System Analysis for Hydrostatic Transmission for Wave Energy Applications - Simulation and Validation

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Abstract

Wave Energy Converters (WEC) are used to transform energy stored in ocean waves into electrical energy. One type of WECs consists of buoyant bodies. To extract energy from their motion, hydraulic cylinders can be used to generate hydraulic power. For conversion into electric power various systems have been analysed in literature. However, the focus was put on efficiency and rigorous analyses of the system behaviour are still missing. In this paper an exemplary system consisting of two hydraulic cylinders, switchable check valves, accumulators and three motor-generator sets is analysed with help of simulation and measurement. This exemplary system is called WavePOD and was installed at the Institute for Fluid Power Drives and Controls (IFAS) of RWTH Aachen University together with Aquamarine Power and Bosch Rexroth for testing. In this paper the data collected during various test phases is used for system analysis and for validating the simulation. The simulation model is presented. The system's response to various switching operations is investigated. Comparing the simulation with measurements validates the system`s dynamic model.

KEYWORDS: Wave Energy Converter, System Analysis, Hydrostatic Transmission, Test, Validation, Response Time

1. Introduction

Renewable energies play an increasing role in today's energy production. To widen the spectrum of renewable sources the power from marine waves could be used. Accordingly, Wave Energy Converters have been developed. One type of these transforms the wave motion into a mechanical motion of at least one moving body. Accordingly, the wave power is transformed into a mechanical power. To extract this mechanical power a variety of Power-Take Offs have been proposed, most of them using hydraulic cylinders. However, no complete set of WEC and PTO is commercially available, indicating a lack in cost effectiveness and reliability.

To improve the reliability and the ratio of power output to costs, WavePOD was developed. Intending to suit various WECs the development costs can be shared as well as knowledge gained. Thus, the cost effectiveness and the reliability can be improved simultaneously.

At IFAS a test-rig has been installed for testing WavePOD. Its main goals are to prove the concept of WavePOD, to show its reliability, to study its performance and to gain knowledge for future development. The performance study in terms of single component and system behaviour is intended to be used for setting up and validating a simulation model. Using this model future development gets easier, because changes to the system and its control can be tested without physical changes.

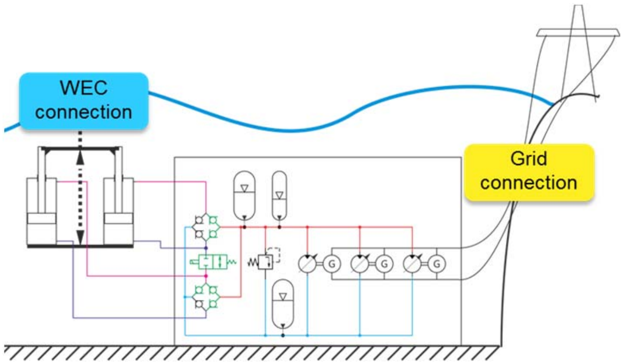

Figure 1: WavePOD circuit and its control

In this paper the system simulation and its validation are presented for WavePOD. As shown in **figure 1**, WavePOD comprises of two cylinders which are attached to the moving body of a WEC extracting the mechanical power from its motion. For transforming the mechanical power into hydrostatic power the cylinders are connected to a low pressure and a high pressure system by check valves. The pre-charged low pressure system fills extending cylinder chambers, while decreasing cylinder chamber volumes lead to pumping into the high pressure system.

For changing the cylinder force without changing the pressure, various cylinder chambers can be connected to the low or the high pressure system by keeping the check valves open. Additionally, two cylinder chambers can be connected directly with each other. The switchable valves are indicated with green colour. Thus the active cylinder area can be varied. The various active cylinder areas are shown in **figure 2** for the different switching steps selected. More steps could be created with the present amount of valves. However, with the presented steps uniform step sizes with relatively balanced active areas in both directions of motions are achieved.

