problems related to the development of the structure are considered, and they are grouped as structural and technological.

B. S2: Conceptual design development

A concept for an innovative axial induction high-efficiency engine with a cage rotor of a new generation for electric vehicles has been developed, based on the conducted research and analysis of existing solutions and formed considerations of a constructive and technological nature. The concept includes the following main nodes and features (Fig. 2).

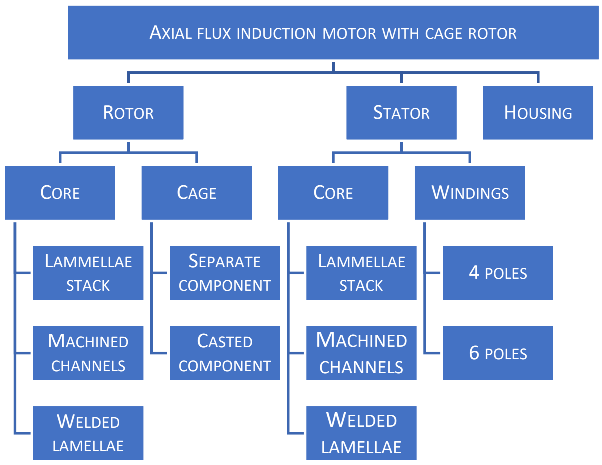

Fig. 2. Diagram of the concept under development.

The main design parameters are those that define the specific version of the engine. They include: design power (18kW); number of poles relevant to the rated speed of rotation (6 poles); outer diameter (≈ 370mm, according to the analysis of existing analogues; inner diameter (≈ 140mm, for a ratio of 0.38); length of the stator magnetic wires (approximate value of 50mm); number of stator windings (36 channels, with two layers of 18 coils); stator winding cross-section and number of wires (to be determined in the next steps); rotor cage (40 radial channels, with section, whatever is determined by design calculations).

C. S3:Virtual prototype creation

Virtual prototype creation is a consequence of design engineering process. Developed AFIM includes a stator composed of stator windings and a stator core, which is made of a spirally wound strip of magnetically conductive material with a winding axis coinciding with the axis of rotation of the machine. On the wound core of the stator are installed in the form of trapezoidal lamellae sheets of magnetically conductive material, with an axial orientation, which play the role of a core for the stator windings. The lamellae are stacked on top of each other and clamped together. The stator windings can be pre-wound by machine and placed around the already built cores with minimal effort.

The rotor is a disc of magnetically conductive material mounted to the shaft of the motor. Trapezium-shaped lamellae, made of magnetically conductive material, are joined to the disc mounted in this way on the area of one or both of its faces, one on top of the other. The lamellae are again axially oriented and form lamellar stacks that are surrounded by a rotor cage, which is made of a material with low magnetic conductivity and high electrical conductivity. The lamellas have a square shape with straight sides, thus providing the desired cage tilt without complex lamella core shapes, produced from strip with universal machines, without specialized punches.

The developed virtual prototype of the design is shown in Fig.3.

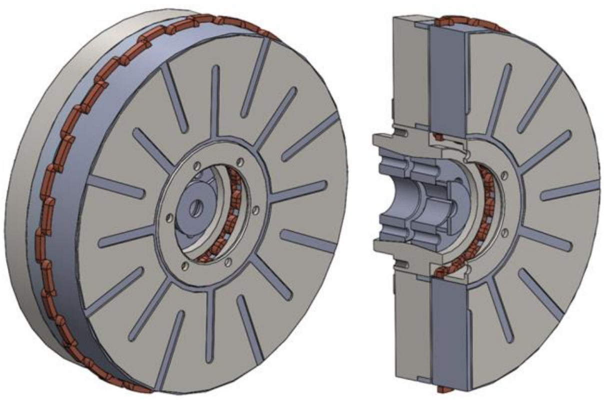

Fig. 3. Virtual prototype of axial induction flux motor.

D. S4: Virtual prototyping

Virtual prototyping mainly consists of the use of computer modeling using the finite element method, followed by simulation analyses. Figure 4 shows a finite element model of the innovative cage rotor axial induction motor under development. The model is created as three-dimensional (3D), with a plane of symmetry, creating a half model, thus significantly reducing the computation time. The studied electric motor is defined as a system that has a stator with 36 windings and 6 poles, and a rotor with 40 radial channels. The poles and number of rotor channels are determined to minimize torque ripple. Set speed is 2895 rpm. The electrical circuit that powers the machine is shown schematically in Figure 4.

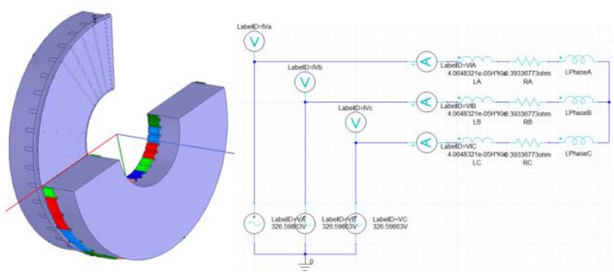

Fig. 4. Simulation model and used electrical supply circuit.

