Implementation of a Vertical Axis Marine Current Turbine for Off-grid Village Electrification in Indonesia

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Abstract

Currently different technologies are studied to harvest energy from marine currents. As one of those, the Kobold turbine, a vertical axis marine current turbine, has been tested in the Strait of Messina, Italy since year 2001. Based on the positive results achieved by the working prototype, further plans were made aiming at applying the technology in developing countries. In a first actual application, a system for electrification of a remote village in Lombok, Indonesia, is planned to be installed.

For this application an electrical system was developed allowing for off-grid operation of the turbine and stable power supply to the consumers. The system comprises the generator-frequency converter system on the turbine and an onshore power station with grid-forming bi-directional battery inverters and battery banks for energy storage. An adapted turbine control scheme was evolved, reducing the turbine output power in case of coincidence of high tidal currents, high battery state of charge and low power consumption to prevent the system from overloading.

The system was successfully tested in laboratory. Installation of the turbine in Indonesia is planned for the end of this year.

Keywords: marine current turbine, off-grid installation, rural electrification.

1. Introduction

Tidal currents offer a sustainable resource for energy production and the technical feasibility of tidal energy conversion has already been proven by several projects [1-3]. In order to make tidal energy conversion also commercial feasible, different projects are currently aiming at the installation of Tidal Energy Converter (TEC) farms [2-3].

Another opportunity is the application of TECs for off-grid electrification in remote areas that are not connected to a local distribution grid. Cost for electricity in these areas – typically based on conventional diesel-generator sets – is often comparably high, due to transportation costs for fuel [4]. Therefore renewable energies offer an attractive alternative. There are many examples where electrification systems in remote areas that rely on mature types of renewable energy forms, like solar, wind and hydro, outperform fossil energy based systems. This is not only from the ecological, but also from the financial point of view [5-7].

The Kobold II Indonesia project [8] aims at the off-grid electrification of a village in Lombok, Indonesia, by means of a vertical axis marine current turbine. To the best of the authors' knowledge, this project is unique, since no other off-grid electrification project based on tidal energy has been carried out so far. This project is funded by the United Nations Industrial Development Organization (UNIDO), the Italian company Ponte di Archimede S.p.A (PDA) and the Indonesian State Ministry of Research and Technology (RISTEK). The turbine technology utilized is termed Kobold [8] and was developed by PDA and the University of Naples (UNINA).

An electrical system for turbine operation and stable power delivery to the village was developed, which takes into account the special requirements arising from the unique use case. The system consists of an onshore power station, comprising grid-forming bi-directional battery inverters with the appropriate battery banks, and the generator system located off-shore on the turbine. The battery banks allow a continuous power supply to the village. Power balancing is achieved by the combination of a frequency shift function, provided by the bi-directional battery inverters [9], small dump-loads and an adapted generator control.

The complete electrical system was successfully tested in laboratory, using the original components to be installed in Indonesia. The final steps of the project – installation and commissioning of the turbine and the electrical system – are foreseen to take place by the end of this year.

This report describes both the electrical system and the control schemes developed for the turbine operation and gives selected results from the laboratory tests. The paper is organized as follows. In section 2 a brief description of the project is given. The electrical system is outlined in section 3. Its development took into account the project requirements, such as turbine characteristics, power demand, etc. Section 4 describes the turbine control schemes. The system was evaluated in laboratory, which is described in section 5. The conclusions give the main project results achieved, the actual project state and an outlook on the next project steps.

2. Project Description

Funded by UNIDO, PDA and Indonesian Ministry RISTEK, the Kobold II Indonesia project aims at the electrification of a village in Indonesia by a vertical axis marine current turbine. Indonesia – with its more than 17,000 islands – has a lot of potential sites for exploitation of marine currents. The choice of the installation site for a first turbine was based on comprehensive investigations, which took into account selection criteria like current velocity, water depth, seabed texture, socio-economic activities, unprivileged areas, and many others [10]. Finally it was decided to install the turbine in the Strait of Alas, between the islands of Lombok and Sumbawa. The turbine will be installed less than 500 m of the coast of Lombok in an area characterized by following properties [10]:

- Water depth between 20 and 40 m,
- Low waves and wind,
- Current velocity above 2 m/s for more than 8 hours/day.