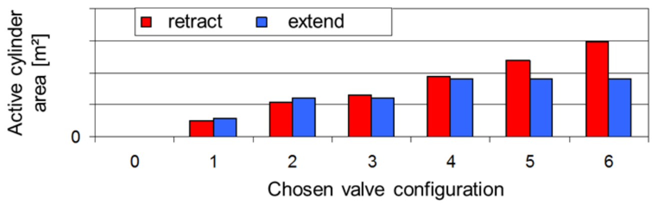

Figure 2: Cylinder switching steps

The fluid pumped by the cylinders is stored in two high pressure accumulator sets at different pre-charge levels. These smooth the volume flow from the cylinders to enable a relatively uniform flow to the motors. The higher pre-charge accumulator is connected to the high pressure system with a valve protecting the accumulators from emptying completely. The lower pre-charge accumulator is never emptied during operation, because the operation pressure is kept above its pre-charge pressure.

Three motor-generator-sets are used. In each set a variable displacement motor uses the flow from the accumulators to drive an asynchronous generator. The asynchronous generator gets connected to the grid directly without any power electronics. With the variable displacement motors the flow used can be altered to enable a pressure control in the high pressure system. However, in operation points with only small power input some motor-generator-sets are switched off. This enables a better operation point of the remaining motor-generator set or sets. The motor-generator sets are close to the cylinders resulting in a compact hydraulic transmission needing installation directly at the WEC. Additionally, all necessary ancillaries are included in the system. A main cooler is fitted into the return line of the motors and filtered fresh fluid is provided with boost pumps either electrically driven or connected to the motors. The working fluid is mineral oil.

WavePOD features three degrees of freedom. The active cylinder area can be switched utilising the switchable check valves, up to three motor-generator sets can be used and the high pressure varies depending on cylinder and motor flow. Accordingly, these three aspects need control. The switching of the cylinders and the motors, as well as the set signal for the pressure control bases on an automatic control system which is not part of this paper. However, the switching leads to effects on the pressure trace. Thus, cylinder and motor switching is considered as inputs for the analysis. Its effect on the pressure control is studied here. The set-up of the pressure control is included in **figure 3**. A set pressure p_{set} is compared with the actual pressure p showing a control error. A PID controller transforms this error into a swash plate angle α which is maintained by the hydraulic motors.

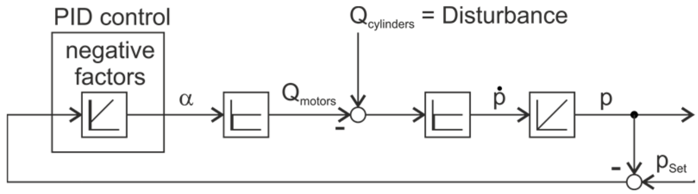

Figure 3: Set-up of motor control

The aforementioned PTO system has similarities to systems proposed in literature. However, important aspects different to single systems are described in /1/. Additionally, simulations of a PTO for WECs and according validation have been published. While some focus on efficiency estimations, e.g. /2/, some simulations of the system dynamics have been carried out, see /3, 4, 5/. However, these either focus on single sub systems or study a different system. Accordingly, this paper presents the dynamic simulation of WavePOD. Additionally, this dynamic simulation is validated with measurements.

The test rig used for the measurement is shown in **figure 4a**). On the left hand side it contains WavePOD with its hydraulic transmission and the electric cabinet housing the control and the grid connection (yellow). Here a scaled model of WavePOD is tested with 80 kW installed generator power. The drive on the right (blue) includes a set of proportional valves controlling the drive cylinder position and a set of accumulators providing peak power. It is driven by the central pressure supply of IFAS laboratory, which is not shown in figure 4a). In the middle the cylinder frame (red circle) is used to transform the drive cylinder motion into the PTO cylinder motion with a rocker at the top of the cylinder frame. For a more detailed overview over the test rig see /1/.

