Preparing the Uppsala University Wave Energy Converter Generator for Large-Scale Production

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Abstract

A technology for converting wave energy to electric energy has been developed at Uppsala University. The system uses a linear direct-drive permanent-magnetized cable wound generator and is intended to be used in farms of up to 1,000 units each. Since the start of the project in 2001, the system has evolved in many aspects, especially the generator. In the present version, the third generation design, the focus has been on lowering the costs and thus facilitating large-scale manufacturing. This paper presents the most important design adjustment introduced in the third generation design and relates these changes to the material cost of the generator as well as to the potential benefits in automated large-scale production. The most important change with the new generator design is the change from $Nd_2Fe_{14}B$-magnets to ferrite magnets on the translator. Recent developments on finding suitable robotized automation solutions for some major generator sub-assemblies are presented as well as those remaining to be done. With the new design, the total generator cost has been much reduced and large potential cost savings through robotized production are indicated. It is reasonable that similar investigations will be crucial for all new renewable energy technologies striving to be competitive on the market.

Keywords: Wave Energy Converter, Large-Scale Production, Cost Reduction, Ferrite Magnet, Industrial Robot Automation

1. Introduction

The wave power technology in this article has been developed at Uppsala University (UU), Sweden. The wave energy converter (WEC), consisting of a direct driven linear generator installed at the seabed, connected by a line to a point absorbing buoy, is illustrated in Figure 1. The direct driven magnetic part of the generator, the translator, follows the motion of the heaving ocean waves. Intermediate energy storages and gearboxes are removed, to increase the lifetime of the system. The first full-scale wave energy converter was installed in 2006 and the experimental site has been continuously updated ever since. Up until the autumn of 2013, eleven different WECs and two marine substations have been deployed. The deployed units have proven their ability to convert the energy in the ocean waves and transmit the electrical energy onshore (1). The latest status update of the project can be found in (2).

As the system evolves, the importance of the economical perspective increases and the reduction of both the material and the production costs has a major impact on the system's final design. The UU WEC generator is designed for use in farms of up to 1,000 units. Hence the required production volumes are suitable for automated production lines. To achieve this it is important to keep production in mind from the start. The latest full-scale prototype, L12, is the first design in the third generation (G3). Steps have been taken to reduce the cost of manufacturing as well as to choose environmentally friendly materials. The first two L12 generators were deployed outside the city of Lysekil, at the Swedish west coast, in March and July 2013.

The ambition of this paper is to introduce the major generator design changes introduced in the G3 design compared to the second generation (G2) of the UU WEC and to relate them to large-scale production. The possibilities for large scale automated production and assembly will be outlined and exemplified. For reference, a corresponding investigation of the G2 UU WEC generator design can be found in (3).

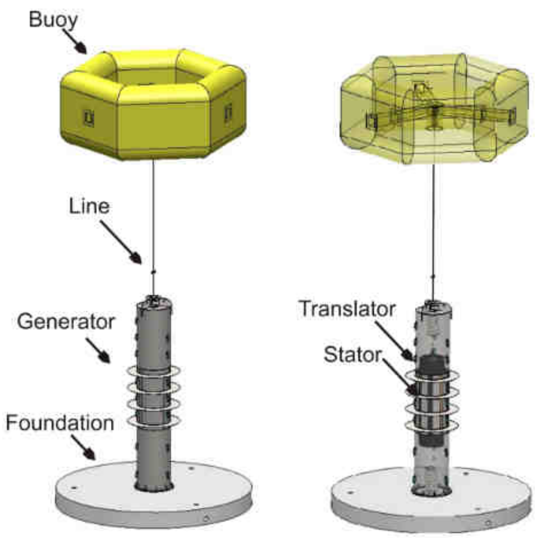

Figure 1: The third generation (G3) of the Uppsala University (UU) Wave Energy Converter (WEC) generator design

2. Generator design

The mechanical and magnetic design of the G3 UU WEC is highly affected by reducing the material and production costs. As in the G2 generator, a direct driven linear generator with a cable wound laminated stator and permanent magnetized translator are used to simplify the design and increase the efficiency and robustness. However, the translator has been completely redesigned for cost reduction by replacing the $Nd_2Fe_{14}B$-magnets from the previous design with ferrite magnets which are less strong but are more environmentally friendly and cost less. To achieve a higher rated power, a pole shoe design has been implemented, which has increased the magnetic material mass compared to the previous surface mounted magnet design. An increased active area has been reached by replacing the eight-sided stator is with a nine-sided design and the number of winding slot hole levels in the stator is increased from eight to ten. The nine sides of the stator are divided into three stator sections, each with three stator stacks which are wound together. Each stator section is wound with a single phase. By mechanically displacing the stator sections 120 electrical degrees relative to each other, a three phase generator design was achieved. The magnetic circuit of the generator is presented in Figure 2.