The electricity produced will be delivered to Ketapang – a village comprising approximately 200 houses without electricity supply.

The Kobold turbine (see Figure 1, Table 1) is a vertical axis marine current turbine, mounted below a floating platform. The technology was developed by PDA in cooperation with UNINA, some features of the Kobold technology are for instance [3]:

- High starting torque due to a patented passive blade pitch mechanism,
- Kinetic energy conversion regardless the flow direction,
- Crucial equipment like generator, frequency converter, etc. installed in a machinery room above sea level.

In [3] detailed descriptions of the first prototype can be found, which has been successfully tested in the Strait of Messina, Italy.

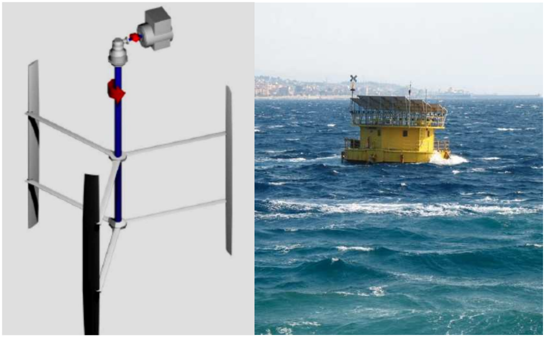


Figure 1: Kobold turbine: Sketch of rotor and drive-train (left), prototype in Messina (right).

Turbine diameter	6 m
Blade span	5 m
Chord length	0.4 m
No. of blades	3
Cut-in speed	1.0 m/s
Rated power	70 kW (at 2.5 m/s)
Overall turbine efficiency	~ 25 %

Table 1: Characteristics of the first Kobold prototype [3].

Based on the Messina prototype a new turbine for the Kobold II Indonesia project was designed, which rates at 150 kW [8]. As one of its main characteristics the power and torque over speed curves of the turbine are given in Figure 2.

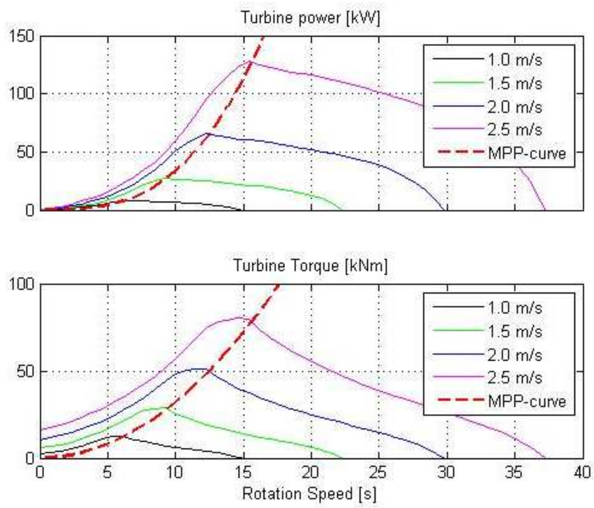


Figure 2: Kobold II Indonesia turbine power over speed (top) and torque over speed (bottom) curves.

To supply the consumers in the village by means of the Kobold turbine an island grid adapted to the application is required. The following section outlines the electrical system developed for the project.

