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

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ABSTRACT

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.

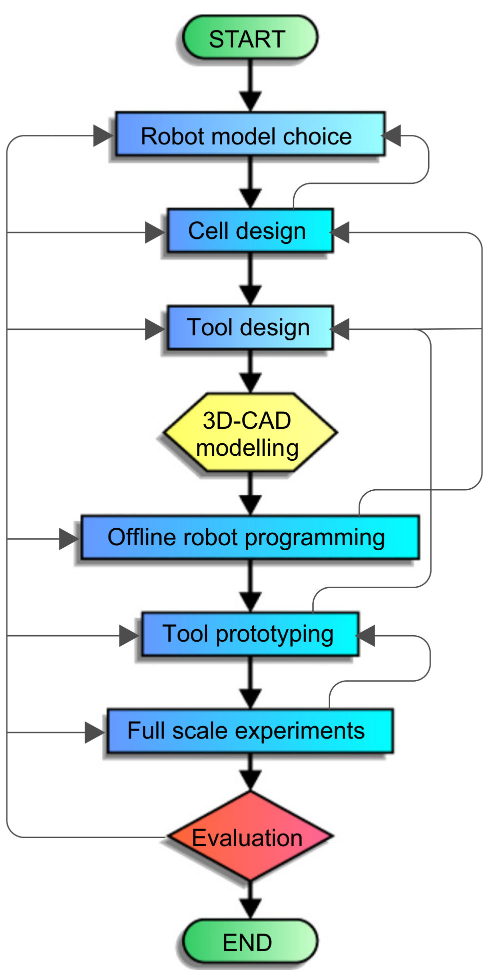

Fig. 1. Method used in the work described in this article.

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].

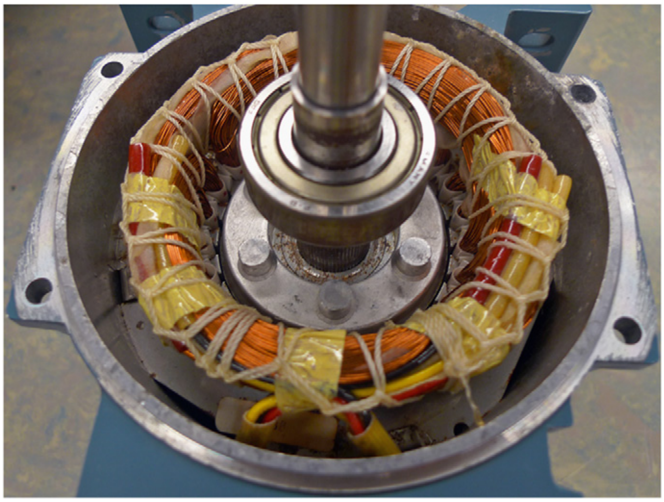

Fig. 2. A stator winding with strands of induction wire, in a small electric motor.

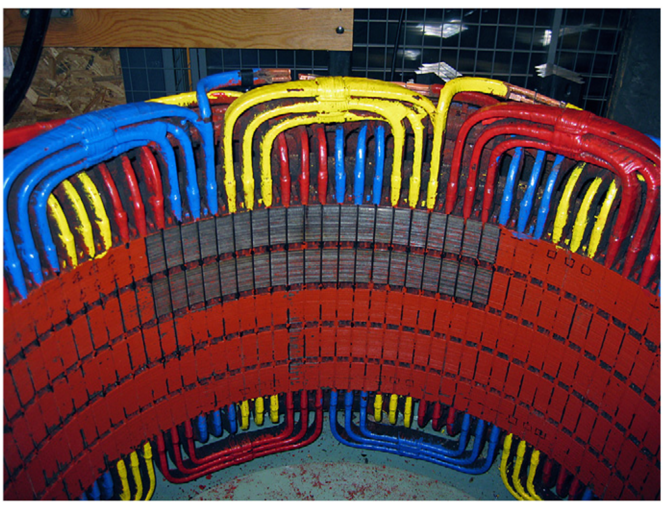

Fig. 3. A stator winding with copper bars, in a hydropower generator.

Preparing the windings outside the stator enables better packed and larger windings with a higher slot fill-factor, but the windings must be inserted into the slots and the stator design must be adjusted for this [9]. An alternative method is to split the stator in tooth-segments and wind each segment separately [29–32]. As a result, a higher slot fill-factor can be accomplished, but an extra assembly production step for the stator is introduced. Other research suggests a sectional stator design that allows the stator slots to be opened to facilitate the winding and improve the slot fill-factor [33]. When it comes to larger machines, mostly generators, rectangular inductor bars are often used for the stator winding. Automation for insulating and forming these bars is available but the insertion is mostly done by hand due to the small production series and the large generator size [3]. Automated winding techniques for other generator designs exist too [34]. Insulation of the windings, winding fixation and end windings connection are important production steps for all conventional electric machine stators.

3.2. Cable wound machines

Cable wound generators, a concept known as the Powerformer or Very High Voltage machines, have some important advantages compared to conventional generators. Using high voltage power cables in the stator winding, a Powerformer generator allows generation of electricity at grid transmission voltage levels, thus eliminating the need for a step-up transformer between the generator and the grid. Among the benefits with this technique are reduced system losses, better network stability, smaller investment costs and less overall environmental impact [10–15].

Another important advantage of cable wound electric machine stators is that the number of manufacturing assembly steps for the stator winding are reduced. Using power cables in the winding eliminates the production steps of insulating the windings during the stator assembling, possible insertion of pre-wound coils into the stator slots and securing the windings in the stator slots, while the need for end windings connection is reduced. The full cable winding process is performed by feeding the power cables back and forth through the stator slots, from the top and bottom of the stator. Since cable wound generators and motors are still much less common than their competitors and because only small series with large machines based on this technique have been manufactured today, there is as yet no method developed for fully automated cable winding of electric machines. Manually assisted cable winding of large-scale generators are these days performed with the help of several cable feeder tools [35].