In **figure 4b)** the drive circuit is displayed. A pump continuously fills an accumulator set. Oil is taken out of the accumulator according to the required cylinder velocity. By opening a set of 2/2 proportional valves, shown as one proportional 4/3 valve in the figure, the drive cylinder chambers are connected to either the high pressure side or to the tank. The drive cylinder motion is transmitted to the PTO cylinders via a rocker mechanism. The PTO cylinders are connected to the PTO. This is not shown in figure 4b). However, details can be taken from figure 1.

For applying realistic waves the full scale hydrodynamic model of Oyster, provided by Aquamarine Power, is simulated in a parallel real time simulation. Hydrodynamic models of other WECs can be included as well, though. The necessary input to the hydrodynamic model is the pressure force from the PTO cylinders, fed back from the measurement. As an output the hydrodynamic model provides the set cylinder position. In order to match the scaled test rig design with the full scale hydrodynamic model, the feedback force is enlarged by the according force scaling factor and the position is reduced by the motion scaling factor. The position control with velocity feed forward uses the test-rig scale set position. Thereby the rocker angle is used for position measurement correlating to the cylinder position via trigonometrical relationships. The position control manipulates the proportional valves and thus achieves a drive cylinder motion.

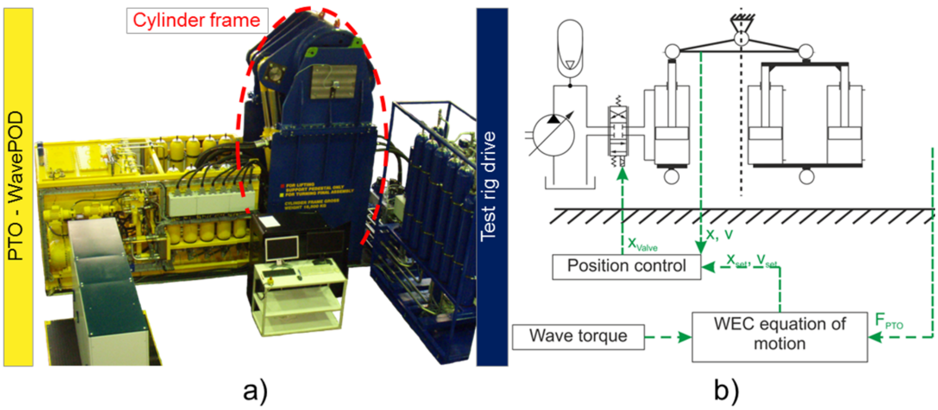

Figure 4: Test rig and drive circuit

2. Measurement

Measurement was carried out by using a parallel real time simulation of the full scale WEC and applying its scaled motion as set position to the drive. Two different types of wave excitations are considered. First monochromatic waves (only one frequency), second polychromatic waves (superimposed frequencies with different amplitudes) will be used for the analysis presented here. Measured wave torques, extracted from tank testing, were provided by Aquamarine Power. The use of these enables to apply realistic WEC motion on WavePOD. Examples for monochromatic (left) and polychromatic (right) waves are shown in **figure 6**. A medium power sea state has been used and both the set position and the actual position are shown. Here the angular rocker position is used for position measurement and the set WavePOD cylinder motion is geometrically transformed into set rocker angle. As can be seen, the difference between the set and the actual position is small. Accordingly, it is assumed that a realistic WEC motion is applied.

