DESIGN AND EXPERIMENTAL SIMULATION OF AN OFF-GRID SYSTEM FOR A WIND-DRIVEN DESALINATION TECHNOLOGY WITH BLACK START CAPABILITY

L. Clasing[1]*, E. Waffenschmidt[1], H. Rost van Tonningen [2]
[1]Cologne Institute for Renewable Energy, TH Köln - Cologne, Germany
[2] Solteq Energy B.V – Leeuwarden, Netherlands

**Corresponding author. E-mail: lionel.clasing@th-koeln.de*

Abstract:
In this work a design and simulation of an off-grid system for a novel wind-driven reverse osmosis desalination technology, which provides drinking water and electrical energy, is presented. The system is designed according to technological, sustainable, ecological and economic criteria on the example of the Johnny Cay Regional Park. The novel wind-driven desalination technology is based on a hydraulic drivetrain and enables seawater desalination by reverse osmosis with low conversion losses and is now intended to additionally generate electrical energy from excess wind energy. Furthermore, the hydraulic drivetrain promises variable-speed transmission for an electrical generator and can take over the network formation. Thus, a new approach for an off-grid system compatible to a wind turbine with variable-speed transmission as a network generator is needed. Additionally, a concept has been developed to black start the wind turbine with a low-budget backup battery inverter, which is easy to find in remote areas with frequent power failures or without grid connection. For analyzing and evaluating the design, measurements in an experimental test setup of the wind turbine were performed in the laboratory.

Keyword: off-grid systems, wind-driven desalination, variable-speed transmission, photovoltaics

1. Introduction

As in many other places around the world, the island Johnny Cay (Colombia) has a simultaneous need for drinking water and electrical energy. Johnny Cay is located in a Regional Park in the archipelago of San Andrés (Colombia) and this area has been declared a marine protected area as part of the UNESCO Biosphere Reserve [1]. Furthermore, the Regional Park is a popular destination for tourists with around 350,000 visitors a year [2]. In biosphere reserves in remote areas or on islands, a connection to a national grid is often uneconomical or can only be realized with great technical effort. For this reason, off-grid systems are often the only chance to enable sustainable tourism in biosphere reserves with flexible energy supplies. Additionally, the special criteria for nature conservation exclude the combustion of fossil fuels to cover the energy requirements.

That leads to the aim of this work to design a battery-based wind photovoltaic off-grid system for a novel wind-turbine technology in the pilot phase on the example of the Johnny Cay Regional Park. This wind-turbine technology is developed by the company Solteq Energy B.V. and the pilot project is intended to contribute to sustainable tourism [3]. The wind-turbine with a novel hydraulic drivetrain technology, which is mechanically coupled via a hydraulic motor to the high-pressure oil pump of a reverse osmosis (RO) can be used for seawater desalination. Drinking water from seawater can be obtained with this technology with low conversion losses [4][5][6]. In addition, the hydraulic drivetrain promises a variable-speed transmission for the operation of an electric generator [7]. As a result, a connected synchronous generator (SG) can be used directly without inverter power electronics for mains supply or the formation of an off-grid system. In particular, the grid quality in off-grid systems with the sole use of renewables can be improved [8]. Thus, a new approach for an off-grid system must be developed in which a SG, driven by the hydraulic drivetrain in a wind-turbine, takes over the task of network formation. The design should also include an analysis of the requirements and conditions as well as the selection and dimensioning of the possible components of the off-grid system, considering the criteria of a biosphere reserve in ecological, economic and social terms. Furthermore, a redundant backup battery inverter with uninterruptible power supply (UPS) for the safe operation and black start capability of the wind-driven desalination system will be implemented.

In an experimental test setup with a three-phase SG and a UPS system, a crucial part of the off-grid system and the wind turbine is to be simulated. This should provide insights into the real operating behavior of the designed off-grid system with the UPS system. The aim of the simulation is to analyze and assess the voltage quality with and without the use of the UPS battery in different scenarios. This work should provide a basis for further installations of the novel wind-turbine technology to enable people to supply drinking water and electrical energy in remote regions, away from national interconnected grids.

2. Literature Review

In previous work [8] an approach for an optimal combination in a hybrid renewable energy off-grid system of installed wind turbines and PV systems was developed for remote areas in which there is no possibility of using a diesel generator. The goal was to determine an optimal configuration at minimal cost, provided that all analytical model equations are known. The design provides for a DC-coupled system in which a battery storage device is to compensate for the fluctuation in the available energy supply. It should be determined which is the optimal proportion of the producers when combining wind turbines and PV systems in order to reduce costs to a minimum. For this purpose, the energy production of PV systems and wind turbines should be considered together. It was found that an increase in the share of wind turbines from 8% to 33% results in a significant reduction in the costs for PV systems and battery storage.