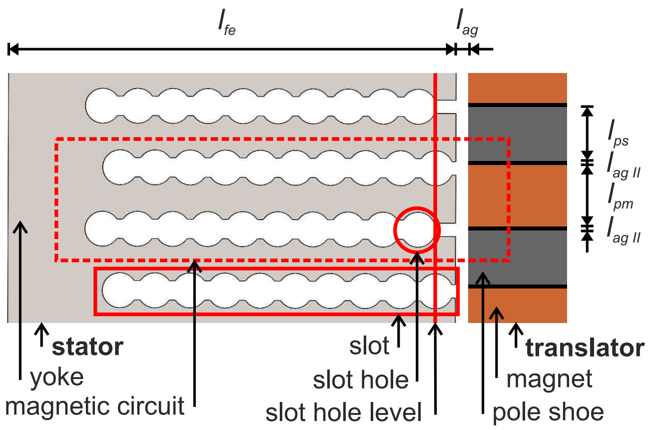

Figure 2: The magnetic circuit of the G3 UU WEC generator

The final generator design was achieved with numerical software calculation and simulation tools as well as results from experiments. In order to simulate the electric machine's behavior at different electrical load conditions, electromagnetic simulations utilizing FEM were performed. The electric and magnetic field within the electric machine is assumed to be axis-symmetrical and is therefore modelled as a two dimensional object. Three-dimensional effects such as end region fields are taken into account by introducing coil end impedances in the circuit equations of the windings. The machine parts are assigned different material properties such as conductivity, permeability, density, sheet thickness etc. and the permanent magnet is modelled by a surface current source. The mesh is finer when close to more interesting parts like the air gap and coarser in areas such as the back iron of the stator. The electromagnetic model is solved in the finite element environment ACE (4). Simulations can be performed either in a stationary mode, where the results are given for a fixed translator position, or in a dynamic mode including time-dependence. The numerical calculations have been verified with experimental results for different generators (5-8), and are further described in (9). A numerical simulation tool is used in order to simulate the mechanical behavior of the electric machines at different mechanical load conditions. The numerical simulation tool works with three-dimensional models, combining one or more components. Simulations can be performed either in a stationary mode where the results are given for a fixed load, or a dynamical mode including fatigue. The mesh for each part is defined separately. The final core design properties of the generator are presented in Table 1.

Parameter	Value
Hull height	6000 mm
Hull diameter	1091 mm
Translator height	3000 mm
Stator height	1976 mm
Number of stator sections	3
Number of stator sides	9
B_r	0.45 T
H_c	330 kA/m
Length of stator teeth	100 mm
Length of air gap l_{ag}	3 mm
Length of air gap inside translator $l_{ag\,II}$	0.5 mm
Length of permanent magnet l_{pm}	19 mm
Length of pole shoe l_{ps}	15 mm
Pole width	35 mm
Rated average power (at installation site)	30 kW

Table 1: The main design properties of the generator

3. Production and assembling

A large scale production line for the UU WEC generator is planned for the G3 design. The ambition is to use as little intermediate storage as possible, to avoid unnecessary transportations, to have clear and logical sub-production lines and to automate and integrate as much of the production line as possible. In contrast to similar large scale production lines, e.g. in the vehicle industry, the UU WEC production line should use as few sub-suppliers as possible. Thus, mainly raw material will enter the building and is processed in the production line. As far as possible, the construction steel used for the different generator parts is laser cut from large sheets, which are limited to two different thicknesses and to local transportation capacities. The desired initial production pace is one finished generator every third hour, i.e. three hours per major sub-assembly since these are to be performed simultaneously. However, by using a scalable production line design, the production pace will also be scalable.

Thanks to their high flexibility, it is believed that industrial robots can perform most of the handling, processing and assembly operations required for the generator production. The production line includes welding, painting and simple pick-and place operations which are suitable for industrial robot automation. Another advantage with robots is that there is a large market of pre-owned robots, which can reduce the crucial initial investment cost for the start-up production.

As a starting point towards a completely automated production, three key production steps have been identified: stator stacking, stator winding and translator assembling. These production steps are all time consuming, labor intense, costly, heavy, hazardous, repetitive, and/or lack suitable existing automation solutions. The research on production automation for these three production steps is discussed in subsections 3.1-3.3 while subsection 3.4 shortly discusses some other research activities in that field at UU.

3.1 Stator stacking

The nine sides of the UU WEC generator stator are stacked separately with thin stator sheets. The stacking is done on a bottom plate fixture; see Figure 3. This facilitates the ensuing assembly chain by enabling easy identification and providing uniform lifting and positioning points. The stator sides are fixed with eight threaded plastic rods and nuts and are screwed to the bottom fixture with four dove tails.