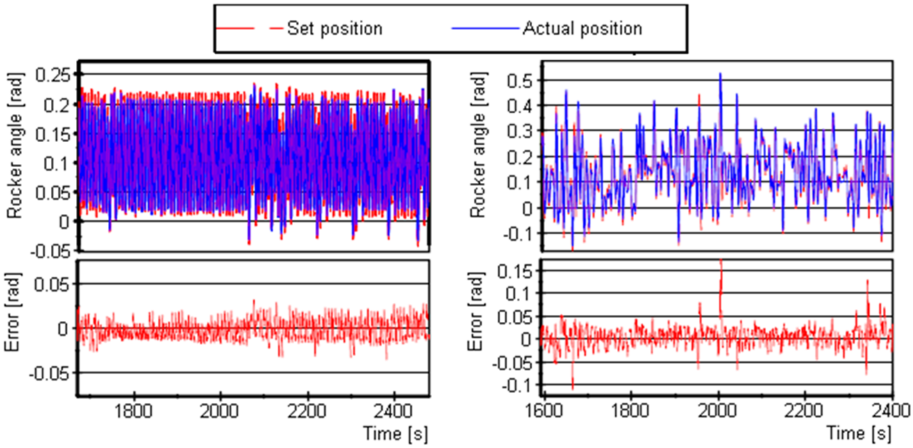

Figure 6: Set and actual position of a medium power sea state with monochromatic (left) and polychromatic (right) waves

Fluctuations in the motion with monochromatic waves in figure 6 result from different cylinder forces applied. The cylinder area is selected by an automatic control system, which selects the cylinder area depending on the current operation point. By changing the active cylinder area, the PTO cylinder force changes. This changes the motion of the WEC. Accordingly, the fluctuations with monochromatic waves show that the force feedback is working as intended.

For evaluating the effect on the PTO when changing the active cylinder area, i.e. the force, monochromatic waves are used and a constant set pressure is applied with a simple control system, see **figure 7**. Additionally, with this simple control system it is possible to manually switch the cylinder area. At the beginning the active cylinder area is switched from a high value to a smaller value indicated by a smaller force. This leads to a smaller volume flow provided to the hydraulic system resulting in a decreasing pressure. The motor control then adjusts the motor swash plate angle. Thus, less volume is taken from the system leading to a pressure increase. This process leads to pressure oscillations and a smaller average swash plate angle. After a certain amount of time (Time = 1200 s) this process is reversed resulting in a higher swash plate angle again. In the next measurements shown the pressure and swash plate angle oscillations are reduced using the automatic control system which adapts the set pressure and thus dampens the control.

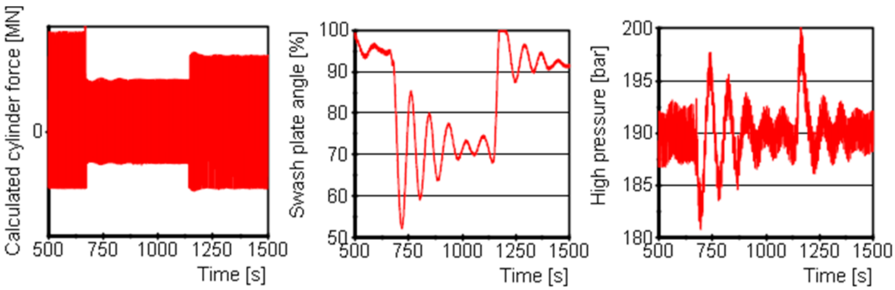

Figure 7: Cylinder switching with monochromatic waves and medium power sea state

During the above shown polychromatic waves (figure 6) the cylinders are switched automatically, adapting the cylinder force to the wave conditions. This method is not in the focus of this paper, however, together with changing cylinder motion the cylinder switching leads to a fluctuating input flow.

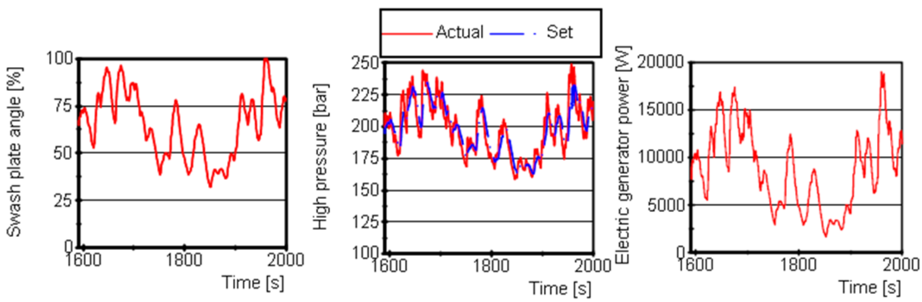

Figure 8: Pressure control during polychromatic waves

For smoothing the input flow and for providing a relatively constant pressure and power output the swash plate angles of the motors are adapted. It is controlled according to a varying set pressure, which is provided by the automatic control system. The pressure being controlled can be seen in **figure 8**. The actual pressure and the set pressure are shown together with the swash plate angle and the power output.