An autonomous wind turbine with hydrostatic transmission that drives a RO directly via a mechanical coupling was developed and installed in Curacao [4]. Because the storage of excess energy for a RO operation during a low wind supply has proven to be very uneconomical, no electrical energy is generated in this wind turbine. For this purpose, an electronic control system was dispensed with in this configuration. Due to the direct coupling, the production of the permeate varies depending on the wind speed. With this system, an average drinking water production of 5-10 m³ per day was achieved. Apart from the uneconomical energy storage for the RO operation, an electronic control system would optimize the operation of the entire system and further increase the permeate capacity.

In further works [5][6] tests and simulations of wind-turbines with hydraulic drivetrains have been done for the reverse osmosis part.

3. Methodology

3.1. Design and Concept

Local conditions like the barriers of the construction site, climatic conditions, generator and load profiles must be analyzed for dimensioning and defining the type of the network system and the components. There are different possibilities when defining a grid system type for an off-grid system. The grid system can be DC-coupled, AC-coupled or AC-DC-coupled [9]. Particularly the requirements of the hydraulic drivetrain with variable-speed transmission must be considered in the choice of the generator. The variable-speed transmission offers the advantage of directly using a generator with synchronous speed, because the frequency no longer needs to be adjusted by a converter.

Furthermore, the system is to be designed on the basis that the electrical energy generators are already set in their dimension, with P_{WIND} = 12 kVA and P_{PV} = 1.7 kWp, due to project requirements.

3.2. Experimental Test Setup

The laboratory test bench, as shown in Figure 1, consists of a SG powered by a Leonard motor control system.

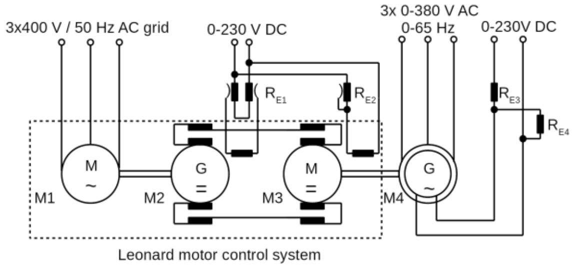

Figure 1. Leonard motor control system with synchronous generator of a laboratory facility in the Institute for Electrical Power Engineering of the Cologne University of Applied Sciences

The Leonard motor control system consists of a three-phase asynchronous machine (M1) connected to the mains as a drive for a separately excited DC machine (M2). At the clamps of the DC machine (M2), a further externally excited DC machine (M3) is connected as a drive for a three-phase synchronous machine (M4).

This makes it possible to variably operate the SG in terms of voltage and frequency within specified limits. Due to the voltage and frequency variability, this test setup is suitable as a simulation of the wind turbine with the novel hydraulic drivetrain.

4. Results and Discussion

4.1. Off-grid System Design and Concept

In this work, an off-grid system for a wind turbine with variable-speed transmission was designed and evaluated according to technological, sustainable, ecological and economic criteria. For the components of the off-grid system, a possible selection, dimensioning and implementation was developed.

The off-grid system was designed as a single-phase AC grid, as seen in Figure 2, in which the generators are both DC and AC coupled and a modular extendable AC bus. The network formation can be done by the wind-turbines generator as well as by a bidirectional battery inverter from a battery storage.

After evaluation of the historic climatic data, the network formation should be done primarily by the generator, thus can be saved in the dimensioning of the bidirectional battery inverter, costs. Other advantages of using a generator as a network generator are in its damping property in switching operations and consequent compensation processes in the network.

The maximum system power calculation has shown that the wind turbine has an apparent power of 12 kVA and an active power of 9.6 kW with a power factor of 0.8. The PV-system has a peak power of 1.7 kWp under Standard Test Conditions. The planned load output of

13.38 kW, considering the own needs of the wind-desalination system, is thus not achieved.

A dimensioning for the battery storage could not be made because the planned energy demand with the required autonomy of one day would require a battery storage with a capacity of 6480 Ah. The investment costs would be very high and therefore a potential profitability must be checked in a computerized yield forecast.

