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Utilizing cable winding and industrial robots to facilitate the manufacturing of electric machines

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A R T I C L E I N F O

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A B S T R A C T

Cable wound electric machines are used mainly for high voltage and direct-drive applications. They can be found in areas such as wind power, hydropower, wave power and high-voltage motors. Compared to conventional winding techniques, cable winding includes fewer manufacturing steps and is therefore likely to be better suited for automated production. Automation of the cable winding production step is a crucial task in order to lower the manufacturing costs of these machines. This article presents a production method using industrial robots for automation of cable winding of electric machine stators. The concept presented is validated through computer simulations and full-scale winding experiments, including a constructed robot-held cable feeder tool prototype. A cable wound linear stator section of an Uppsala University Wave Energy Converter and its winding process is used as a reference in this article. From this example, it is shown that considerable production cycle time and manufacturing cost savings can be anticipated compared to manual winding. The suggested automation method is very flexible. It can be used for the production of cable wound stators with different shapes and sizes, for different cable dimensions and with different winding patterns.

1. Introduction

Fully automated manufacturing of conventional electric machines, both motors and generators, is well known today and has been globally introduced in factories for a few decades [1–5]. It has been widely recognized that automated production lines are necessary to survive in today's global electric machine market [6–8]. Designing with production in mind has been an important key in the process towards automation of electric machine manufacturing [2,5,9].

One of the most challenging operations to automate in electric machine manufacturing is the winding of the stator. For conventional machines using coils of inductor wire or rectangular inductor bars, different automated winding methods have been developed. A less common electric generator design, known as the Powerformer, utilizes cables for the stator winding. This concept has some important advantages, including reduced system losses and fewer winding production steps [10–15]. However, no published fully developed automated cable winding production method has been found.

Advances in the industrial robot technology during the last years have enabled robotized automation of advanced tasks that could only be done manually before, some with similarities to winding technology. They also allowed increased production volumes and flexibility for already existing automated production lines [16–22]. A driving actor in this is the automobile industry, with large investments in fully robotized automated production lines along with research and development of new robot applications for manufacturing [23–25]. Industrial robots often introduce more flexible automation solutions, due to their large workspace and programming possibilities, compared to methods based on task-specific, stiff automation machines. This flexibility is very suitable for the production of electric machines since rapid changes in production due to small and often varying product series are common. Thus robots are sometimes used for stator winding operations [7,26].

A specific cable winding process, the stator winding of a direct-driven linear permanent magnet cable wound generator stator section used in an UU WEC,[1] will be used in this article to exemplify a full-scale cable winding production step.

The aim of the work presented in this article is to suggest and validate a production method to facilitate electric machine manufacturing by using industrial robots to automate cable winding in electric machine stators. Even though the generator example presented here is a linear generator used in a WEC, the presented method should be applicable for other cable wound electric machines as well, including the more common rotating machines.

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2. Method

The development of an industrial robot production cell is a complex task with many different steps. Some key methods used in this work have been: the choice of an appropriate robot model, the design of equipment in a 3D-CAD environment, offline robot cell programming and experiments, the construction of a cable feeder tool prototype and full-scale winding experiments. The main process chain is explained in Fig. 1.

Since this is an iterative process where the cell and tool design, robot programming and winding process are adjusted to each other numerous times before a satisfying solution is found, the results in Sections 4–6 only present the final versions of the automation method, the robot cell layout, the cable feeder design and the robot cell simulations.

2.1. Computer simulations of the robot cell

Offline robot programming can be an important key in evaluating and designing a new robot cell, before building a full scale cell. In this paper, ABB RobotStudio [27] is used for offline robot simulations. With this computer software, appropriate industrial robot models and number of robots regarding reach and positioning can be investigated. Also, the reach of the robots over the work object can be optimized with different tool designs. As the robot models, tool design and cell design are decided, the full robot programming can be tested with the simulation cell, including simulating sensors. However, even though offline software can save expensive robot and production time, some special events and physical states, including deformable objects, might be hard to fully simulate. Thus offline simulations must often be followed by full scale physical robot cell experiments.