As the final aspect in dynamic regards the motor switching needs to be analysed. This is shown in **figure 9**. After the starting signal the motor-generator-set speeds up, driven by the hydraulic motor, as can be seen with the swash plate angle at approx. 15 %. After reaching grid frequency of 50 Hz correlating to 1500 rpm the electric contactors are closed connecting the generator to the grid. This starts the generation of electric power. Simultaneously, the swash plate angle increases for driving the generator.

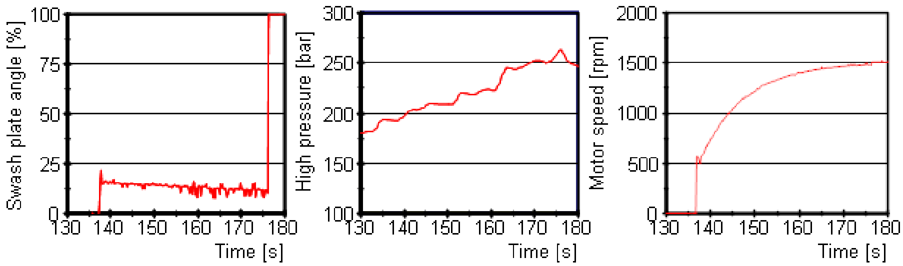

Figure 9: Motor start-up behaviour

3. Simulation

The simulation was set up in Matlab/Simulink as shown in **figure 10**. It contains all relevant items such as motion excitation (left), cylinders (light blue), check valve blocks and other valves (orange) and high and low pressure accumulators (turquoise).

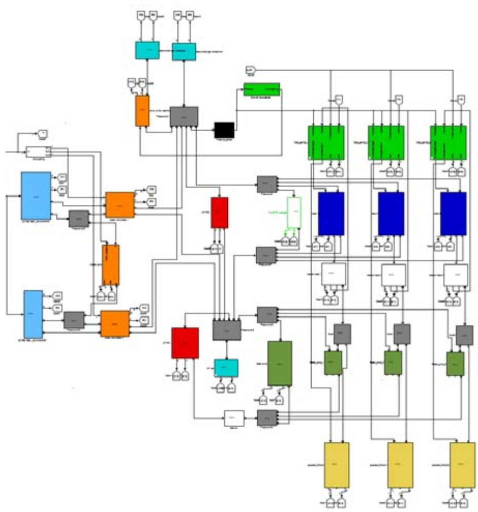

Figure 10: Simulation model set-up in Matlab/Simulink

The motor-generator sets include the motor controls (green), motors (dark blue), rotational inertia (white), generators (yellow) and boost pumps (dark green). Furthermore pressure relief valves (PRV) (red) and signal distributors modelling T-pieces or shafts (grey) are used. The green box with white filling models unintended leakage. The component models for the cylinders, check valves, accumulators, PRVs and the leakage have been presented and validated in /6/, but system analysis is still missing. The model presented here uses constant oil properties.

The models for motor, generator and boost pumps contain characteristics from measurement. These are presented in the following. In **figure 11a)** the generator torque is shown versus its rotational speed when connected to the grid. As can be seen, the torque is positive for speeds below grid frequency indicating motor mode and negative above grid frequency indicating generator mode. In **figure 11b)** the approximated friction of the generator is shown versus speed. Both characteristics have been extracted from measurement with the help of simplified calculations, because no torque sensor is integrated in the test rig. Generator friction includes the torque required to run a boost pump attached to the motor.