3. Electrical concept

In the design of an off-grid electrical system some special requirements have to be addressed. Firstly, regardless if powered by conventional fossil fuel based (e.g. a diesel-generator set) or by renewable energy sources (e.g. solar, wind, etc.), a grid-forming unit is needed. Secondly, if renewable forms of energy are used, a storage device is required to allow continuous power supply to the consumers independently from the power source. Lastly, a supervisory control is required, which balances the power flow in the island grid by adapting power production to power consumption or vice versa. If a storage device is included, it will be mainly used by the supervisory control to balance the power. A critical situation arises when the power delivered to the island grid exceeds the maximum feed-in power of the grid. This could happen if at the same time there is a high availability of power from wind, solar etc., low power consumption and a high battery state of charge. This situation can be handled either by increasing the power demand or reducing the feed-in power. In case of village electrification, control of the power consumption can only be achieved by additional large and thus expensive dump-loads. Thus, the power balancing is preferably achieved by reducing the power output of the sources. This approach is widely used in island grids fed by renewable energy (see for example [11]) and was also applied in this project.

According to these requirements a system was developed comprising two main parts – the generator system installed on the offshore platform and a grid forming power station located onshore that includes a battery bank and a supervisory power control.

Power station

The power station comprises a battery bank, controlled dump-loads and bi-directional battery inverters. The turbine and the village grid are connected to the power station via a sea-cable (as depicted in Figure 3). The battery inverters form a three phase grid, using the batteries to balance the power flow in the system. In case the turbine power exceeds the maximum feed-in power of the grid, the bi-directional battery inverters raise the grid-frequency f_g. Thus the information that the grid is overloaded is transferred to all connected devices via the three-phase power cables, avoiding further communication paths like signal cables or radio connections. Two subsystems evaluate and react to the grid frequency. Firstly the dump-loads are switched on and the dissipated power P_{DL} is increased linearly with the frequency by their controllers:

$$P_{DL} = \begin{cases} 0\,kW\ ;\ \text{if}\ f_g < 51\,Hz, \\ 12\,kW * \dfrac{f_g - 51\,Hz}{2.5\,Hz}\ ;\ \text{if}\ 51\,Hz < f_g < 53.5\,Hz, \\ 12\,kW\ ;\ \text{if}\ f_g > 53.5\,Hz. \end{cases} \tag{1}$$

Because the dump-loads are designed particularly for this application, their controllers are adapted to the frequency shift function of the bi-directional battery inverters, and are capable of dealing with fast transients in the grid (such as load jumps and current turbulences). As the dump load capacity is rather low when compared to the turbine's rated power, due to the economic reasons mentioned above, secondly the power output of the turbine is reduced. This procedure is described in detail below.

It should be noted that both the bi-directional battery inverters and the dump-loads are off-the-shelf components, particularly developed for off-grid installations. The control functions described above are part of these off-the-shelf products. The whole control system is embedded in the battery inverters and the dump-loads. Therefore no additional supervisory control is required to operate the island grid.

The power station rating was done according to estimations of the village power demand and economic aspects. In a first step 6 battery inverters operated in parallel allow for a continuous power supply of 30 kW to the village, backed-up by a battery capacity of around 150 kWh. Two dump-loads can dissipate up to 12 kW of surplus power. To adapt the system to future increased demand, the whole system can easily be scaled up by connecting further inverters, batteries and dump-loads in parallel. In Table 2 references for the applied components are given.

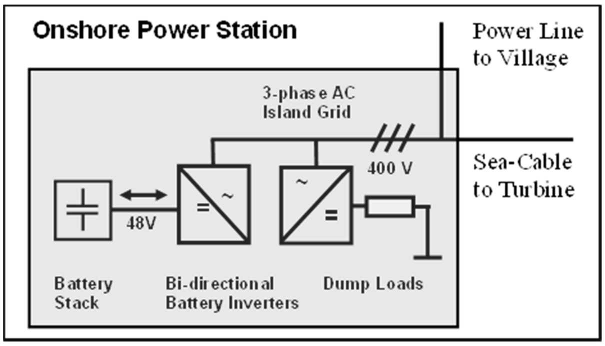


Figure 3: Layout of power station.

Device	Reference	Capacity
Bi-directional battery inverter	Sunny Island 5048 / SMA	5 kW
Dump-load	Smart Load / SMA	6 kW

Table 2: Power station components.