3.3. The UU WEC stator cable winding example

The specific cable winding example considered in this article is the stator winding of a direct-driven linear cable wound generator used in a WEC unit prototype constructed within the *Lysekil project* at *The Swedish Centre for Renewable Electric Energy Conversion at Uppsala University*. This technology is described in more detail in [36,37]. Fig. 4 shows the UU WEC generator design, Fig. 5 shows a cable wound UU WEC stator section that is mounted inside an UU WEC. The stator section is about 2 m long, about 0.5 m wide and is divided in the middle by a 30° angle. The slot hole diameter, through which the winding cable is fed, is 8 mm and the average outer diameter of the winding cable is 7.2 mm. A three-phase wave winding pattern with some modifications is used. This article will however assume and focus on a pure three-phase wave winding, see Fig. 6, since this is an obvious starting point even for other winding patterns.

A condition for this WEC technique to be competitive on a global market is that the production cost is low. The technique is intended for future large series production, which makes the manufacturing suitable for automation. Automated cable winding has an important role in this process.

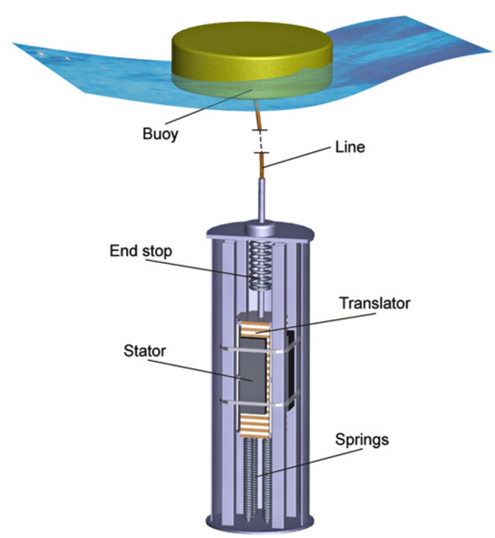

Fig. 4. The UU WEC unit design.

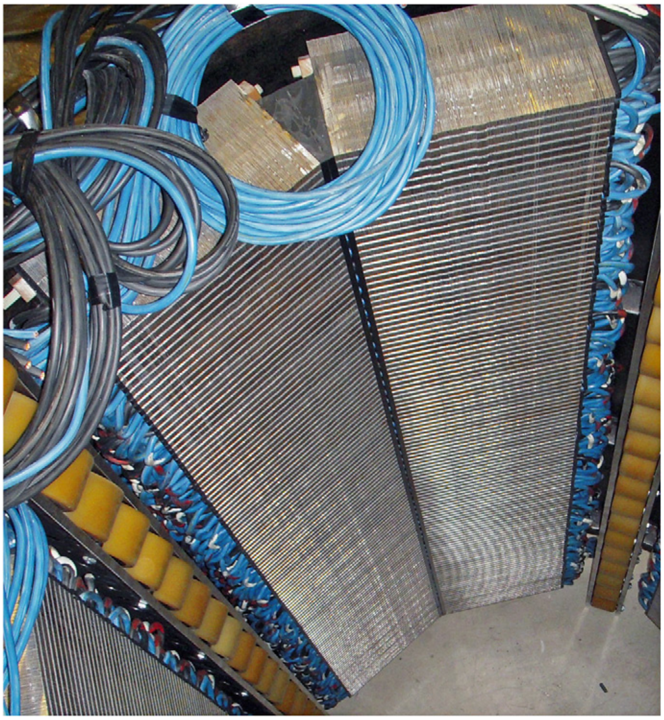

Fig. 5. A cable wound UU WEC stator section mounted inside an UU WEC.

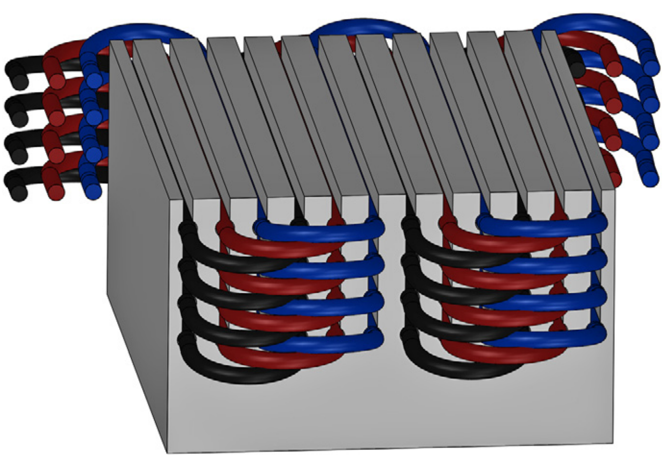

Fig. 6. Pure three phase wave winding pattern used as reference in this article. Note that this illustration is simplified compared to the UU WEC stator, for example there are eight slot holes per slot in the UU WEC stator.

3.4. Requirements of automated cable winding

In developing an automation method for cable winding, some important general cable winding issues, presented in this subsection, must be considered.

As can be understood from the UU WEC stator example in Figs. 5 and 6, a cable must be fed from the sides of the stator slot by slot, so insertion of a complete winding from above is not possible. Numerous cables are instead fed back and forth through the whole stator in a specific winding pattern. The cables are then connected to each other at the end of the windings. A high stator slot fill-factor is desired; therefore the cables must be fitted tightly into the slots. The cable must be handled with care to avoid being damaged due to for example a too small bending radius, buckling or wear. Enough high cable feeding forces must be guaranteed so that the cable does not get stuck inside the stator during winding. The fed length of the cable must be controlled in order to get short end windings on the stator sides. During the winding process, earlier created end windings must sometimes be pushed down to prevent them from covering unwound slot holes and disturb the winding process.

Some further general requirements of the automation are that the layout of the automation should be suitable for direct implementation in a factory production line, the need for human interaction in the production is kept to a minimum and the automation method is as simple and robust as possible. Moreover, high flexibility is needed to enable adjustments to production of different machines and the winding production cycle time and investment cost must be low.