Stator stacking is a very repetitive and time consuming task, requiring large reach, medium high accuracy and medium high stiffness and is thus suitable for industrial robot automation. A robotized stator stacking method for the G2 UU WEC stator has been developed and demonstrated by UU (10). The most important differences when stacking the G3 stator are an increased number of slot hole levels, a larger slot hole diameter, a narrower yoke and an increased number of stator sides. It is likely that the same robot stacking tool concept as for the G2 stator, with rubber-damped electromagnets, can be used with the G3 stator.

Ongoing research for robotized stacking at UU has shown that the same electromagnets, only slightly adjusted in position on the robot tool, can be used for lifting the G3 stator sheets. A higher payload robot, equipped with a stiffer robot tool, has been shown to reduce vibrations during the assembly; see Figure 4. With the stator sheets delivered in well-organized piles inside a well-defined frame on a pallet, the work object positional calibration is facilitated since the robot only needs to know the position of the pallet in order to know the position of all the piles. With even stator sheet piles to pick from, the automation robustness is also improved, since the risk of large relative displacement of the sheets in the same pile is eliminated. The robustness could also be improved by refining the control of the voltage level to the electromagnets and introducing supervision of the lifting force. The stacking fixture can easily be adjusted for the bottom plate fixture and to facilitate lifting out the finished assembly, e.g. with linear pneumatic actuators on both short ends of the fixture. A robot tool for automation of the threaded rod assembly step, to be handled by the same industrial robot through an automatic tool changer system, is under development at UU (11). A similar solution is needed for the dove tail assembly step so as to fully automate the stator stacking.

From a recent robot stacking experiment on the G3 UU WEC stator, it is reasonable to assume that picking up the stator sheets from the pallet frame will take somewhat longer compared to the previous robot stacking concept, while the need for measuring the position of the stator sheets during stacking has been eliminated. Based on this, the total handling time per G3 stator sheet can be approximated to about 5 s. Additionally, it can be estimated that about 3 min are needed for the in-flow of components, about 2 min are required for the threaded rod robot assembly (11) and about 10 min are needed for manually screwing the dove tails and lifting out the finished stator side. This results in a total cycle time of about 35 min per stator side. One full G3 UU WEC stator could therefore be stacked in about 315 min and two parallel robot stacking cells would be needed to fulfil the desired production pace.

Figure 3: A G3 UU WEC stator being manually stacked

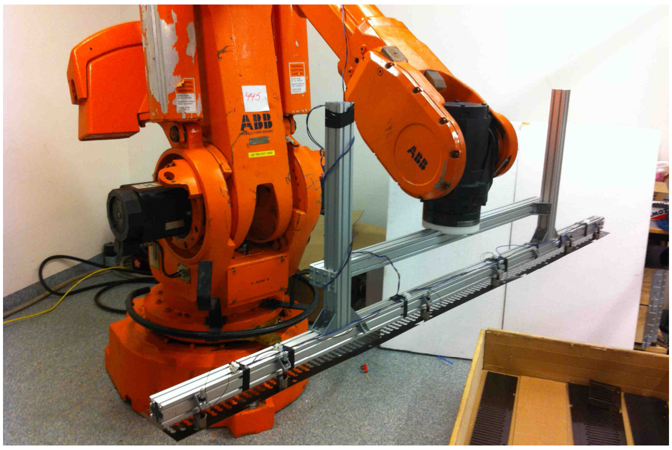

Figure 4: An industrial robot lifting a G3 UU WEC stator plate using a prototype stacking tool currently under development

3.2 Stator winding

The nine-sided stator is divided into three sections, one for each phase; see Figure 5. These stator sections are wound straight, in line. To achieve the angle between the different stator parts, the sections are folded relative to each other before installation in the generator hull; see Figure 6. The winding cable is wound through the stator slots in a single phase wave winding pattern with two cables per slot hole level. The bottom eight slot hole levels are wound separately for the three sides of the stator sections, while the two top levels are wound through the full stator section before being folded. The bottom plate fixtures are used to position and fix the stator parts on winding fixtures during the winding and during the folding, while also providing lifting points for mounting the wound stator sections into the generator hull.