Generator system

From the turbine characteristics in Figure 2 it can be seen that the turbine and thus the generator has to be operated with variable speed to optimize the power output. The dashed red line in Figure 2 depicts the Maximum Power Point (MPP) curve. By tracking this curve the turbine gives the maximum power at each current speed. Variable speed operation also includes the possibility of reducing the power output. By leaving the MPP-curve – no matter if by increasing or decreasing the speed – the turbine power is reduced. This is used to adapt the power output of the turbine to the maximum feed-in power of the grid (see next section for details).

From the turbine characteristics the required power and speed range of the generator system can be derived. According to these requirements a generator system comprising a gear box, an asynchronous generator and a frequency converter (FC) was designed (see Figure 4). The gear box (ratio 51.1) adapts the turbine speed to the speed range of standard industrial machines. The generator is an off-the-shelf marine 6-pole asynchronous generator (rated power 150 kW at 1008 RPM). By means of the FC the generator can be operated in a speed range from 0 to around 6000 RPM (0 to around 120 RPM when related to the turbine side). As the grid-forming function is provided by the power station, a standard industrial full back-to-back converter can be applied – no special functions for off-grid operation are required. The FC provides control algorithms for the torque control of the generator and an interface to a higher-level control, where torque reference, operation control values (start/stop commands, etc.) and feedback signals can be exchanged via analogue/digital IOs of the FC. The higher-level control that controls the turbine is implemented on an industrial programmable logic controller (PLC). Besides the interface to the FC, a set of sensors is routed to the PLC by analogue and digital terminals. These are used to control and monitor the turbine. The main measurands are the current speed, the turbine speed and the generator temperature. By means of an additional sensor, that measures the grid-frequency, the required information for the load balancing is provided to the PLC.

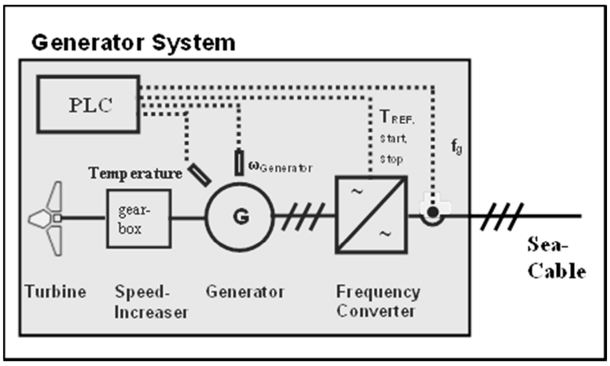


Figure 4: Layout of generator system on the off-shore platform.

The combination of the power station and the generator system fulfils the criteria described above. Two further benefits of the system are: Firstly the robustness of the system, achieved by the frequency shift function – avoiding signal cables or a radio connection to the off-shore platform – and the use of off-the-shelf components and secondly the scalability of the system allowing for adaption to increased power demand in the future.

4. Turbine control schemes

As described above the turbine control mainly aims at optimizing the power output according to the feed-in capacity of the island grid. The control circuit is depicted in Figure 4, showing that two different controllers are used.

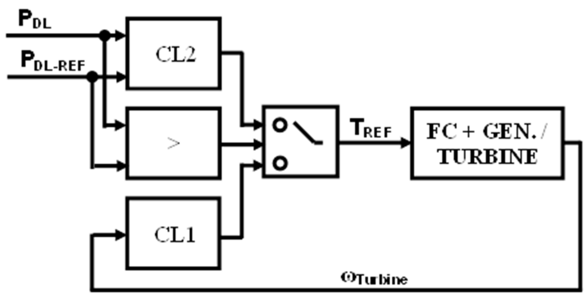


Figure 5: Block diagram of control circuit.

Controller 1 controls the rotational speed of the turbine aiming at tracking the MPP-curve of the turbine. Controller 2 is applied, when the turbine output power exceeds the maximum feed-in power of the village grid. The decision on when to switch between the controllers depends on the measured grid-frequency (see below).