Regarding flexibility, there are a few aspects to keep in mind. To begin with, it is important that the final automation method can be adjusted for different cable dimensions and different winding patterns. Equally important is that both linear and circular stators of different sizes can be wound with the same production technique.

4. Suggested developed automation solution

In this section the suggested developed automation solution for cable winding is presented together with the design and the constructed prototype of an essential winding tool used in this solution.

4.1. Basic conceptual automation method choices

None of the existing stator winding automation techniques for conventional machines described in Section 3.1 can be implemented for cable wound machines, mainly because the existing techniques are not able to deal with cables and feed them through the stator. Therefore another winding method is required. The work presented in this article will focus on the conceptual cable winding method described in [38], since this concept has the potential to deal with the requirements presented in Section 3.4.

To push and pull a cable through the stator during winding, a cable feeder must be used. Preferably one cable feeder is used on each side of the stator so that the cable end can always be caught when being pushed through from the opposite side. Some of the demands on this cable feeder are that it must be capable to create and transfer a high enough feeding force to the cable, it must be able to catch, hold and let go of the cable, it must be able to direct the cable straight into the stator slots, it must not damage the cable, it must be possible to position it close to the stator sides without colliding with completed end windings and it should have the capability to push down end windings blocking a stator slot. Further, it should be possible to position the cable feeder against the stator sides with high accuracy, so that it can feed the cable straight into a slot and catch a cable coming out from a slot. A final requirement on the cable feeder is that it must be fairly easy to adjust within reasonable limits to different cable dimensions, stator sizes, stator shapes and winding patterns.

There are some cable feeders on the market today, but they are mostly designed to be used with large diameter cables. Consequently, these tools are often space consuming and lack options such as cable steering and the possibility to easily open up fully, which are essential for automated cable winding. No ideal feeder that can fulfill the requirements mentioned above has been found. Therefore a new cable feeder has been designed by developing an automated winding cell.

Since the cable cannot be fed through all the stator slots at the same time, a cable parking with temporary cable storages is needed. In addition, a cable supply from where new cable can be collected is needed together with equipment to prepare the cable

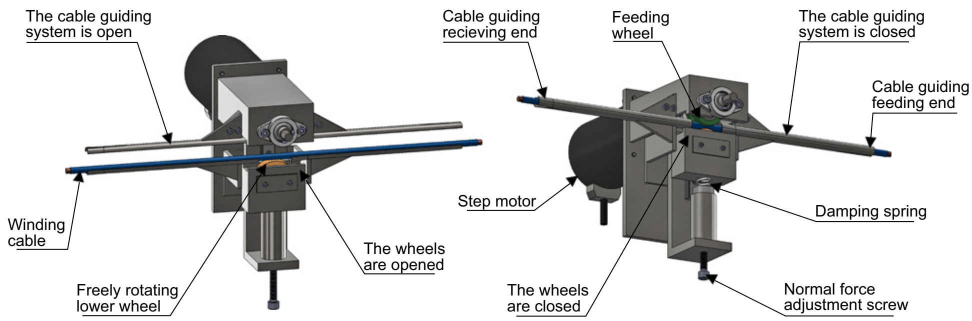

Fig. 7. Designed cable feeder tool and its components, in cable-drop position to the left and in feeding position to the right.

end so that it does not get stuck in the stator while being fed through.

The reasoning above indicates that a flexible positioning system with at least four degrees of freedom and a wide reach is needed to position the cable feeders. A natural solution to this is to use industrial robots holding cable feeder tools.

A robot cell layout for this cable winding automation solution has been developed and the final version is presented in Section 5.

4.2. Cable feeder tool design and prototype

A simple, controllable and compact cable feeder tool prototype, adjusted for robotized cable winding, has been designed and constructed. The final cable feeder design, main components and its working principle are shown in Fig. 7.

The feeder uses a single feeding wheel, driven by a step motor, to transfer a high feeding force from the motor to the cable. A freely rotating second wheel is then mounted below the driven wheel. By adding mechanics so that the lower wheel can be moved against and away from the upper wheel, the cable feeder is then able to grab the cable between the two wheels and to feed the cable. In order to maximize the frictional force against the cable, the outer part of the feeding wheel was made of high-friction rubber with a well defined radius, see Fig. 8. To reach a high normal force between the cable and the driven wheel, allowing higher feeding forces without slipping, the lower wheel is able to push the cable against the driven wheel with a pre-defined force. The position of the lower wheel is changed manually by rotating a screw at the bottom of the feeder. Since the cable's outer diameter is not perfectly constant, the second wheel is coupled to a spring that keeps the force on the cable fairly constant by adjusting for deviations in cable diameter. Hence, the positioning screw for the lower wheel can be used to adjust the normal force on the cable.

Through experiments it was decided that the cable feeding force must be around 250 N to ensure uninterrupted winding of an UU WEC stator section. The required force varies substantially from slot to slot depending on the wear of the cable, the small irregularities in the cable diameter and on how well the stator sheet slots are aligned to each other. The static friction coefficient between the winding cable PVC insulation and the feeding wheel was experimentally determined to about 0.9.

An important feature of the feeder tool is the cable guiding system, whose main function is to direct the cable into, through and out of the feeder. The guiding stretches about 200 mm from each side of the wheels and has three different operating modes. To begin with, it is possible to open up the guiding together with the wheels, thus enabling the feeder to drop the cable. Secondly the guiding can be closed while the wheels are opened so that the cable can be directed and fed through the feeder, and finally, the guiding can be closed together with the wheels in order to fix the cable between the wheels and enable cable feeding. One side of the cable guiding, the receiving end, is adjusted for receiving the cable by adding a funnel at the end of the steering and thereby facilitating the cable end to be directed into the feeder. The other side of the guiding, the feeding end, is designed as a narrowing cone that facilitates precise steering of the cable into a stator slot hole. The same principle was used on the inner sides of the guiding system to ease feeding of a cable through the cable feeder, between the two wheels.