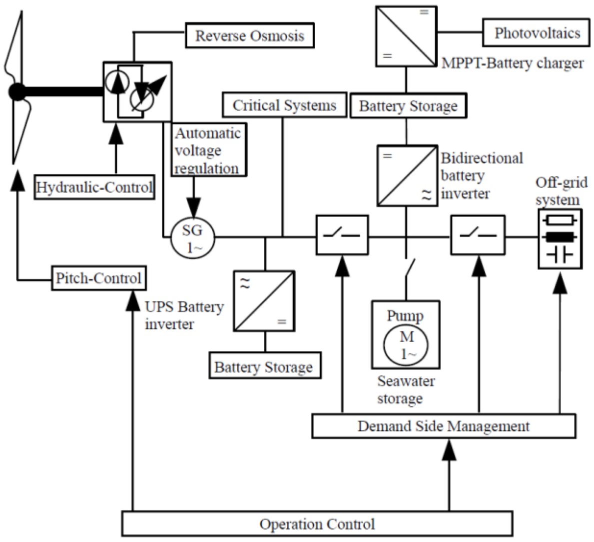

Figure 2. Example of an off-grid system design for a stand-alone wind-drive desalination-system with black start capability

In the designed system, the excess energy from the RO is to be used to generate electrical energy. For this purpose, a hydraulic motor is available as the drive machine for the generator, which is fed by the hydraulic drivetrain of the wind turbine. As described in section 3.1, the speed of the hydraulic motor from the hydraulic drivetrain and the hydraulic control should be variable and permanently adjustable. This should be used as the basis for the selection of a generator and the formation of the off-grid system.

There are different types of generators with which a conversion would be conceivable, but some are associated with complex power electronics or even higher technical expenditure such as reactive power generators. SGs are used almost exclusively in stand-alone grids because they can provide both active power and reactive power without additional equipment. It follows from this and from the fixed speed of the drive machine that a SG can be used directly as a network generator in stand-alone networks, since the speed of the generator is directly linked to the frequency of the phase voltage via the number of pole pairs in the stator winding. The selection was therefore restricted to the SG. The specification of the nominal speed n of the drive machine or hydraulic motor was specified with n = 1800 rpm at a mains frequency of 60 Hz. Due to the high centrifugal forces, all-pole machines can only be used in this speed range [11]. Due to the fixed speed of the hydraulic motor, the operating behavior of a diesel unit can be assumed as drive for the generator.

4.2. Experimental Test Setup

In this section the developed experimental test setup, which is presented in this work, is described. All used devices of the setup are listed in Table 1. The SG is connected to an adjustable power resistor set, which simulates the loads in the off-grid system, as shown in Figure 3. This will be used to investigate switching operations in the off-grid and its impact on grid quality.

Table 1. Device list of the experimental test setup

Device	Device characteristics			
	Type	U (V)	I/C (Ah)	P/E (kWh)
Leonard motor control system	AC/DC	-	-	-
3-phase AC Synchronous Generator	AC, Siemens, 1FA3 144 B3	380/ 230	33/ 55	12.5
UPS Battery Inverter [12]	Line-Interactive, Panda, SP5000VA	110	.	3.5
Battery Bank	Panasonic, LC-P12120P	12	120	5.76
Resistor Bank	Ohmic	-	-	-

The low-budget backup UPS has a battery bank consisting of 4 series-connected batteries with a battery voltage V_{BAT} = 12 V DC and a total capacity C = 120 Ah. The important difference to the off-grid design, is that in this experiment, the 3 phase windings of the SG are led out to a three-phase network. This allows a simultaneous investigation of the performance of a string with and without connected UPS. It should be noted that the phase windings are loaded unbalanced in the SG as a result of unbalanced load, this leads to additional losses in the massive iron.

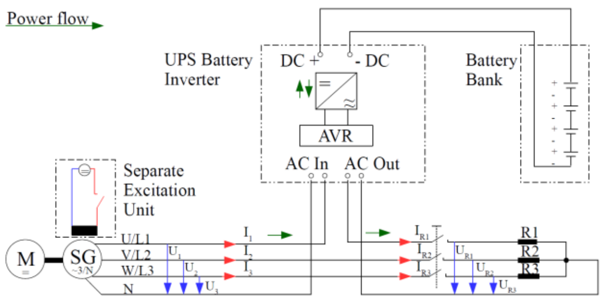

Figure 3. The circuit design diagram of the experimental test setup used for the simulation