For the tracking of the maximum power point a control scheme well-known from wind energy conversion is applied. The reference torque T_{REF} for the generator is obtained by the following equation:

$$T_{REF} = k_1 * \omega_{Turbine}^2, \qquad (2)$$

where k_1 is a constant adapted to the characteristics of the turbine.

The decision on when to apply controller 2, reducing the power output of the turbine, is made based on the power dissipated in the dump-loads P_{DL}, obtained from the grid-frequency f_g according to equation 1. The limit value $P_{DL\text{-}REF}$ for activating the power reduction was set to 1 kW. The same value is used as set point for the controller, avoiding losses of produced power due to small deviations from the set point and at the same time leaving a reserve of 11 kW of dump-load power, in case of rapid increase of surplus power.

The control law for the power reduction is given by equation 3:

$$T_{REF} = T_{REF\_OLD} - k_2 * \left(P_{DL} - P_{DL_{REF}}\right)^2, \qquad (3)$$

where k_2 is constant determined by simulations and T_{REF_OLD} is the torque reference value from the last PLC cycle.

Reducing the generator torque proportional to the square of the surplus power leads on the one hand to a smooth power reduction in case of low surplus power and on the other hand to a rapid reduction in case of high surplus power. The torque imbalance due to the reduction of the generator torque results in an acceleration of the turbine, i.e. the turbine is operated in the falling slope of the power over speed curve. This holds some advantages:

- Some of the surplus power is stored in the turbine inertia,
- Open-loop circuit is stable and
- Ripples in the hydrodynamic torque are lower in this operation area [12].

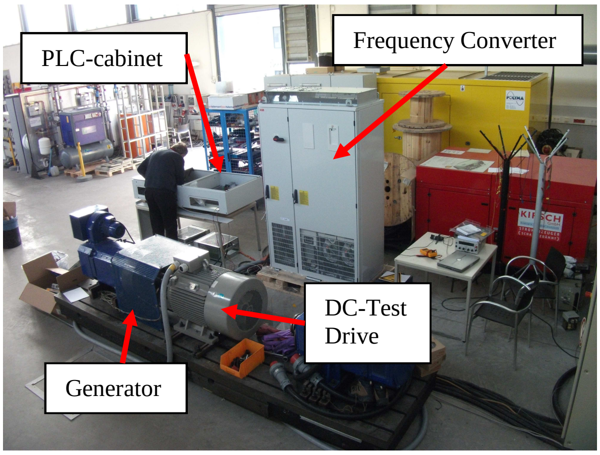
The possible disadvantages – cavitation and stress on the drive train components, both due to high rotational speeds – were addressed in the design and specification of the turbine and the generator system components.

The controllers were tested and evaluated by means of comprehensive off-line simulations, considering scenarios like run-up, run-down, transition between the controllers, switching of loads, different load curves, behaviour under turbulent current velocities etc. During these tests the controllers proved to perform well in terms of both MPP-tracking and power output reduction, but comparably high ripples were found in the generator torque. In order to smooth the generator torque a filter function was incorporated in both controllers, limiting the increasing of the generator torque.

5. Laboratory Tests

The laboratory tests aimed at validating the electrical system and the control schemes prior to installation, thus reducing both the risk of the system not performing as expected and also the commissioning time during installation of the turbine in Indonesia.

In the laboratory all available components from the island grid were installed and connected in the same manner as in the real application. Generator and battery were not available for testing in laboratory, as they were directly delivered to Indonesia. These two components were replaced by an appropriate asynchronous generator and a battery stack. Similar to the configuration in the real application the test bench system is divided in two areas connected by a power cable. In Figure 6 both areas of the test bench are depicted. Besides the components of the power station and the generator system Figure 6 shows a DC-test drive. This DC-machine coupled to the generator is used to simulate the Kobold turbine, using the characteristic curves of the turbine (see Figure 2) and different current speed time series to control the DC-machine.



