Emulation of a Micro-Hydro-Turbine for Stand-Alone Power Plants with Z-Source Inverter

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***Abstract*- This paper proposes an emulation model of a small scale hydro turbine driving a micro generation system and using a Z-Source inverter. The turbine emulator utilizes the hill charts to scale the characteristic curves of the turbine according to different turbine sizes and different head and water flow conditions. In the experimental set-up a Permanent Magnet Synchronous Machine (PMSM) is used as a generator and an induction machine drive with field oriented control emulates the behavior of the turbine. A Z-Source inverter is utilized to convert the available electrical power with a voltage that varies in amplitude and frequency and delivers a voltage with constant amplitude and frequency.**

I. INTRODUCTION

For generating power in outlying regions small regenerative energy sources like small hydro power plants or solar panels can be used. They can provide small amounts of energy for electric light, refrigerators or other applications. As an example, small hydro turbines can provide up to 1 kW of power from a small river. They are low-cost, rather small and rugged, which makes them ideal for the use in rural and remote areas, where a grid is not available or the connection to it is too expensive. They can easily be maintained and manufactured by local suppliers in many less-developed country and emerging countries. A problem arises by using these simple systems namely to overcome the variation of the amplitude and frequency of the output voltage according to the water flow, the hydraulic head and the load applied to the turbine.

Therefore, the varying input voltage has to be converted by a power electronic system to a voltage with constant amplitude and frequency. In most standard topologies the voltage is rectified and boosted to a DC value in a first stage of conversion and is converted into the desired voltage (mostly AC) in a second stage. Typically, a boost converter feeds a standard H-bridge in such applications. The Z-Source inverter (ZSI) provides this functionality in only one stage [1]. It can cope with a widely varying input voltage converting it directly into the desired voltage. In comparison with a standard voltage-source inverter (VSI) a shoot-through state of the output inverter is not just tolerated but an important part of the functional principle. This feature makes the ZSI ideal for standalone power generation in outlying regions as it increases the inverters ruggedness and therefore fits well to the characteristics of the turbine.

II. TURBINE EMULATOR

The turbine emulator proposed in this work is used to emulate the behavior of a small hydro turbine in laboratory applications so that no water laboratory is required. The block diagram of the basic set-up can be seen in Fig. 1. The characteristic curves representing the behavior (M-n) of the turbine are stored in a PC, in which the emulation runs and delivers the command values for the torque to the induction machine drive based on the measured velocity. In this way, the mechanical power at the shaft of the PMSM - generator is not provided by a turbine but by the induction machine drive that exhibits the steady state behavior of the hydro-turbine. The generated electric power is delivered to the ZSI that converts the power to the desired format. The machine setup and the data of the utilized PMSM can be found in Fig. 5 and Table 2 in the appendix.

The power, which is available through the water flow, is defined by

$$P_{hyd} = \rho g H Q\,, \tag{1}$$

where ρ is the density of the water, H the hydraulic head, Q the volume water flow and g the gravity constant. Potential energy is converted by the turbine as a result of water pressure applying a force to the runner's blades. The mechanical power delivered to the shaft can be calculated by multiplying the hydraulic power with the efficiency of the turbine.

$$P_{mech} = \eta_{hyd} P_{hyd} \tag{2}$$

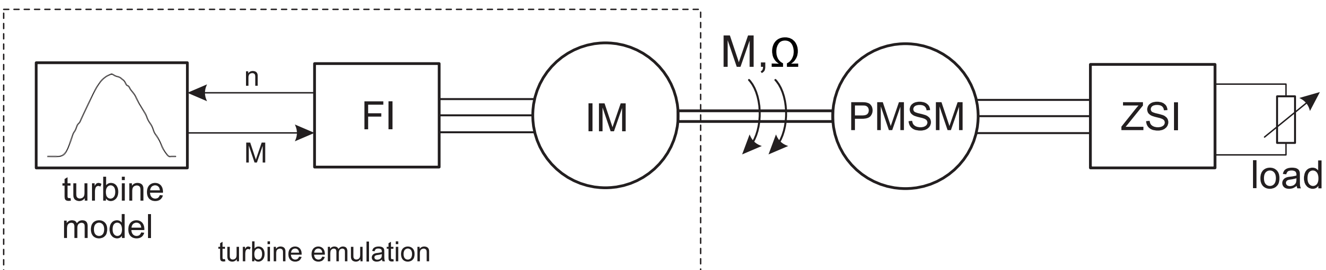

Fig. 1 Structure of the proposed laboratory setup including turbine emulation and ZSI