Stator cable winding is a very repetitive and time consuming task, requiring large reach, medium high accuracy and handling medium high assembly forces and is consequently suitable for industrial robot automation. The only existing cable winding automation method is the robotized cable winding concept for the G2 UU WEC stator that has been developed and demonstrated by UU (12-14). The most important differences when winding the G3 stator are that the stator sides are now partly wound separately and that the stator sections are folded after being wound. Furthermore, the winding scheme is simplified to single-phase wave winding, with two cables per slot hole level. As a result, more compact end windings can be achieved. The winding cable diameter is increased to about 9 mm and the number of slot hole levels to wind is increased to ten. It is likely that the same robot winding and cable feeder tool concepts as for the G2 stator can be used for the G3 stator design. However, temporary cable storage equipment is required for the new winding scheme. It will also be important to automate the winding of the two top slot hole levels and the folding of the stator sections.

Figure 5: A cable wound G3 UU WEC stator section, (**Left**) before being folded and (**Right**) after being folded

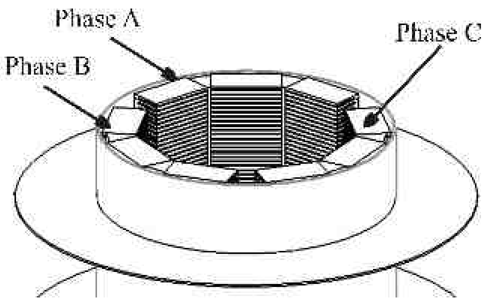

Figure 6: The nine-sided G3 UU WEC stator mounted inside the generator hull

Ongoing research on robotized cable winding at UU focus on adapting the cable feeder tools and the cable drum feeder to the new stator design. The tool design is adjusted to increase process robustness and to improve control and communication. Previous robot winding experience with the G2 stator and the manual winding experience of the G3 stator indicate that a higher feeding force is required to ensure that all the end windings are pulled correctly. To achieve this, a higher normal force between the feeding wheel and the cable is required. In addition, monitoring of these forces, combined with an improved cable feed length measurement system, could be implemented to further improve the pulling of the end windings. Combined with a reliable sensor system that detects when the cable is dropped from the tool, this could possibly eliminate the need for manual supervision. Furthermore, since the new winding cable has a lower friction surface, it is likely that the cable feed velocity can be increased. By moving the main cell control from the industrial robot controllers to a single industrial PLC system, improved data handling capacity, communication and synchronization could be achieved without changing to newer robots. To fully eliminate the need for manual work within the cell, automated solutions for cutting the cable and forming the cable ends need to be developed and implemented.

So far, no robotized stator winding experiments have been performed on the G3 stator. It is however reasonable to assume that, compared to the robot winding of the G2 (12), the average robot positioning time is kept to 4 s, the average cable feed velocity is increased to 1 m/s and a slot-by-slot winding procedure is used for the robot winding of the G3 stator. With the calculation procedure from (12), and adding about 90 min for the positional calibration of the stator parts (13) plus the inflow and outflow of components, the cycle time for the robot winding of the eight lower slot hole levels on the complete stator can be approximated to 16 h. Six parallel robot winding cells are needed to fulfil the desired production pace.

3.3 Translator assembling

A robotized PM surface mounting method for the G2 UU WEC stator has previously been developed and demonstrated by UU (15,16). However the G3 translator is completely redesigned, with a new magnetic material and more of a big sandwich structure alternating between magnets and steel; see Figure 7. The $Nd_2Fe_{14}B$-magnets used in the G2 came with a protective metallic coating and were relatively hard and wear-resistant, while the G3 ferrite magnets are unprotected and are in comparison very brittle, with a structural integrity closer to that of untampered-glass or burnt-clay. Hence, since the magnet at one point has to make an uncontrolled jump to the translator surface, the assembly approach presented in (15) is unsuitable for use in the G3 translator assembly as it would damage the ferrite magnets.

The development of an automated robot cell for the G3 translator assembly is currently in the start-up stage. At present the focus is on finding methods for handling the brittle magnets. A prototype robot cell, with a large reach and high handling capacity robot, as well as a rotary table, on which the translator is to be placed, have been set up; see Figure 8. In this way, one robot is able to reach all sides of the translator. In the prototype cell, the magnets are handled by a robot tool equipped with a vacuum suction cup, which is surrounded by plastic guiding walls. The holding force has been shown to be sufficient to hold the ferrite magnet in place in the presence of solid steel and other magnets. Thus, the robot can gently place the magnet in its place, avoiding uncontrolled jumps. Another important tool in development is the plate-lifter, designed to lift and place the translator pole shoes. This is done with electromagnets with a holding force at around 2.5 kN. This force is required to be able to withstand the attractive force, in the range of 1 kN at one mm distance, as the pole shoe is gently assembled on four already assembled ferrite magnets. Currently, work is also carried out in building a smart control system for these electromagnets, not limiting them to an on/off operation but instead allowing a more precise control of the lifting force. The third important robot tool is the bar-handler, which picks up and fastens the nuts and threaded bars used to fixate the translator structure. The main components of this tool are a pneumatic wrench and long arms which should stabilize the up to 500 mm long threaded bars. To reduce costs, no torque feedback is used. Instead the torque will be controlled by the air pressure to the wrench. Since the structure contains both M8 and M10 threaded bars and nuts, the wrench socket is specially designed to be able to take both dimensions, thereby eliminating the need to change socket or have an additional wrench.