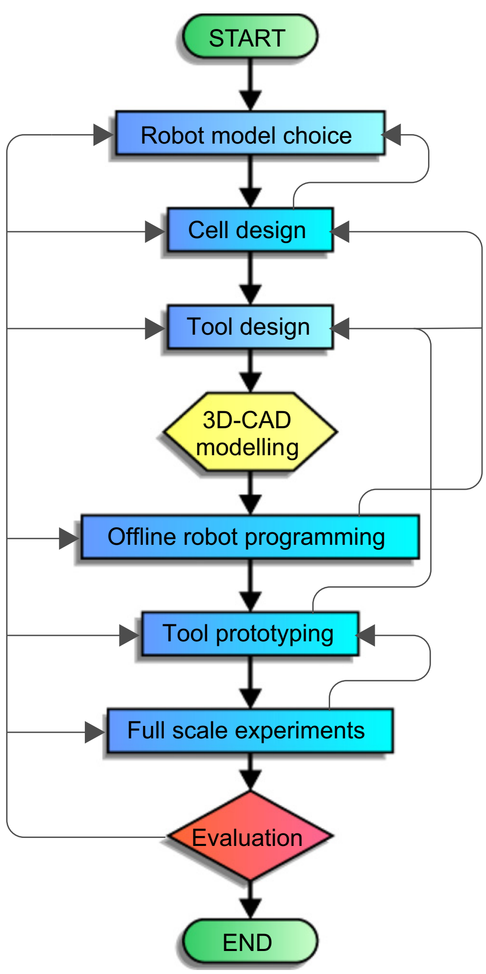

Fig. 1. Method used in the work described in this article.

2.2. Economical calculations

A new automated robot cell should be economically evaluated and compared to present and alternative production methods. One important figure, used to determine the value of the investment, is the net present value, which is calculated using Eq. (1) where *NPV* is the net present value, *n* is the economical lifetime of the investment, C_t is the net cash flow at time *t* and *i* is the discount rate. Another useful figure is the payback period, which is calculated by solving Eq. (2) where *T* is the payback period.

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t} \tag{1}$$

$$\sum_{t=0}^{T} C_t = 0 \tag{2}$$

3. Automated cable winding

This section presents some necessary background theory in developing an automated cable winding production cell, including existing stator winding techniques, the Powerformer concept, the WEC stator winding example used in this work, the most important design requirements and the basic conceptual choices used as a starting point for this automation.

3.1. Stator winding schemes

An electric machine can either be a motor, converting electric energy to mechanical energy, or a generator, converting mechanical energy to electric energy. The two main parts of an electric machine are a rotating rotor and a stationary stator. For linear machines, a linearly moving translator replaces the rotor. The basic process of the electromechanical energy conversion can be demonstrated by moving a magnet in and out of a closed conductor loop. The mechanical energy moving the magnet converts to electric energy, inducing a voltage and a current starts to flow in the conductor. This represents a linear generator design where the magnet illustrates the translator part and the conductor loop illustrates the stator. In an electrical machine the conductor loop is usually mounted inside slots in the stator and is referred to as the stator winding.

The ratio of the in-slot winding cross section area to the total available slot area, referred to as the slot fill-factor, is often used to describe stator windings. For a given stator design, the slot fill-factor represents the level of material utilization in the machine and therefore it is desired to have this ratio as high as possible. However, the slot fill-factor cannot be used by itself when comparing different stator designs since other aspects often influence the overall machine performance more.

Conventional electric machines mainly use strands of inductor wire or rectangular inductor bars for the stator winding, see Figs. 2 and 3. Using the inductor wire strand design, the coils can either be wound directly in the stator slots using special tools or be prepared outside the stator and then inserted into the stator slots. In-slot winding eliminates the extra production step of inserting the coils into the stator. On the other hand this method is not able to create windings with as high a slot fill-factor as outside winding, since the winding tool requires some space inside the slot and there is a minimum distance required between the stator teeth in order for the winding tool to be able to reach inside the slots [28].