E. S4.1/ S4.2/S4.3: A cycle to reach improved virtual prototype

The results of the virtual prototype are represented by several characteristic quantities as induction voltage and stator current - for all phases; generated torque; electrical and mechanical power; magnetic flux. These are presented, as an example, in Fig. 5 – for induced voltage and in Fig.6 – for the generated torque.

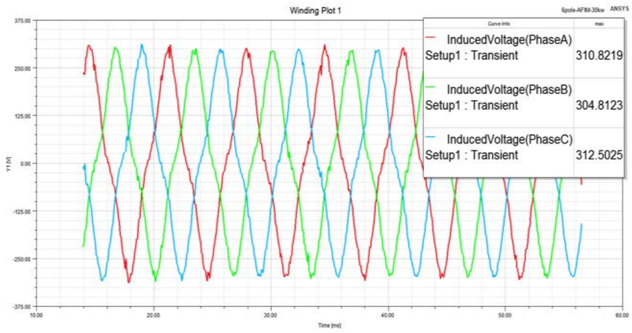

Fig. 5. Simulation results: induced voltage by phases.

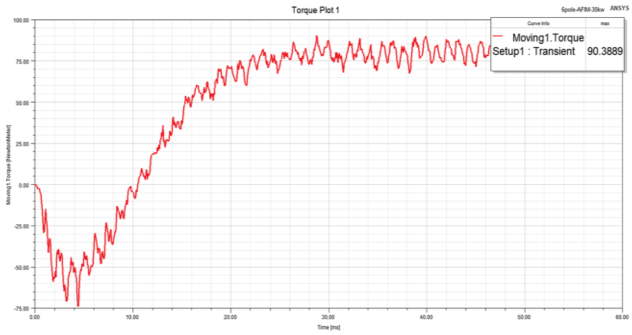

Fig. 6. Simulation results: generated mechanical torque.

The magnetic flux distribution is important for studying the electromagnetic behavior of the structure under consideration. The magnetic flux distribution is shown in Fig. 7 on both the stator and the rotor. The maximum reported value is 3.8 T, and it is expected to be significantly lowered - up to 2.5 T - upon improvement of the quality of the computational model and, in particular, of the generated mesh of finite elements. This assumption should be confirmed subsequently, by performing measurements on a physical prototype of the engine under study, which would also help to validate the computational model.

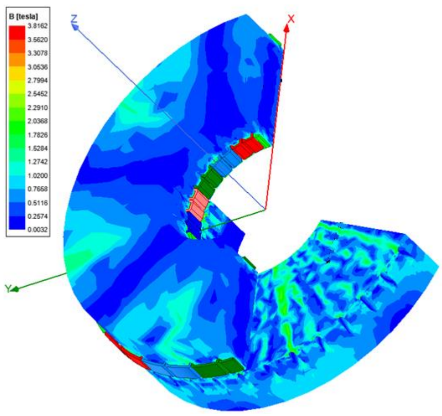

Fig. 7. Simulation results: magnetic flux distribution.

F. S5: Physical prototype

The physical prototype of the developed cage rotor axial induction motor design aims to investigate its characteristics. The aim is to measure mechanical quantities such as torque and revolutions, as well as electrical quantities such as voltage and current magnitude. For this purpose, a stand was constructed, which should control the physical prototype of an axial induction electric motor with a cage rotor, as well as an additional motor to realize the load of the tested prototype. In addition, it is necessary to provide an inverter to make it possible to drive the physical prototype under test. It is shown in Fig.8.

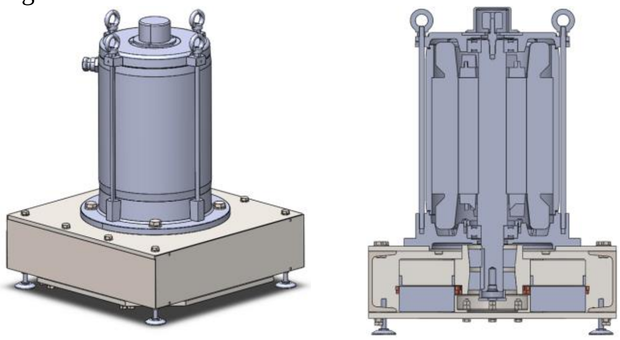

Fig. 8. Test stand with tested AFIM and additional radial induction motor.

Photos of the manufactured stator and rotor for the physical prototype are shown in Fig. 9. The mounted unit of the entire system is shown in Fig. 10.

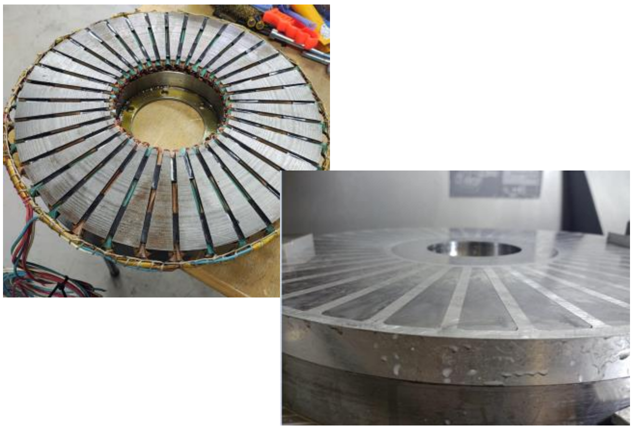

Fig. 9. Components of the physical prototype of developed AFIM.