The initial experimental results are promising and suggest that placing four magnets and putting a pole shoe on top could be done in about 60 s. With twelve magnets and three pole shoes per layer in 72 layers, the whole assembly could be done in approximately 3.5 h. Adding the time for the bar-handler to fasten every eighth layer and for the robot to do positioning and measuring, the final assembly time should be around 5-6 h. Hence, either one robot cell with two robots or two robot cells with one robot each would be needed to complete the translator assembly at the desired production pace.

Figure 7: A G3 UU WEC translator

Figure 8: An experiment with an industrial robot assembling ferrite magnets on G3 UU WEC pole sheets placed on a rotary table

3.4 Other automation developments

A robot tool layout for picking, sorting and delivering the G2 UU WEC components that are cut in a laser cut machine has been designed (17). Further development work is needed to adjust this tool for handling the G3 parts. Other G3 UU WEC generator production steps that are investigated at UU are machining operations where the production pace is rather low and the required tolerances are rough to medium high. Using industrial robots in such tasks can improve the production flow, since the robots can also handle the produced parts, the inflow, the additional process steps, the assembly, the quality control and the outflow.

One such machining task is robotized machining of dove tails (18-20). The dove tails are used to mount the stator sections and bearings inside the generator hull. The concept is that the robot picks up a laser cut steel bar, which is then positioned and moved by the robot against stationary drilling, threading and milling machines. In order to minimize vibrations, the robot tool is supported by sliding against stationary low friction surfaces. Finally the completed dove tail is delivered to the ensuing assemblies. There remains work to be done on e.g. evaluating the robustness of the method, the quality variations and the machining tool wear. However, the results from earlier and recent developments indicate that the required dimensional tolerances for the dove tails could be achieved with the investigated method. From these results, the achievable total cycle time for machining all dove tails used in one G3 generator is estimated to be roughly 15 h. Hence, five robots will be needed to achieve the desired production pace.

Another robotized machining method is the machining of rubber damping discs (21). These rubber discs are used as dampers in the generator. The concept is that a milling machine, mounted on the robot tool, is used to cut the discs from a large rubber sheet. The robot tool is also equipped with pneumatic suction cups to sort the cut parts and with an air blow nozzle to clean the table from rubber chips. There is work remaining on e.g. evaluating the tool wear, the handling of the rubber chips and designing the side equipment. However, the results from earlier and more recent developments indicate that the required dimensional tolerances for the rubber discs can be achieved with the investigated method. It has been estimated that the desired production pace can be fulfilled with one robot.

4. Large-scale production

With the G3 UU WEC generator design, the material cost of the generator is reduced with up to 50 % compared to the G2 design. The most important reason for this cost reduction is shift from using ferrite magnets to using $Nd_2Fe_{14}B$-magnets on the translator. Even though a much higher magnet volume and mass is used in the G3 design, the magnet cost per generator is reduced to less than 10 % compared to the G2 design. A rough estimation is that the material costs are about two thirds of the total G3 generator cost, while production costs are about one third.

The cycle time estimations for the robotized production steps presented in Section 3, can now be roughly compared to a manual production in terms of the number of robots and number of labor required to realize the desired production pace; see Table 2. The required number of staff for a manual production are extrapolated from the present manual production cycle times at Seabased Industry AB[1]. Regarding the number of labor required per robot cell, the numbers are rough estimations for the early stage of the implementation, including the need for some supervision and manual operations. For the stator stacking, stator winding and translator assemblies, the corresponding numbers for the G2 generator are extrapolated from earlier experimental results (10,12,15). It should however be noted that the values for the stator winding of the G3 include only the winding of the bottom eight slot hole levels and that the values for the translator assembly of the G2 include only the mounting of the magnets.

The results in Table 2 can also be used to give a very rough indication of the potential production cost savings through robot automation for the discussed production steps. To be able to do this in a general way, with the very limited amount of data, two very rough assumptions were made. First, the cost per industrial-robot operator labor was approximated to be 120 % of the cost per assembler labor. Secondly, it was assumed that all other robot cell life-time

[1] A spin-off company from UU, commercializing the UU WEC concept using the G3 generator design.

costs were directly related to the number of robots used and that this cost per robot was about 50 % of the cost per assembler labor. With these assumptions, it was possible to work out an indication of the potential cost savings in relation to the cost for manual production, without using any actual values. The result, indicating large cost savings especially for robotizing the stator winding and translator assembly production steps, is presented in Figure 9.