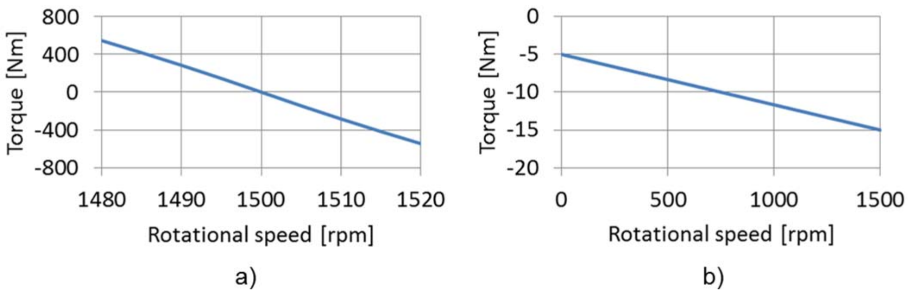

Figure 11: Generator characteristics a) during grid connection b) friction

From **figure 12** motor leakage and friction can be taken. They were measured previously to the work on WavePOD. As expected, the leakage rises with pressure and the friction rises with the swash plate angle.

The excitation of the simulation was considered from measurement. The PTO cylinder motion was calculated from rocker angle and fed into the simulation. Additionally, the cylinder switching measured was used as an input for the simulation as well. The motor switching and the pressure control was carried out automatically in the simulation.

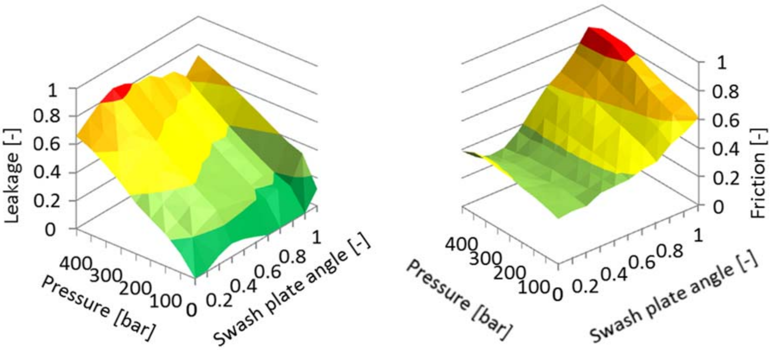

Figure 12: Normalised motor leakage and friction characteristics

4. Discussion

In this chapter the simulation results are compared to the measurements for the effects shown in chapter 2. First the response on cylinder switching was investigated. The cylinders were switched in the simulation as it was done on the test-rig. This led to identical cylinder forces, as can be seen in **figure 13** on the left. The swash plate angle and pressure responses are shown on the right. Generally, the oscillations of the simulations were slightly slower and did not diminish as fast as during measurement. Additionally, the simulated swash plate angle was smaller than the measured one. Thus, adaptions are necessary in terms of improving the correlation of damping and natural frequency. However, the general behaviour was similar. With using the automatic instead of the simple control system the correlation is improved, shown in the following part.

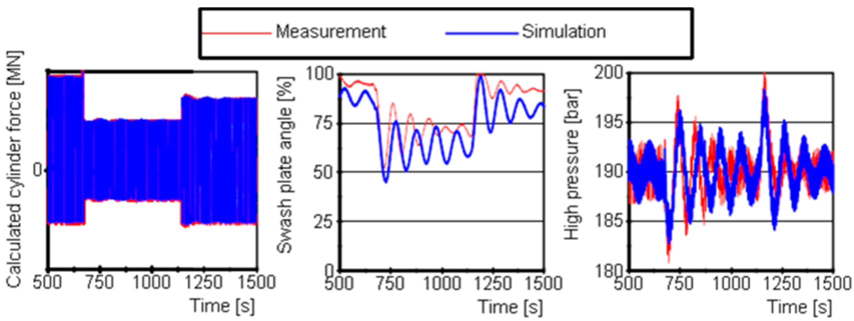

Figure 13: Force, swash plate angle and pressure for cylinder switching validation

In **figure 14** the pressure control is shown with its swash plate angle, pressure and output power for both, measurement and simulation. As can be seen, the swash plate angle is slightly smaller for the simulation again, while the other curves match very well. However, for each comparison it becomes apparent that the dynamics are modelled adequately, because the spikes are very similar.