The change of the angular speed strongly affects the output power of the turbine. If the water flow does not fit the speed of the rotor of the turbine, the pressure difference gives less force than expected. Therefore, a linear torque speed characteristic cannot be used. To scale the torque-speed characteristic curves according to the operating conditions, the scaling laws based on the hill charts are obtained. Some typical hill curves for a propeller hydro turbine can be seen in Fig. 3. For our particular turbine type, that is depicted in Fig. 2, a hill chart was extracted from laboratory measurements [3][4].

TABLE I
CHARACTERISTIC VALUES FOR THE EMULATED LOW HEAD TURBINES

	small size hydro turbine	medium size hydro turbine	big size hydro turbine
rated output power	200 W	500 W	1 kW
diameter	20 cm	30 cm	42 cm
minimum water flow rate	20 l/s	28 l/s	52 l/s
maximum water flow rate	36 l/s	75 l/s	135 l/s
head	1,5 m	1,5 m	1,5 m

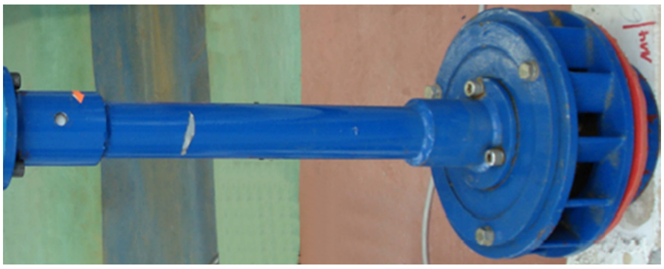

Fig. 2 Low head turbine used as prototype for the measurements in the hydraulic engineering laboratory.

The three non-dimensional coefficients, which are the flow coefficient φ, the energy coefficient ψ and the power coefficient Π can be used to describe the turbines performance curves.

$$\varphi = (Q / \omega D^3) \quad (3)$$

$$\psi = (gH / \omega^2 D^2) \quad (4)$$

$$\Pi = (P / \rho \omega^3 D^5) \quad (5)$$

$$\eta = (\Pi / \varphi \omega) \quad (6)$$

Once they are calculated or measured for a known turbine (prototype) they can be used to recalculate the power and the speed by choosing new parameters for the diameter D, the potential head H and the flow rate Q by assuming that these characteristic coefficients remain constant while the dimensions of the turbine change.

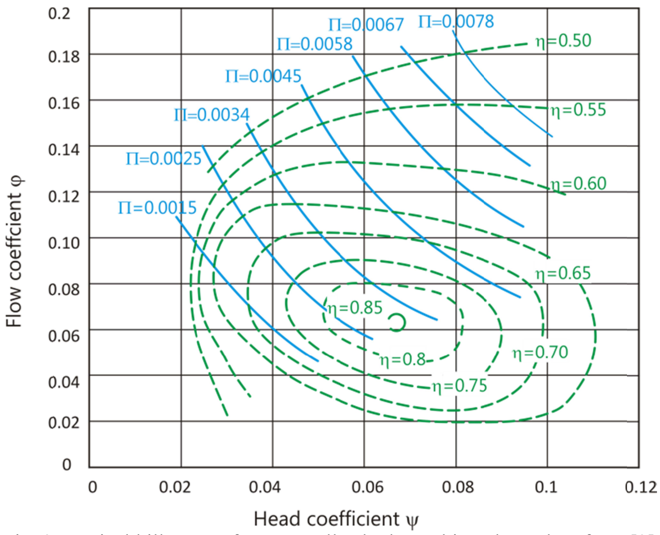

Fig. 3 Typical hill curves for a propeller hydro turbine, data taken from [2]. Regions of same efficiency can be recognized in green.