By summarizing all the presented costs for manual and robotized production for the G3 generator from Figure 9, the total estimated production cost savings with robot automation can be estimated to two thirds compared to manual production. Hence, it is indicated that the total cost of the G3 UU WEC generator can be reduced with about 20 % using robot automation.

Finally, a simplified draft of a complete G3 UU WEC generator production line can now be outlined; see Figure 10. This draft includes illustrative placements of industrial robots for the automated production steps as well as for the pick-and-place from the laser cutter, the welding of the hull and the painting. The guiding and transmission system sub-assemblies and the final assembly are assumed to be manual in the beginning.

Production step	Number of labor *G2*	Number of labor *G3*	Number of robots *G2*	Number of robots *G3*
Manual stator stacking	12	4	0	0
Robot stator stacking	2	1	2	2
Manual stator winding	54	36	0	0
Robot stator winding	3	3	20	24
Manual translator assembly	28	21	0	0
Robot translator assembly	1	1	1	2
Manual dove tail machining	-	5	-	0
Robot dove tail machining	-	1	-	5
Manual rubber machining	-	2	-	0
Robot rubber machining	-	0.5	-	1

Table 2: A summary of the number of labor and robots required to perform manual and robotized operation of the previously described productions steps with the desired production pace

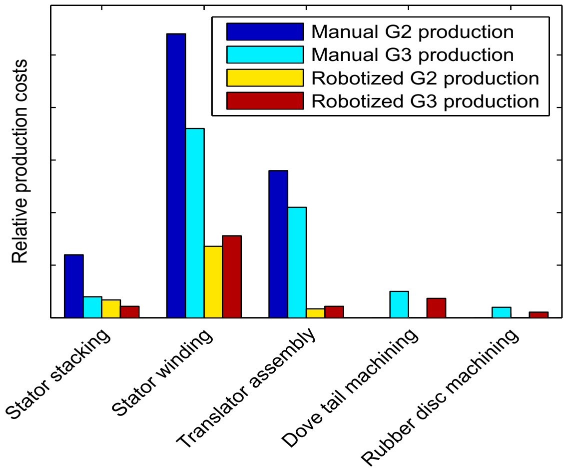

Figure 9: Very rough indications of potential production cost savings, in relation to manual production, for the presented UU WEC generator production step automations

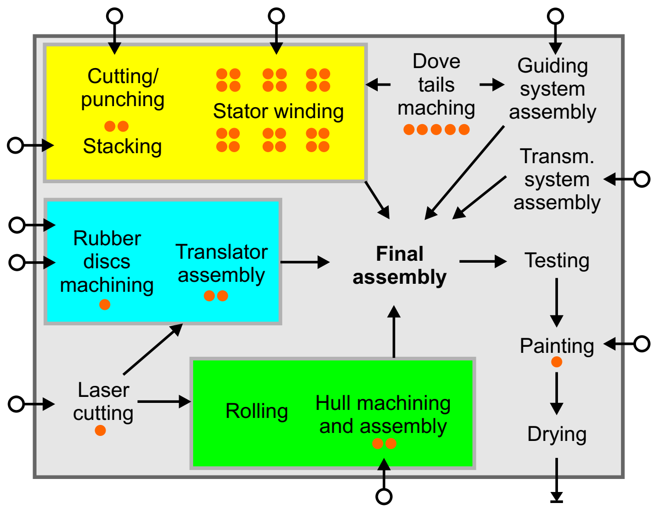

Figure 10: A simplified draft of a complete G3 UU WEC production line, where the stator sub-assembly line is highlighted in yellow, the translator sub-assembly line is highlighted in blue, the hull sub-assembly line is highlighted in green, industrial robots are illustrated with orange dots, the inflow of material into the production line is illustrated with circles followed by arrows, the main flow of parts within the production line is illustrated with simple arrows and the outflow of finished generators is illustrated with an arrow followed by a straight line

5. Discussion

Sustainability as well as economy and production have been a major focus during the design of the G3 UU WEC generator. A considerable amount of knowledge has been gained during the development. The most important difference of the G3 generator, compared to earlier designs, is the ferrite and pole shoe based translator. This change, as well as the increased active area, the decrease of the machined surfaces and the reduction of the material used, put higher demands on the analytical and numerical calculations as well as on the mechanical tolerances in the system. Hence the manufacturing and assembly of the different parts are important and need attention as well. As the UU WEC project has evolved, the generator design has been adjusted step-by-step for production. With the G3, the design is now ready for production. The development of an automated production line can now be accelerated.