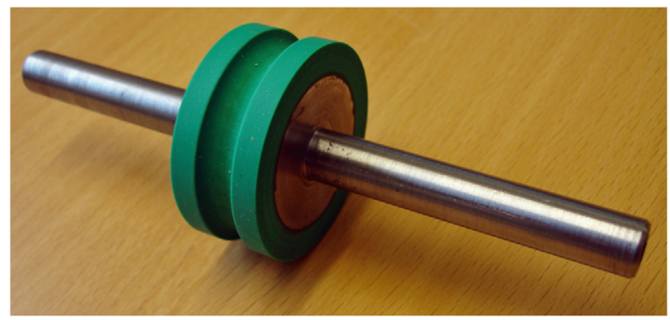

Fig. 8. High-friction feeding wheel used in the constructed cable feeder prototype.

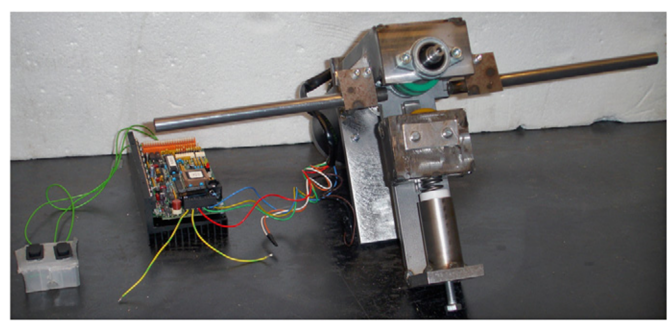

Fig. 9. Constructed cable feeder tool prototype.

A full-scale cable feeder tool prototype was constructed, identical to the described design apart from the fact that the cable guiding system was simplified and not possible to open, see Fig. 9.

5. Robot cell layout and simulation results

This section presents the suggested final robot cell layout for stator cable winding automation and the offline robot programming experiments performed in ABB RobotStudio.

A robot cell offline simulation was built and used during the development of a functional automated cable winding production cell to validate its function. To minimize the winding cycle time of an UU WEC stator section, four ABB IRB4400/60 kg robots were used in one production cell, see Fig. 10. The robots were programmed to work together, interacting and controlling tools and other equipment and sensors through digital signals. The simulated work procedure could also be used to estimate the total winding cycle time.

The winding of a cable starts from the middle of the stator section, from the middle of a cable and is done in two directions simultaneously by the two robot pairs. About 700 m of cable is used for the stator winding. A three-phase winding pattern is used and the total cable length is divided into 24 cables, each stretching over the full stator length. The cable sections are then connected to each other at the ends of the stator section.

The robot cell winding procedure starts with an unwound WEC stator section being automatically fed into the robot cell and fixed between the robots. Using positioning sensors on the cable feeder tools, the robots can then measure the exact stator section position. In this way, a less exact stator section positioning in the cell is required. The winding begins as one robot picks up the cable end from the cable drum. The cable drum setup is equipped to hold and prepare the cable end and feed cable from the drum. Next, the cable is fed through the stator section and then picked up on the other side by the co-operating robot. Using a temporary cable storage, the cable end can be parked while the full length of the cable is fed through and then picked up again by the second robot. Again, the cable is fed through the stator section and the first robot picks up the cable end. The cable is then immediately fed back through the next to-be-wound slot hole in the stator section and the second robot parks the cable on another shelf in the temporary storage. This way, by using both robots to pull the cable on both stator sides at the same time, the cable can be fed through two slots simultaneously and the winding cycle time is reduced considerably. This winding operation principle is repeated until the whole cable is wound, after which the next cable is wound until the winding is completed. When the winding is completed, the finished stator section is automatically fed out from the robot cell in the opposite direction from where it was originally fed in, creating an easily implementable production flow. Fig. 11 shows a summary of the winding method described above.

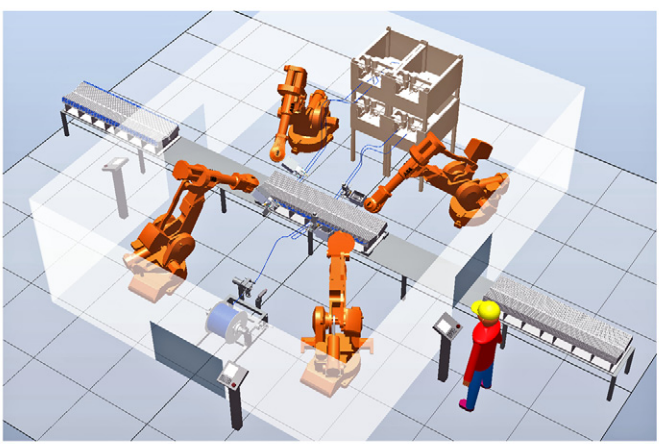

Fig. 10. A simulation of the suggested automated cable winding cell in ABB RobotStudio.

The performed robot cell simulation validated that the selected robots, equipped with cable feeder tools, could carry out all necessary movements and positioning to achieve the suggested winding procedure. It was also confirmed that the cable feeder tool geometry design is suitable for the winding operation.

6. Experimental results

This section presents the experiments and calculated results from the different experiments using the constructed cable feeder tool and an industrial robot together with the results from Section 5.