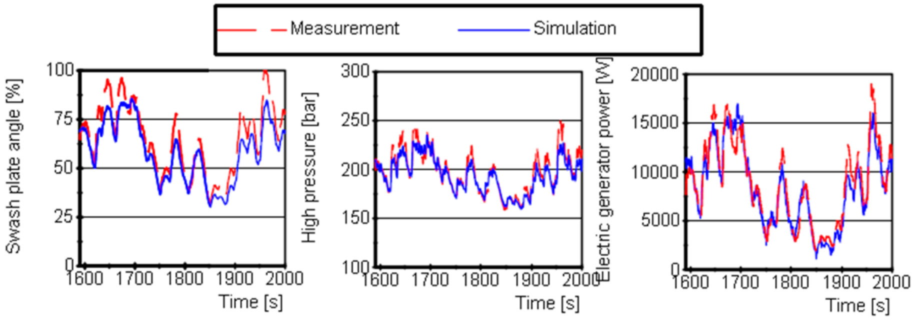

Figure 14: Pressure control during a polychromatic sea state

Figure 15 depicts the motor-generator-set starting performance. With a swash plate angle above zero the motor-generator-set speeds up. Since this depends on the pressure as well, it is included, too. In simulation the process starts slightly earlier and is slightly faster. This problem is enlarged when considering the pressure. The faster start is achieved despite the simulated pressure being approx. 10 bar below measurement. Accordingly, the simulation has too little friction or inertia, or the control parameters are too high. However, the speed curves are very similar indicating correlation despite possible future improvements.

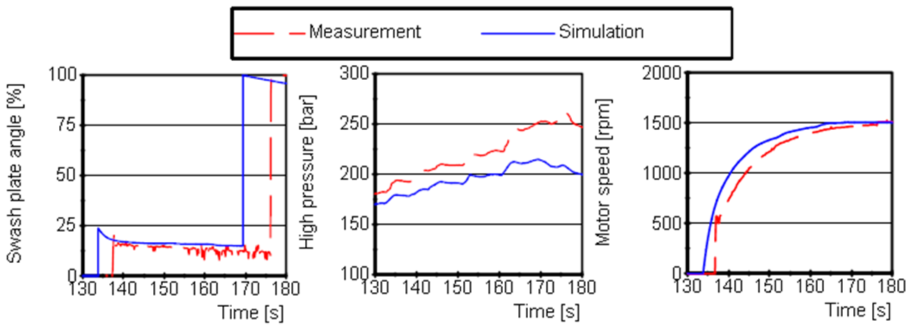

Figure 15: Start-up of a motor-generator set

5. Summary and Outlook

In this paper the simulation and validation of a Power-Take Off (PTO) for Wave Energy Converters (WEC) were presented using WavePOD as an example. First the system, its degrees of freedom and its testing were explained. Then measurement results were shown. Here the focus was put on dynamic effects due to switching operations. These are the switching of the active area of the cylinders, the switching of the motors and controlling the pressure. In order to simplify future developments a simulation model was set up. It was presented in the third chapter and validated in terms of dynamics in the fourth. It comprises all relevant components and controls, which are active during operation. However, it does not include changes of the oil properties. The validation of the simulation shows that a good correlation between measurement and simulation could be achieved regarding the dynamics, despite differences in swash plate angle and oscillations with a simple control system.

In future the validated model will be used for further improvements of the hydraulic circuit and the control. Here the focus will be put on reducing oscillations at various points in the system by optimizing control parameters. Additionally, an energetic validation will be carried out. Thus, forecasts not only regarding the dynamics but also regarding the energy production performance can be made reliably.

6. References

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