The material costs for the G3 generator design are much lower compared to the G2 generator. Still, there are probably several smaller steps to be taken in in this direction, which together can make an important contribution. As the production volume is further increased, it will be possible to further reduce the material costs, as larger volumes will generate better prices attract more potential sub-suppliers. For very high volumes, it might be economically favorable to move more production steps in-house, such as producing the ferrite magnets. It is also probable that the generator can be further improved in terms of rated power in relation to material costs. As the material costs thus are further decreased, the production costs will become relatively larger.

As concluded already for the G2 generator, completely new assembly methods are required mainly for the stator winding and the translator assembly tasks. From Table 2 and Figure 9, it is clear that the stator winding and the translator assembly are overall the most resource demanding production steps, with the highest potential cost saving through robot automation. So it is crucial to continue focusing on developing these automations. It would also be preferable to, if possible, further adapt the stator design for facilitate robot winding, as this production step is indicated to be the far most costly. Developing a fully working robotized stator stacking for the G3 is likely to be mainly a matter of adjusting the G2 robot stacking solution and increasing the robustness of the automation. Regarding the machining of the dove tail and the rubber discs, further work is required to determine e.g. the quality variance, the robustness and the need for maintenance. An alternative method could be to have robots feeding CNC and punching machines. For the other main sub-assembly steps, it is plausible that the guiding system assembly could be fully automated. The transmission system and the final generator assemblies, on the other hand, might necessarily be kept partly manual, since these operations involve many advanced and heavy sub-assemblies. Production steps such as welding, painting and pick-and-place however, will require less extensive development. Since manual welding is today a large part of the production costs, it is important to start details investigations on robotized welding operations for the generator production line.

From Figure 9 it can be concluded that, for all of the presented G3 production steps, the production costs are indicated to decrease with robot automation compared to manual production. It can also be concluded that manual production is less resource demanding for the G3 design compared to the G2. The main reason for this is probably that experience has been gained and that new manual production methods has been developed as more generators of the third generation has been built. The exception is the stator winding. From the Figure 9, it seems as if the manual winding cycle time has been reduced for the G3. However, when the winding the top two slot hole levels and the folding the stator sections are included, the cycle times are similar. When it comes to robotized winding, the results indicate that winding the complete G2 stator is less time consuming, and this also less costly, than winding only the bottom eight slot hole levels of the G3 stator. The main reason for this is that the stator sides are now wound individually. Hence nine stator sides are wound for the G3, while four stator sections were wound for the G2. On the other hand, the benefits with the new method are that shorter cables lengths must be handled by the robots and that the risk of damaging the cable when being fed through the stator is reduced. This might in turn improve the robustness of the automation. For the robotized translator assembly, the results again seem to indicate that the G2 assembly was less costly than the G3 assembly. The reason for this is however that the G2 assembly only included mounting of the magnets, while the G3 assembly include the complete translator.

Putting the number of labor and the number of industrial robots against each other, as in Table 2, might be provocative, especially in the light of ongoing discussions about technological unemployment. However, it should be stressed that, for the UU WEC technology to become economically competitive and thus create a new industry with new jobs, reducing the production costs through automation is likely to be necessary. It should also be stressed that the discussed production steps to a large extent involve repetitive, heavy and potentially hazardous manual operations, which could be eliminated through automation.

The presented results on potential cost savings with production automation are very rough. To make a more certain conclusion, parameters such as the net present value and the payback period should be calculated for each production step. This would require more and better data, and therefore further development on the suggested automations. The intention here is only to indicate if the suggested robot cells are economically motivated and to point out which automations should be focused on to begin with. As described above, these calculations are simplified, generalized and made per unit, with the cost for one manual labor as the base unit. When the results are presented in Figure 9, the values of the production costs are intentionally left out, to stress that the actual numbers are very uncertain and that the information that is intended to be communicated is the relation between the sizes of the production costs only. To investigate the assumption on the cost per robot, e.g. the following scenario could be used: 20 EUR/h assembler labor cost[2], five years economical investment life-time, 5 % discount rate, 15,000 EUR per robot and year for running costs[3] and no investment rest value. With these figures, the remaining available equipment investment cost, including installation and commissioning, can be approximated to 45,000 EUR/robot. Considering that the suitable pre-owned robots cost about 10,000 EUR[4], this seems to be reasonable assumption[5]. It should however be noted that the required robot cell investment cost, expressed per robot, will in reality probably differ largely between the cells and also that several robots in the same cell can share equipment, thus reducing the cost for additional robots. It should also be noted that if the required number of robot operators can be reduced, the cost for robotized production will further reduced. It should also be pointed out that fully functional robot cells, with minimal downtime, has been assumed and that the costs for work related assembler labor injuries, due to repetitive heavy tasks, is neglected.