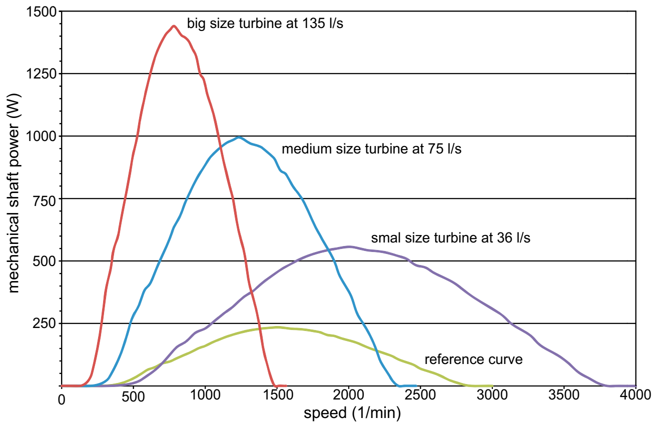

Fig. 4 Performance curves for the three emulated turbine sizes each at its maximum flow rate and the reference curve at the bottom

Fig. 5 The utilized PMSM can be seen on the left, the induction machine on the right side. The IM is controlled by a frequency inverter according to the performance curves. The PMSM feeds the generated power to the ZSI.

So for a new unknown model, the values of the physical variables can be computed by scaling the known ones and applying the following relationships:

$$Q_m = Q_p \left(\frac{n_m}{n_p}\right)\left(\frac{D_m}{D_p}\right)^3 \quad (7)$$

$$P_m = P_p \left(\frac{\rho_m}{\rho_p}\right)\left(\frac{n_m}{n_p}\right)^3\left(\frac{D_m}{D_p}\right)^5 \quad (8)$$

$$H_m = H_p \left(\frac{n_m}{n_p}\right)^2 \left(\frac{D_m}{D_p}\right)^2 \quad (9)$$

The index "m" indicates the values for the new model; the index "p" describes the values from the known turbine (prototype) [5].

The model for scaling the curves is implemented with LabView. The water flow rate and the head can be changed and the turbine type can be selected. The program scales the performance curves accordingly. It works in continuous operation. The velocity of the induction machine drive is used as an input of the emulation system. Based on the actual curve reference value the torque is fed back to the inverter, which controls the induction machine. Table 1 shows the turbine types that are implemented in the proposed emulation. Fig. 4 shows the power speed characteristic for all three implemented turbine sizes each at its maximum flow rate and the reference curve which is the basis for scaling. Only for the reference curve a measurement is required.

It can be seen that the no-load speed drops when the turbine size increases. As expected, the maximum available power increases when the turbines diameter or the water flow is increased. The machine unit can be seen in Fig. 5.

III. Z-Source Inverter

A. Circuit Analysis of the Z-Source Inverter

The utilized circuit for the power conversion is depicted in Fig. 6. The input power is provided by a PMSM feeding a rectifier bridge. The resulting DC - voltage is smoothed by a capacitor.

For analyzing the ZSI, a symmetric design for the z-network is assumed, which means that both inductances and both capacitances have the same value.

$$L_{Z1} = L_{Z2} = L_Z \text{ and } C_{Z1} = C_{Z2} = C_Z \quad (10)$$

When analyzing the ZSI generally, different states within the switching period T have to be distinguished: Short circuiting the output of the inverter by closing two switches of one leg of the H-bridge leads to the shoot-through state which is applied for the duration of T_S. The remaining time T_1 is short circuit free and is available for standard PWM strategies. T_1 is again subdivided into an active part where the voltage $\hat{u}_Z$ is applied to the load and a freewheeling part, where the output voltage of the H-bridge is zero. In this way the following duty cycles can be defined:

$$D_S = \frac{T_S}{T}; D_1 = 1 - D_S = \frac{T_1}{T} = \frac{T - T_S}{T} \quad (11)$$

When short circuiting the output of the inverter, the topology is changed. The capacitors are now parallel to the inductances because U_{CZ} is at least loaded to the same value as the input voltage U_{IN}, the voltage u_D becomes negative and the diode D is biased in reverse:

$$u_D = U_{IN} - 2U_{CZ} < 0 \quad (12)$$

$$u_{LZ} = U_{LC} \quad (13)$$

As a result, the current i_L through each inductance will rise. The output voltage of the inverter is zero in this state.