Fig. 10. Assembled physical prototype of developed AFIM.

G. S6: Physical prototype testing

The testing of the physical prototype was performed through a series of measurements of basic parameters (voltage, current, in established mode and quality indicators); experimental studies for basic parameters (voltage, current, time for transient processes and qualitative indicators in transient modes). The testing process is illustrated by a photo of the work environment during tests, shown in Fig. 11.

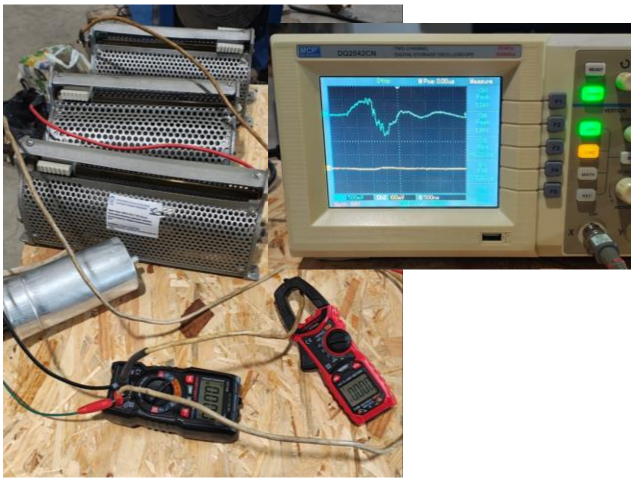

Fig. 11. Measurements over physical prototype.

H. S7: Virtual prototype validation

The validation of the virtual prototype is carried out through a series of measurements of the physical prototype to achieve an acceptable correspondence between the virtual and physical prototype. The approach includes experimental studies to evaluate the operating parameters of the prototype. For all of them, it is planned to carry out the necessary number of observations, using appropriate measuring and control equipment.

Experiments were carried out at different rotational frequencies of the axial induction motor with a cage rotor. As a result of the tests and measurements, the following was established:

- The manufactured prototype of an axial induction motor with a cage rotor corresponds to the intended parameters and no significant changes are required;
- An experiment was conducted to operate the tested axial motor in the “generator” mode, which shows the presence of induced voltage in the windings of the axial motor;
- The obtained values and parameters of the tested sample correspond to the data obtained during virtual prototyping, with the maximum deviations being within the permissible limits (below 10%)
- General conclusion – no significant changes are required to the virtual prototype of the system, since a good correspondence was found to the values of the physical prototype obtained during measurement of the individual parameters.

I. S8: Final design and technical documentation

The design is finished, adding some minor changes as to improve its performance and moreover – to facilitate its manufacturing. There are no significant changes that need special attention. Prepared documentation for manufacturing is demonstrated briefly in Fig. 12. It includes also documentation for the test stand, as it is also shown in Fig. 12.

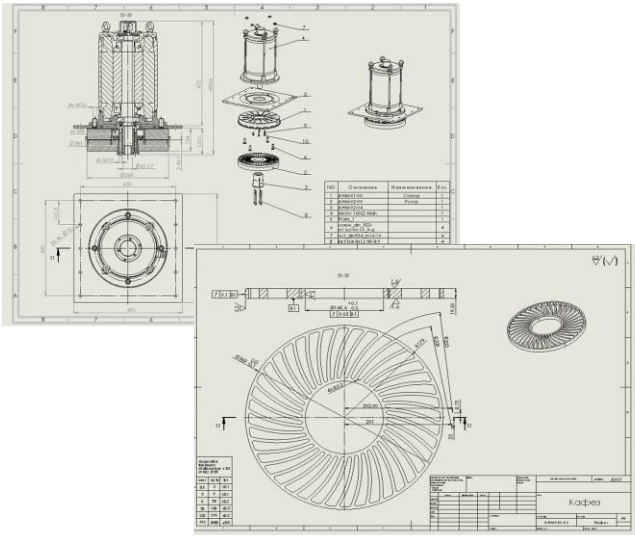

Fig. 12. Ready for manufacturing technical documentation.

IV. CONCLUSION

Presented study emphasize over the combination of virtual and physical prototyping. It also represents a successful application of a scientific approach in engineering practice. Next major conclusions, related to scientific contribution of this study are listed:

- a newly developed hybrid methodology for electrical motors design that combines existing approaches for prototyping – virtual and physical. The specific sequence of both prototyping applications is defined;
- an innovative design of axial flux induction motor, with possible application in automotive industry, is developed, using presented methodology;
- performed approbation of the methodology resulted in ready for manufacturing new product.

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