The intention with the presented production line draft, Figure 10, is to show the major sub-production steps and how they are related to each other than to go into details. The stator winding assembly is actually divided in robotized winding of the eight lower slot hole levels and then manual winding of the top two slot hole levels and the folding of the stator section. Two other examples are the hull machining production step and the final assembly production step, which include several welding operations, and the painting production step, which includes blasting.

It is clear that the material costs for the G3 UU WEC generator has been much reduced. It is also clear that the production costs can be much reduced through automation. The drawback is that several sub-assemblies for the G3 design are more complicated and/or more time-consuming compared to the G2 design. Most obviously, the new translator structure is more difficult to assembly with

[2] According to Statistics Sweden, the average hourly total pay for an assembler in the Swedish manual workers private sector 2013 was 17.20 EUR/h, while an industrial-robot operator was in average paid 20.42 EUR/h. Adding 31 % social fees and 15 % for other related costs, such as insurances, the total hourly cost can be calculated to about 25 EUR/h for an assembler and about 30 EUR/h for an industrial-robot operator. The cost per industrial-robot operator is thus about 120 % of the cost per assembler. The number taken from: www.statistikdatabasen.scb.se/pxweb/en/ssd/START__AM__AM0103__AM0103B/SLP2a/table/tableViewLayout1/?rxid=4524ab87-e0a8-45b5-87ca-3bca8774b152 www.skatteverket.se/foretagorganisationer/arbetsgivare/socialavgifter/arbetsgivaravgifter.4.233f91f71260075abe8800020817.html

[3] Including electricity (could be complemented with other power sources), service and spare parts, while the floor space cost is assumed to be the same as for manual production. Assuming an average electricity consumption of 15 kW during 2,000 h/year and an electricity cost of 0.1 EUR/kWh, the total yearly electricity cost would be about 3,000 EUR. The yearly cost for robot service is likely to be similar (information from ABB Robotics). Hence there is about 9,000 EUR/year left for spare parts and other maintenance. Assuming that the industrial-robot operators can deal with this, this amount would be enough to replace the complete robot cell once during the five year economical lifetime. It is however unrealistic that this will be needed, however it might be that some equipment must be replaced several times.

[4] When UU recently invested in suitable pre-owned ABB industrial robots of version S3, the prize was about 20,000 EUR each, while similar version S4 robots were offered at about 80,000 EUR each.

[5] The investment cost could e.g. by divided as following: robot 10,000 EUR, robot tooling 10,000 EUR, side equipment 15,000 EUR, safety 5,000 EUR and installation 5,000 EUR.

industrial robots and the new winding assembly will probably take longer time to perform. The automation robustness might have been improved for the winding, but is rather decreased for the stator stacking, due to a shorter stator sheet yoke. However it has been shown to still be reasonable to assume that the investigated G3 generator production steps can be performed with industrial robots, at low costs. It is therefore reasonable to say that with the G3 design, the UU WEC generator is now considerably better adapted for large-scale production due to large cost savings on the generator. More work is currently being put into adapting the design to facilitate automation. This involves balancing between lower material costs, lower production costs and simpler assemblies. Finally, it should also be kept in mind that e.g. the total number of machining operations and the number of different raw material dimensions used have been reduced, changes that affect mainly parts of the production line not investigated in detail in this paper.

The presented results for the UU WEC generator can be generalized for other generators as well. Especially, within renewable energy it is crucial to lower the life-time device cost per delivered kWh to the electric grid. Hence, reducing the generator cost in the order of magnitude that has been presented for the G3 UU WEC generator is an important step towards commercialization. It is then important to focus on the costs for both material and production. For larger production volumes, industrial robot automation can be very useful.

6. Conclusions

The third generation design of the Uppsala University Wave Energy Converter generator has been presented. It has been described how this new design has reduced the total generator cost with up to 50 %, mainly through changing from $Nd_2Fe_{14}B$-magnets to ferrite magnets in the translator. Furthermore, the electromechanical design has been optimized and the design has been simplified e.g. by limiting the need for machining operations and the number of different raw material steel sheet dimensions. Some important production steps have on the other hand become more complicated and time consuming. Three such assemblies have been investigated in detail; the stator stacking, the stator winding and the translator assembly. The development work needed to automate these assemblies with industrial robots, for the third generation generator design, has been outlined. It has been shown that the stator winding and translator assembly should be focused on to begin with. Potential production cost savings through robotized production of about 20 % of the total generator cost has been very roughly indicated, compared to manual production. A simplified draft of the complete generator production line has been outlined. The magnitude of the presented generator cost savings indicate that it is reasonable that similar investigations will be crucial also for other renewable energy technologies striving to be commercialized.

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