6.1. Cable feeder prototype experimental winding results

Experiments with the constructed cable feeder tool validated the feeding and guiding functions of the cable feeder. The feeder tool prototype was used to both push and pull the cable through a full-scale UU WEC stator section using the experimental set-up shown in Fig. 12. Cable feeding velocities of up to 0.5 m/s through the stator section and up to 2 m/s feeding the cable through the feeder only were performed successfully. The normal force on the cable was set manually to prevent the cable from slipping against the feeding wheel. The use of a damping spring in order to keep a fairly constant normal force on the cable showed to be a really helpful function. The cable guiding system used to steer the cable though the feeder and straight into a stator slot hole proved to be very useful, avoiding buckling and wear of the cable and thereby

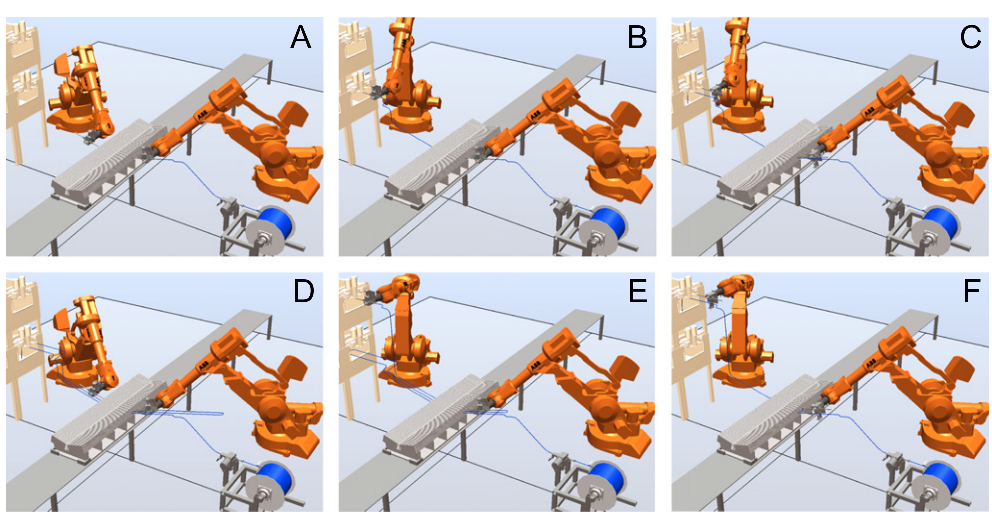

Fig. 11. A summary of the suggested robotized cable winding method, with one of the two robot pairs in one production cell. The cable is delivered from the cable drum holder and a cable parking is used to enable cable winding through two slots simultaneously. The process goes from step (A)–(F) and is repeated until all the slots are wound, after which a new cable is wound until the whole stator section is wound.

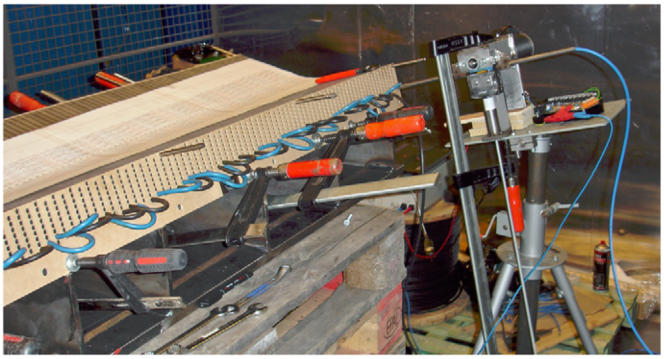

Fig. 12. Experimental setup used for validating the cable feeder tool function with a full scale UU WEC stator section.

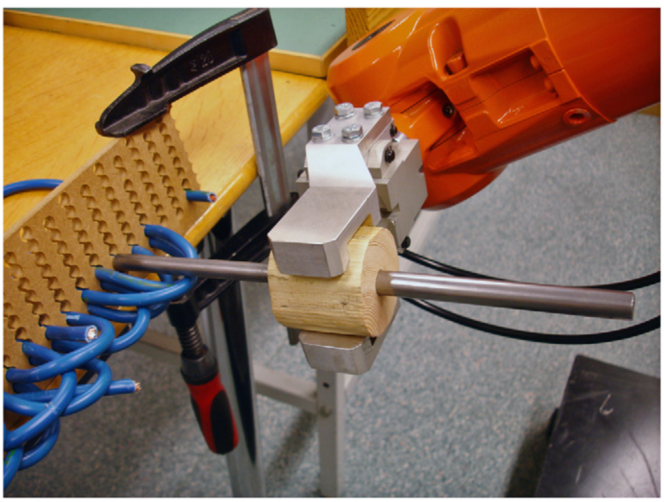

Fig. 13. Cable feeder tool dummy and the stator dummy used with an ABB IRB1400 robot in positioning experiments.

greatly facilitating pushing the cable through the stator section. Another benefit of using a cable feeder tool was that a constant cable feeding velocity, with a controlled maximum velocity, reduced the wear of the cable. An important result of this characteristic is that melting of the cable insulation as a cable is fed against an end winding can be avoided by keeping a high feeding velocity but avoiding the short extreme velocities that can occur during manual winding.

Finally, it was understood through the experiments that a cable feeder tool for robot winding must be robust and precise, both in construction and positioning, and enable a high normal force and a high feeding force on the cable. In addition, a sensor-based control system that can prevent the feeder from occasionally slipping against the cable might be a useful function for further experiments and development of the feeder tool.

The experiment thus both validated all the functions of the cable feeder tool prototype and suggested some future tool improvements.

6.2. *Experimental winding method and robot positioning validations*

An ABB IRB1400/5 kg M98 S4C industrial robot equipped with a cable feeder tool dummy was used for robot positioning experiments against an UU WEC stator section dummy, see Fig. 13. Within these experiments, it was validated that the industrial robot could provide the required positioning accuracy for the suggested cable winding automation method. This experiment also proved the functions to direct the cable end into a stator slot hole, to position the cable guiding system against a stator section side and to push away earlier wound end windings. Robot tool and work object coordinate systems were defined and the robot was programmed to move between the stator slot holes using these coordinate systems and offset values to simulate a three-phase cable winding pattern. All simulated movements from ABB RobotStudio were validated, only without the full reach of an ABB IRB4400/60 kg robot.

6.3. *Winding cycle time*

From the results of the robot cell winding simulation and the winding experiments with the constructed cable feeder tool prototype, the winding cycle time for one UU WEC stator section can be calculated. The total winding cycle time will be divided into robot positioning time and cable feeding time, while cable end connecting and stator section transportation will be neglected.