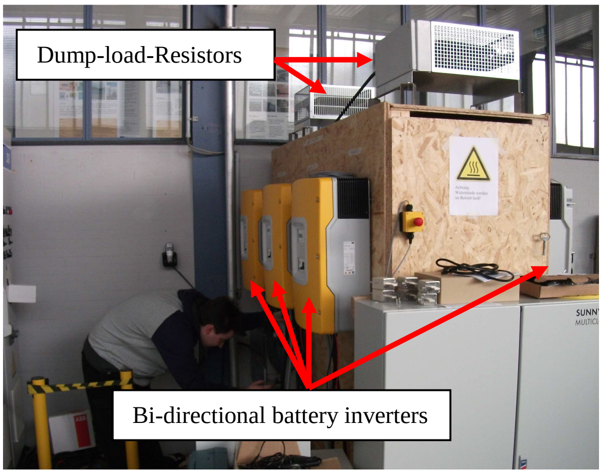


Figure 6: Test bench setup. Power station components (top), generator system and test drive (bottom).

Using the test bench as described above a comprehensive set of tests was carried out, comprising:

- Interface PLC to FC,
- Start and Stop procedures of the FC connected to the island grid,
- Stability of the controllers under steady and turbulent flow,
- Transition between controllers,
- Load jumps in the island grid and
- Reduction of turbine output power.

As one example Figure 7 depicts in detail the behaviour of the system during transient conditions – switching of a 12 kW load in this case. The following phases can be seen in the Figure. In phase 1 the turbine output power is below the maximum feed-in power of the island grid. Thus controller 1 is active operating the turbine at the maximum power point (around 13 kW at 1.1 m/s). The power in the dump-loads equals zero indicated by a grid frequency below 51 Hz. In phase 2 after a load of 12 kW was disconnected from the island grid the bi-directional battery inverters start to increase the grid-frequency. At the border between phase 2 and 3 when the grid-frequency has passed the limit value of 51.21 Hz – equalling a dump-load power of 1 kW – the transition between controller 1and 2 occurs. In section 3 the generator torque is reduced according to equation 3 – resulting in an acceleration of the turbine and a reduced output power. In section 4 the system has reached a new stable operation point, whereas still controller 2 is active. The turbine output power is adapted to the maximum feed-in power of the grid and the power dissipated in the dump-loads equals the reference value of 1 kW.

In summary it can be said, that all test were successfully passed. After the laboratory tests the components were disassembled, packed and shipped to Indonesia.

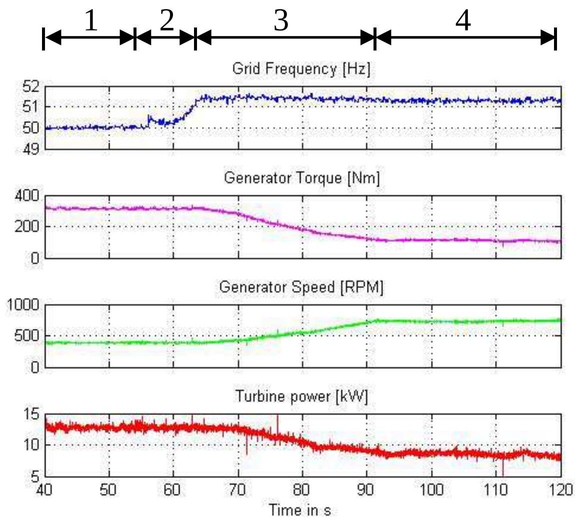


Figure 7: Transition between controllers after a 12 kW load jump in the island grid.

6. Conclusions

This paper has described control schemes and the electrical system for village electrification in Lombok, Indonesia, by means of a vertical axis marine current turbine. The electrical system consists of an onshore power station and the generator system located on the turbine. An adapted turbine control was developed to adapt the turbine output power to the maximum feed-in power of the island grid. Robustness of the system is achieved by the use off-the-shelf components and by transferring the information on the power balance status of the island grid by means of the grid frequency, avoiding further signal cabling or a radio connection. The power station can easily be adapted to increased future power demand.

The whole system was successfully tested in laboratory. The last project steps – installation and commissioning of the turbine – are foreseen for the end of this year.

Acknowledgements

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