The measuring setup consists of two measuring units, whereby a time-resolved measurement of voltage U is recorded by an opto-coupler and current I by a Hall-sensor. The measurement signal is transmitted to a LabView program by an analog/digital converter. As shown in Figure 3, the measuring sensors are located between the generator and the converter, as well as between the converter and the power resistor. The root mean square (RMS) values of voltage and current as well as the resulting quantities of power P, reactive power Q, apparent power S and frequency f were determined by the program from the following equations 1-5:

$$U_{RMS} = \sqrt[2]{\frac{1}{T}\int_{t_0}^{t_0+T} u^2 dt} \qquad \text{[Eq. 1]}$$

U_{RMS} : Root mean square voltage (V)
T : Time of one AC period (s)
t_0 : Time (s)
u : Instantaneous value of voltage (V)

$$I_{RMS} = \sqrt[2]{\frac{1}{T}\int_{t_0}^{t_0+T} i^2 dt} \qquad \text{[Eq. 2]}$$

I_{RMS} : Root mean square current (A)
i : Instantaneous value of current (A)

$$P = U_{RMS} * jI_{RMS} = Re \qquad \text{[Eq. 3]}$$

P : Electrical power (kW)

$$Q = U_{RMS} * jI_{RMS} = Im \qquad \text{[Eq. 4]}$$

Q : Reactive power (var)

$$S = U_{RMS} * j * I_{RMS} = |Re + Im| \qquad \text{[Eq. 5]}$$

S : Apparent power (VA)

4.3. Simulation

Different scenarios are simulated in the experimental test setup described above and the results are determined by using equations 1-5. Voltage and frequency behavior are observed when switching loads in the off-grid system. The rotor speed of the hydraulic drivetrain is assumed to be constant, but there are still slight speed fluctuations on the SG to be expected by the control [10]. Therefore, the fluctuating rotor speed of the wind turbine is simulated.
Finally, the operating behavior and operation limits of the selected UPS battery inverter in network and off-grid operation is to be examined in more detail.

4.3.1. Switching Operations and Transient Voltages

There are no general limit values for transient voltage increases in off-grid systems, everything is expediently permissible if the consumers are not harmed.
Therefore, the guide values given in [9] are applied so that the voltage may deviate transiently by up to ± 20% from the nominal value for a maximum of 1.5 s. The curves in Figure 4 were measured and represent the course of the RMS value of the voltages with and without the UPS battery inverter with a step-by-step increase and decrease of the current through ohmic power resistors of different sizes depending on the time.
The red curve represents the voltage U_{R1} across resistor R1 and the green curve represents voltage U_{R2} across resistor R2. The yellow curve was also measured and represents the time course of the effective value of current I_{R1} through resistor R1. In this experiment, current I_{R1} is intended to simulate the load on the consumer. The expected transient voltage deviations due to network perturbations during switching operations in an off-grid system can be clearly seen on U_{R1} and U_{R2}. The dependence of the transient voltage deviations on the power of the consumer can be seen from the different voltage peaks.

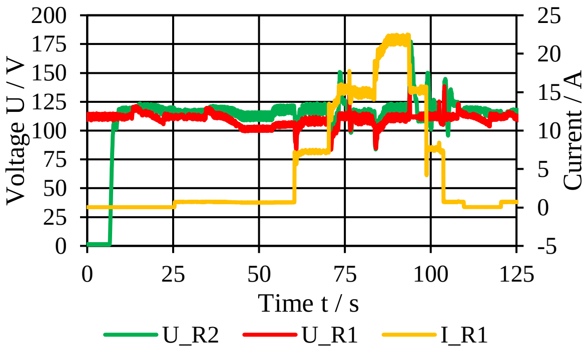

Figure 4. Measurement of the transient voltage behavior with gradual switching of loads in the off-grid system with ohmic resistors

It can be seen that U_{R2} has a significantly smaller and shorter voltage deviation than with U_{R1}. This is due to the voltage stabilizing property of the UPS battery inverter. According to a calculation from the measured values, there is a transient voltage deviation of + 45% over a period of 2 s for U_{R2} and approximately + 20% for a period of 300 ms for U_{R1}. This would make U_{R1} in the permissible range and U_{R2} in the impermissible tolerance range of the guidelines used. It can still be seen in the course that the voltage-stabilizing property increases as the power is reduced but increases again when the load is completely disconnected. This property contributes to voltage stability and can protect the connected loads in the island grid from damage caused by overvoltage. An improvement by an automatic voltage regulation (AVR) integrated in the SG in combination with the UPS battery inverter could achieve a good result.