The remaining time is short circuit free and yields the following equations:

$$u_{LZ} = U_{IN} - U_{CZ} \quad (14)$$

$$u_Z = U_{CZ} - u_{LZ} = 2U_{CZ} - U_{IN} \quad (15)$$

As the main voltage of the inductance must be zero, the voltage U_{CZ} can be calculated from (11) together with (13) and (14) as:

$$\overline{u}_{LZ} = \frac{T_S U_{CZ} + T_1 (U_{IN} - U_{CZ})}{T} = 0$$
$$\Rightarrow U_{CZ} = \frac{T_1}{T_1 - T_S} \cdot U_{IN} = \frac{1 - D_S}{1 - 2D_S} \cdot U_{IN} \quad (16)$$

For the non-shoot-through state the voltage $\hat{u}_Z$ can be calculated by utilizing equations (15) and (16). u_Z is zero during shoot-through and has its peak value during T_1. $\hat{u}_Z$ is also the value that is applied to the load through the H-bridge.

$$\hat{u}_Z = 2U_{CZ} - U_{IN} = \frac{T}{T_1 - T_S} \cdot U_{IN}$$
$$= \frac{1}{1 - 2D_S} \cdot U_{IN} \quad (17)$$

This leads to the achieved voltage boost B, which depends on the shoot-through duty cycle D_S.

$$B = \frac{\hat{u}_Z}{U_{IN}} = \frac{T}{T_1 - T_S} = \frac{1}{1 - 2D_S} \geq 1 \quad (18)$$

The maximum boost will be achieved when applying a D_S of 0.5. This would lead to a theoretic boost of infinity. Considering the modulation index of the PWM, the maximum boost factor of the ZSI is:

$$B_B = B \cdot M_{MAX} = \frac{1}{1 - 2D_S} \cdot (1 - D_S) \quad (19)$$

B. Control structure

For the proposed control structure the voltages U_{IN} and U_{CZ} must be measured. A current measurement is not required, although it is measured and used for detecting inverter failures. In most control schemes U_{CZ} is regulated [6] - [8]. Here the peak output voltage $\hat{u}_Z$ is controlled. $\hat{u}_Z$ is the voltage at the input of the H-bridge during T_1, so it determines the modulation index M for the PWM.

As seen in Fig. 8 the desired boost factor B* is calculated by using the measured value of U_{IN} and the value of $\hat{u}_Z^*$ that should be achieved.