By analyzing the developed winding procedure in the robot cell simulation, it turns out that each robot pair must perform about 1800 positioning tasks during the winding of one stator section. A reasonable approximation from the robot cell simulation is that one such movement, including feeder tool tasks, takes on average four seconds to perform. Some examples of positioning tasks are to collect the cable end at the cable parking and position against a stator slot hole, to collect a cable that is fed through the stator section and position against the next slot hole, to drop a cable and position against a slot hole or to park a cable end at the cable parking. Positioning operations that can be performed simultaneously by both robots are counted as a single positioning. From this, the total robot positioning time during the winding of one stator section can be approximated to about 130 min, including additional operations such as preparing the cable end and measuring the position of the stator section.

Next, the total cable feeding time must be calculated. Since the robots work in pairs, it is important to separate between when the cable is fed through only one slot hole and when it is fed through two slot holes simultaneously. It is desired that the feeding should be done through two slots at the same time whenever possible, but during some winding operations this cannot be done. From the winding procedure explained in Section 5, it can be understood that these operations are when the cable end has been picked up at the parking and is fed through the stator section, when the cable is fed back through the stator and parked again and finally as the end windings on the cable drum stator section side are formed. Table 1 presents approximations of the necessary winding parameters for calculating the total cable feed length during the winding of one UU WEC stator section. The total feeding length per winding cable is calculated from the suggested robot winding principle. During the first and last feeding operations, the cable is fed through a single slot hole only, while the other operations utilize the cable parking to feed the cable through two slot holes simultaneously. For the last slot holes to be wound the cable parking cannot be used, this is however neglected in these calculations.

The total length of cable that must be fed by one robot pair during the winding of one stator section, i.e. the total cable feeding length, is easily approximated from the parameters in Table 1 to be about 2500 m. From the cable feeder tool prototype winding experiment, it was concluded that a reasonable cable feeding velocity through the stator section is about 0.5 m/s. The total winding cycle time can now be calculated using Eq. (3), where t_{tot} is the total winding cycle time, l_{feed} is the total cable feeding length per UU WEC stator section and robot pair, v_{feed} is the average cable feeding velocity and t_{pos} is the total robot positioning winding cycle time.

$$t_{tot} = \frac{l_{feed}}{v_{feed}} + t_{pos} \tag{3}$$

Table 1
Approximations of winding length parameters and calculated feeding length results, per robot pair, for the suggested automated winding cell and one UU WEC stator section with a three-phase winding pattern.

Parameter	Value
Number of cables per stator section	24 Cables
Average distance between cable parking and stator section	1.5 m
Total length of one (half) winding cable	12.6 m
Number of slot holes through which each cable is wound	22 Slot holes
Cable length per slot hole penetration, including end winding	0.55 m
Extra cable winding length	0.5 m
Total feeding length per winding cable	104.15 m
Feeding length first feeding, through a single slot hole	12.6 m
Feeding length second feeding, through two slot holes	14.0 m
Feeding length third feeding, through two slot holes	12.9 m
Feeding length fourth feeding, through two slot holes	11.8 m
Feeding length fifth feeding, through two slot holes	10.7 m
Feeding length sixth feeding, through two slot holes	9.6 m
Feeding length seventh feeding, through two slot holes	8.5 m
Feeding length eight feeding, through two slot holes	7.4 m
Feeding length ninth feeding, through two slot holes	6.3 m
Feeding length tenth feeding, through two slot holes	5.2 m
Feeding length eleventh feeding, through two slot holes	4.1 m
Feeding length twelfth feeding, through a single slot hole	1.05 m

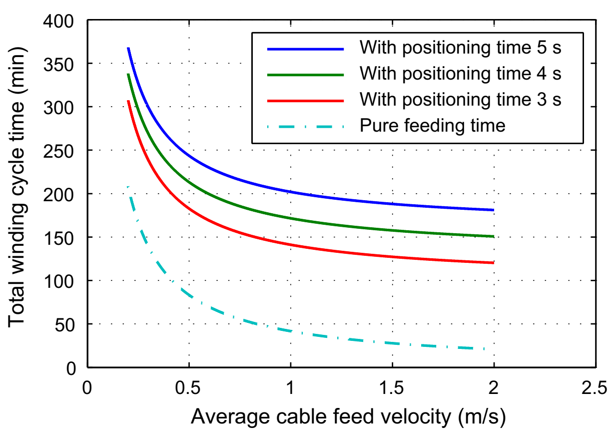

Fig. 14. Calculated total winding cycle times for one UU WEC stator section with the suggested automated winding cell for different positioning times, as a function of cable feed velocity. The dotted line represents feeding time only. All results are based on a three-phase wave winding pattern and the suggested winding method through two slots simultaneously.

The total winding cycle time results for some different average robot positioning times, as a function of cable feed velocity are shown in Fig. 14. Pure positioning time, as a function of cable feed velocity is also shown. For low cable feed velocities, the cable feeding time is the dominating part of the total winding cycle time, while positioning time is more important for high velocities. Faster robot positioning and higher winding feed velocities are both important tools to lower the total cycle time. A consistent first approximation is to use an average cable feeding velocity of 0.5 m/s, 4 s as average positioning time and the winding procedure explained in Section 5. This results in a total cycle time of about 215 min. In this case, the robot positioning time is longer than the cable feeding time.

Apart from speeding up the cable feeding and robot movements, one approach for optimizing the cycle time is to adjust the winding method, for example by pulling the cable through more slots at the same time using guiding wheels for the cable on the sides of the stator section or excluding the cable parking and feeding the cable through the slots one by one. It is even possible to change the winding pattern and number of winding phases, but this approach will of course also change the electromagnetic machine design. Fig. 15 shows the total winding cycle time, separated into positioning time and feeding time, with different winding methods and different winding patterns. Some important winding parameters for these approaches are shown in Table 2. Three-phase winding results in more but shorter cables to be wound, while one-phase winding results in fewer but longer cables, compared to the two-phase winding pattern. Both winding the cable slot-by-slot, without the cable parking function, and winding through four slots simultaneously reduces the number of robot positionings required. Slot-by-slot winding involves the fewest positionings and the longest total cable feed length, while four-slot winding has the shortest feed length for two-phase and three-phase winding patterns. For the chosen cable feed velocity and average positioning time, the shortest total winding cycle time of an UU WEC is reached using a three-phase winding pattern. In this case, the different winding methods give similar results. With two-phase and one-phase winding patterns, feeding the cable through more slot holes simultaneously lowers the total cycle time.