4.3.2. Rotor Speed Variation

The influence on the battery charging current is to be examined and a limit value for the speed change of the SG is to be set. Figure 5 shows the curve of the effective value of the load current and the frequency across a resistor as a function of time.
The curves were measured, the red curve represents the frequency f_{R1} at the resistor R1 and the green curve the frequency f_{R2} at the resistor R2. The yellow curve shows the time course of the effective value of the battery charging current I1 at the input of the UPS battery inverter. The frequency curve of the SG can be observed at f_{R2}, this corresponds exactly to the speed n of the SG of approximately n = 1350 rpm. From this value on, the charging process of the battery is interrupted and resumed. This is repeated periodically until the 45 Hz are exceeded again.
For the UPS battery inverter, this means that the battery can no longer be properly charged from a frequency of 45 Hz. The speed control of the hydrostatic drive train must therefore be observed for this limit value.

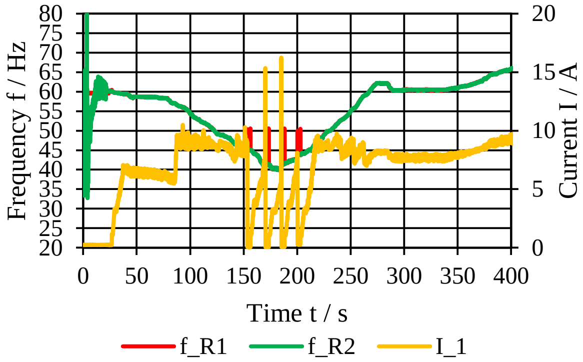

Figure 5. Measurement of the frequency behavior and the battery charging current at the resistor when the rotor speed of the three-phase synchronous generator changes

An increase in speed could have a similar effect on the battery charging process but could only be simulated in this test up to 65 Hz, as this would exceed the maximum speed of the SG in the test.

4.3.3. Generator Voltage Variation

In this experiment, a voltage change at the terminals of the SG is to be simulated. This is achieved by changing the excitation direct current in the rotor winding. With an AVR, this happens automatically and cannot be controlled. The purpose of this investigation is to determine the limits within which battery charging is possible and to provide a guideline for the design of the AVR. Figure 6 shows the curve of the voltages across the resistors R1 and R2 as well as the battery charging current of the UPS battery charger. The red curve and the green curve were measured and represent the course of the effective value of the voltage U_{R1} and U_{R2} across resistors R1 and R2. The yellow was also measured and represents the effective value of the battery charging current I_1.

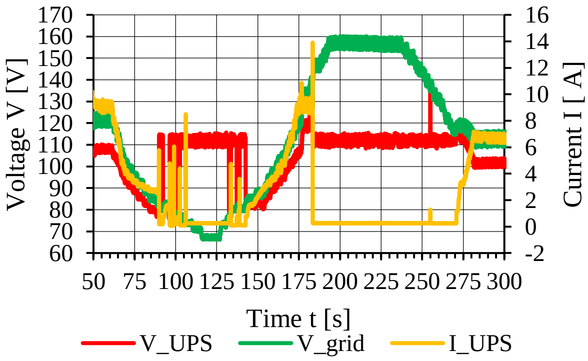

Figure 6. Measurement of the voltage and current behavior at the load resistor with voltage variation of the three-phase synchronous generator

U_{R2} is analogous to the RMS voltage curve at the input of the UPS battery charger and can be used as a reference for the unmodified terminal voltage on the SG. It can be observed that from a terminal voltage of 85 V and 120 V, which corresponds to a voltage deviation of + 9.1% and - 22.7%, the system switches to the UPS battery inverter which is parallel to the grid. The inverter now provides a stable voltage of U_{R1} = 110 V at resistor R1. It can also be seen from I_1 that the battery charging current also decreases with decreasing voltage and sets the battery charge when switching to inverter operation.

This represents the system tolerances for the effective input and thus terminal voltage between 85 V and 120 V, the mains-parallel UPS in the off-grid. The lower limit of the voltage tolerance of - 22.7% would not be permissible regarding the applied guidelines from [9]. The upper limit of the voltage tolerance represents a permissible deviation of + 9.1%. Based on this knowledge, an AVR would have to be adjusted to the permissible voltage tolerances of the guidelines.

Another alternative to influence the system tolerances would be manual load separation by means of a load relay, at the generator's feed point into the off-grid. A voltage-stabilizing property could not be determined in comparison to the transient deviations in the network feedback caused by switching operations in the island network.