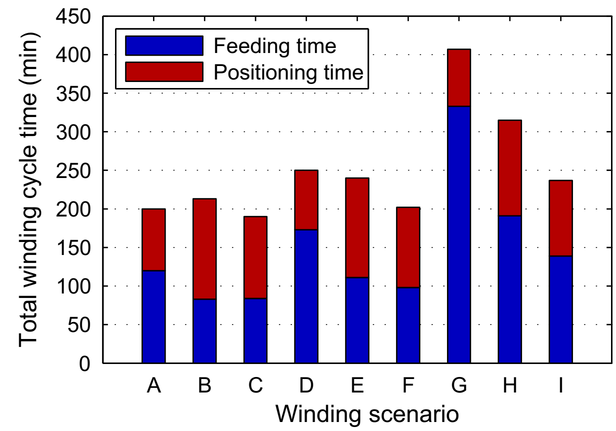

Fig. 15. Total winding cycle time for some different winding scenarios, separated into positioning and feeding time. Scenario (A), (B) and (C) are for three-phase winding pattern, while (D), (E) and (F) are for two-phase winding and (G), (H) and (I) are for one-phase winding. Scenarios (A), (D) and (G) represent winding slot-by-slot, while (B), (E) and (H) represent winding through two slots simultaneously and (C), (F) and (I) represent winding through four slots simultaneously. All scenarios are using 0.5 m/s average cable feed velocity and 4 s average positioning time.

Manual winding of an UU WEC stator section, based on the stator design and three-phase winding pattern discussed in this article, has been performed at Uppsala University for two different WEC units, both with four stator sections each. All eight stator sections were manually wound by two personnel, resulting in a manual winding cycle time per stator section of about 40 h. An important observation from this manual production was that the winding task is very tiresome and boring for the workers. Experience from winding these stators, and from winding somewhat different stators for earlier UU WECs, implies that manual cable winding occasionally introduces human errors, especially when complicated winding patterns are used. These issues are essential arguments for automated cable winding.

6.4. Economical analysis

To make an economical analysis of automated winding, the total investment cost of one robotized cable winding production cell, as presented in this article, must be roughly estimated. The dominating cost unit is the industrial robots. It is likely that pre-owned robots of older models can be used for this task, thus reducing the total investment cost substantially. Approximations of the different cost units are shown in Table 3. From these costs, the total investment cost can be calculated to be about 282,000 EUR using new robots and about 182,000 EUR using older robots. However, the following calculations will assume that new robots are used.

Table 2
Winding and positioning parameters, per robot pair, for automated winding of one UU WEC stator section with different winding methods and winding patterns.

Parameter	Value
Number of cables per stator section one-phase winding	24
Number of cables per stator section two-phase winding	16
Number of cables per stator section three-phase winding	8
Total feeding length per winding cable one-phase, slot-by-slot winding	1249 m
Total feeding length per winding cable one-phase, two-slot winding	717 m
Total feeding length per winding cable one-phase, four-slot winding	521 m
Total feeding length per winding cable two-phase, slot-by-slot winding	325 m
Total feeding length per winding cable two-phase, two-slot winding	207 m
Total feeding length per winding cable two-phase, four-slot winding	184 m
Total feeding length per winding cable three-phase, slot-by-slot winding	150 m
Total feeding length per winding cable three-phase, two-slot winding	104 m
Total feeding length per winding cable three-phase, four-slot winding	106 m
Number of positionings one-phase, slot-by-slot winding	1064
Number of positionings one-phase, two-slot winding	1816
Number of positionings one-phase, four-slot winding	1432
Number of positionings two-phase, slot-by-slot winding	1072
Number of positionings two-phase, two-slot winding	1856
Number of positionings two-phase, four-slot winding	1472
Number of positionings three-phase, slot-by-slot winding	1080
Number of positionings three-phase, two-slot winding	1824
Number of positionings three-phase, four-slot winding	1464

Table 3
Investment cost by cost units for the presented automated winding cell.

Cost unit	Investment cost	Number of units	Total cost
New industrial robot	50,000 EUR	4	200,000 EUR
Pre-owned industrial robot	25,000 EUR	4	100,000 EUR
Cable feeder robot tool	8000 EUR	4	32,000 EUR
Cable drum holder	5000 EUR	1	5000 EUR
Cable parking	20,000 EUR	1	20,000 EUR
Stator section feeding and positioning table	10,000 EUR	1	10,000 EUR
Cell enclosure, safety, control and installation	15,000 EUR	1	15,000 EUR

The production of one automated robot cell, one stator section per 215 min, should be compared to the production through manual winding, one stator section per 20 h with four personnel. This gives a rough approximation that the production of one robotized winding cell is equal to the production of about 5.5 manual winding cells. By comparing the investment and running costs for one automated robotized winding cell to the running costs for 5.5 manual winding stations, an economical evaluation of the robot cell can be performed. The cost parameters for both manual and automated winding are presented in Table 4. The investment cost for a manual winding cell is neglected.

Using Eq. (1), the net present value of the winding automation investment, compared to manual winding, can be calculated to about 7,000,000 EUR. The payback period, compared to manual winding, can be calculated from Eq. (2) to about two months. Fig. 16 shows the total cost per year, divided into major cost units, for manual and automated cable winding. The dominating cost difference between manual and automated cable winding is the personnel cost, which is very high with manual winding. Fig. 17 shows the accumulated costs and cost difference for manual and automated cable winding during the economical lifetime of the robot cell investment.

7. Conclusions

Using cable winding technology in electric machine stators is likely to facilitate automated production compared to using conventional winding techniques. Production steps such as pre-insertion of insulation in the stator slots, possible insertion of pre-wound coils into the stator slots and winding fixation are eliminated and the need for connecting end windings is reduced compared to conventional windings. Apart from the electrical benefits of cable wound machines, the concept is also suitable for automated production.

Previous research indicates that automated stator winding in production is an important but at the same time complex field. Automation methods for stator winding of conventional electric machines have been developed and implemented in production lines for many years. However, since cable wound stators are not very common today, a published method to automate cable winding has not been found. Advances in robot technology, together with high flexibility demands, make industrial robots suitable for implementation in a solution to this problem. Existing winding automation methods for conventional stator winding cannot be used for cable winding automation.

A production method using industrial robots for automation of cable winding of electric machines has been suggested in this article.

Table 4
Cost parameters for both manual winding and the suggested automated winding cell.

Parameter	Winding cell	Value
Winding personnel cost	Manual winding	20 EUR/h
Number of personnel per winding station	Manual winding	4
Factory floor space per winding station	Manual winding	12 m^2
Winding personnel cost	Automated winding	30 EUR/h
Number of personnel	Automated winding	0.5
Factory floor space	Automated winding	32 m^2
Power consumption	Automated winding	60 kW
Yearly robot and cell equipment maintenance cost	Automated winding	30,000 EUR
Investment economical lifetime	Automated winding	5 years
Investment discount rate	Automated winding	4%
Robot cell installation and commissioning cost	Automated winding	25,000 EUR
Investment cost	Automated winding	282,000 EUR
Investment rest value	Automated winding	75,000 EUR
Number of manual stations per automated winding cell	Common parameter	5.5
Factory floor space cost	Common parameter	0.1 EUR/m^2/h
Electricity cost	Common parameter	0.1 EUR/kWh
Yearly winding production time	Common parameter	4000 h

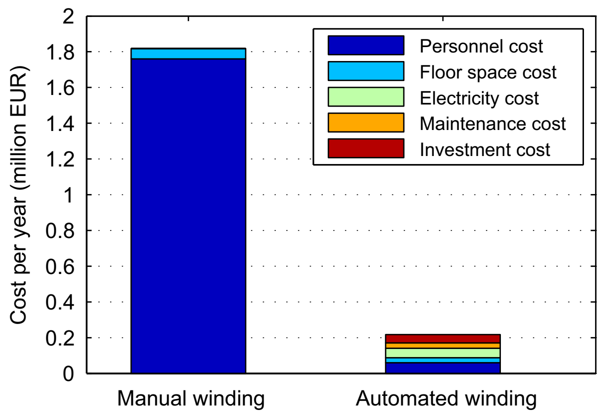

Fig. 16. Yearly cost for manual and automated cable winding, divided into major cost units and compared as described in Section 6.4.

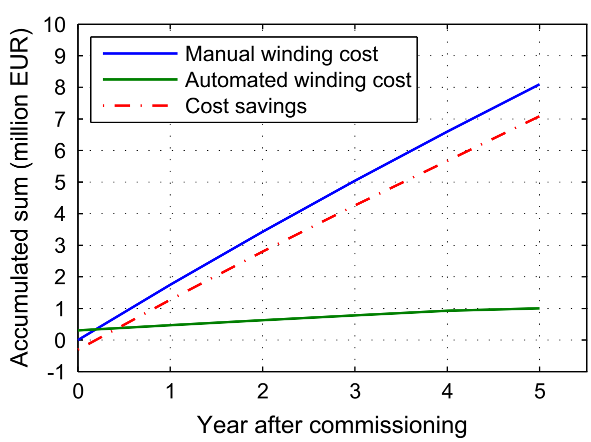

Fig. 17. Accumulated costs and cost difference for manual and automated cable winding during the economical lifetime of the robot cell investment, compared as described in Section 6.4.

The function of the method has been validated by computer simulations, robot positioning experiments and experiments using a constructed cable feeder tool prototype to feed cable through a stator. Using a linear, cable wound UU WEC generator stator section as an example, considerably production time and production cost savings are indicated compared to manual winding. However, manual cable winding is not performed today in serial production. An economical analysis comparing manual and automated cable winding can therefore only investigate two hypothetical cases. Since manual cable winding is a very personnel-intensive and time consuming task, it is also very costly and thus not suitable for large scale production. The automated winding solution suggested in this article does as a result have a very high net present value and short payback period compared to the hypothetical manual winding case.

The suggested method is adapted to fit into a production line and is very flexible in order to make it possible to use this method for many different cable wound electric machines. For example, cable wound stators of different sizes, shapes, with different cable dimensions and with different winding patterns can be handled. For this, only small adjustments to the feeder tool is needed, mainly regarding the cable guiding size, the feeding wheel size and the feeder motor torque. Also, different robot models can be used and the robot programming is easily changed to different winding scenarios. For stator winding with cables of a much larger diameter than the cable used in the UU WEC example in this article, the cable feeder tool feeding mechanism may need to be adjusted for much higher feeding forces and larger cables.

More work is needed to improve the cable feeder tool, e.g. adding sensors to supervise and facilitate the winding, to construct side equipment and more. There is a large potential to reduce the winding cycle time further within the suggested winding automation, for example by increasing the cable feed velocity through the stator, improving the winding procedure and reducing the feeder tool operation time and robot positioning time. When deciding on a suitable cable winding automation method and adjusting the winding parameters, aspects such as desired winding pattern, cable lengths, cable wear and method complexity must be considered as well. However, if an automation method for cable winding is developed further and prepared for industrial implementation, this will be an important improvement of the production of direct drive machines, such as the Powerformer. Automated cable winding should then be more carefully compared to conventional stator winding production.

Some interesting areas for the application of such machines are wind power [39–42], hydropower [43,44], wave power [36,37], thermal power [43] and high-voltage motors [45–47].

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