5. Conclusion

The design for the off-grid system meets the requirements that have been developed in this work and have been applied for the novel hydraulic drivetrain. The use of a hydraulic drivetrain in wind-turbines with variable-speed transmission, above all can play an important role in network stability in renewable energy off-grid systems but can also contribute to network stability in interconnected networks. The simulation with the UPS battery inverter has shown that a voltage stabilization is achieved during transient compensation processes by switching operations, but this does not significantly contribute to the stabilization of the voltage at permanent voltage deviations. To ensure optimum charging of the UPS battery storage, the voltage deviation must not be greater than - 9.1% and + 22.7%, as seen in Figure 6, and not lower than 45 Hz, as seen in Figure 5. The reaction to the frequency of the UPS battery inverter in off-grid mode under load is greatly modified. Therefore, the inverter is only suitable for an off-grid system in accordance with these limits. The switchover time of the UPS is 3 ms and is considered sufficient for all critical devices of the system. The operating limits of the UPS and battery charging function have been checked and must be included in the voltage and speed control system. Additionally, black start capability is achieved by the implementation of a redundant UPS with a low-budget backup UPS available in the local market. This makes an important contribution to the social aspects in this project.

It should also be mentioned that wind-driven desalination offers many advantages for a rural drinking water and electrical energy supply far away from national interconnected networks, both in specially protected biosphere reserves and, above all, in developing countries with high fuel prices. Considering long transport routes and high prices for fossil fuels, an off-grid system powered by renewables can already be profitable today. In the future, prices will rise due to the scarcity of fossil fuels such as crude oil, making the installation of off-grid systems based on hybrid renewable energy sources economically more interesting.

Acknowledgements

The authors would like to thank the Dutch Ministry of Foreign Affairs and the community of Leeuwarden for financing the project. Also, we would like to thank the German Academic Exchange Service (DAAD) for supporting the journey to the conference "COA_ER 2020" with the Erasmus+ program.

REFERENCES

[1] United Nations Organization for Education, Science and Culture, "Seaflower Marine Protected Area (MPA)", available: http://whc.unesco.org/en/tentativelists/5166/, 2007, accessed on January 29th, 2020

[2] Solteq Energy, "Freshwatermill: Wind driven desalination: An alternative for coastal areas. First project in the world: Johnny Cay – Colombia", available: Http://www.fresahwatermill.com, accessed on August 12th, 2019

[3] TU Delft, "Freshwatermill for the island of Johnny Cay", Faculty of Civil Engineering and Geosciences, available: https://www.tudelft.nl/citg/over-faculteit/afdelingen/watermanagement/research/chairs/sanitary-engineering/new-projects-grants/2014/sustainable-fresh-water-and-energy-production-for-the-island-of-johnny-cay-colombia/, 2015, Delft, Netherlands

[4] S.G.J.Heijman et al., "Sustainable seawater desalination: Stand-alone small scale windmill and reverse osmosis system", in Desalination, Volume 248, Issues 1–3, 15 November 2009, Pages 114-117

[5] Eduardo Bologna, "Experimental and Computational Study of a Wind Powered Reverse Osmosis System", Master's Thesis, TU Delft, 2017, Page 1

[6] Elisabeth Insam, "Optimal Sizing of Stand-Alone Renewable Energy Systems for Electricity & Fresh Water Supply", Master's Thesis, TU Delft, 2017, Page 3

[7] H. Murrenhoff et al., "Hydrostatic transmission for wind turbines - lessons learned from five years of research", Conference Paper, Conference for Wind Power Drives, CWD 2017, Aachen 7th-8th March

[8] A. Ahadi et al., "A novel approach for optimal combinations of wind, PV, and energy storage system in diesel-free isolated communities", Applied Energy Volume 170, 15 May 2016, Pages 101-115

[9] M. Meinhardt, Alfred Engler, "AC-coupled island grids for integration into growing energy supply structures of the future", ISET, Kassel, 2006

[10] S. Michel, "Hydrostatischer Triebstrang für Windkraftanlagen", available: https://www.konstruktionspraxis.vogel.de/hydrostatischer-triebstrang-fuer-windkraftanlagen-a-280777/, accessed on January 8th, 2020

[11] R. Fischer, Book: „Elektrische Maschinen", 2013, Munich, S. 159f., S296f.

[12] Datasheet: I-P-SP5000VA, I-Panda Electronics accessed on October 9th, 2019