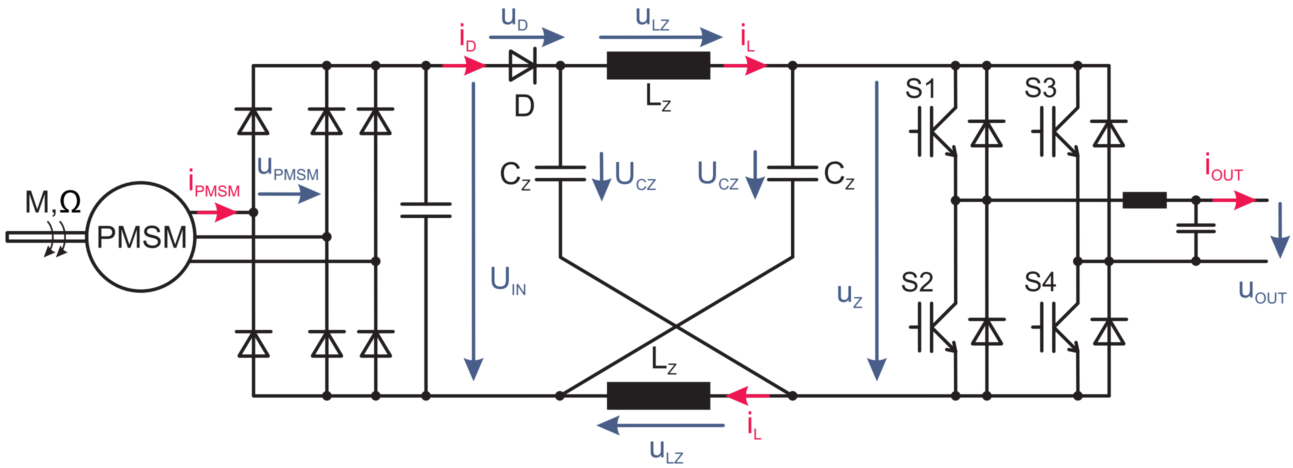

Fig. 6 Structure of the Z-Source inverter

Rearranging (18), the set point value for the shoot-through duty cycle D_S^* can be obtained as

$$D_s^* = \frac{B^* - 1}{2B^*}. \quad (20)$$

This value could directly be applied to the PWM, but unfortunately the real voltage values differ from the desired ones, due to finite switching times, inverter dead times and other non linearities. Therefore, the actual shoot-through duty cycle is calculated, utilizing U_{IN}, U_{CZ} and (16). A PI-controller is used for the calculation of the PWM in a way that the difference $D_S^* - D_S$ is controlled to zero. The equations (18) (19) describing the ZSI maintain valid and $\hat{u}_Z$ can be directly used for computing the PWM for u_{OUT}. In order to reduce voltage stress and losses, the set point value of $\hat{u}_Z^*$ is changed according to the input voltage. As can be seen in (18) the shoot-through duty cycle must be changed inversely proportional to U_{IN}.

The H-bridge is basically driven by alternate switching. In standard VSI a dead time is required to prevent short circuits in the H-bridge. Since a short circuit is part of the function principle no dead time is required. Therefore, the dead time is replaced by the shoot-through state practically by applying a negative dead time. In this way the amount of switching actions in comparison to standard switching patterns is not increased.

The proposed control scheme features a better dynamic behavior as it reacts directly to changes of U_{IN} because the desired D_S is pre-calculated and used as feed forward. This control method is easy to implement and runs stable, proven by an implementation of a laboratory setup controlled by a simple dsPIC microcontroller [8].

The output has a value of 230 V RMS with a frequency of 50 Hz. The self-designed ZSI can be seen in Fig. 7.

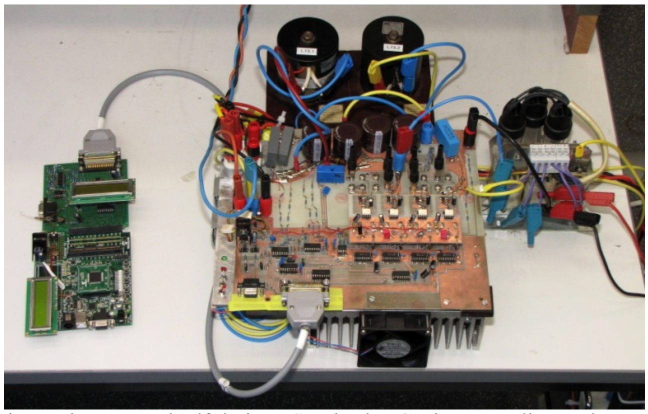

Fig. 7 The proposed self-design ZSI. The dsPIC microcontroller can be seen at the left. It is connected to the main board containing the actual ZSI, gate drivers and measurement circuits. The Z-Source inductors can be seen at the top of the picture.

IV. Experimental Results

The measurements are performed by choosing the medium size turbine at a water flow rate of 75 l/s. The characteristic can be seen in Fig. 4. According to (1) there will be 1100 W of power provided through the water flow. The load at the output of the inverter was increased from no-load to the maximum available power in steps of 50 W.

When operating at no-load, the velocity of the machine goes up to 2100 1/min. As the load is increased, the velocity of the drive decreases. According to the model the torque is increased to reach the needed shaft power. This results in an operation point on the right side of the curve. The system does not include any kind of energy storage and only the energy consumed on the load is harvested from the water flow and no MPP tracking is needed which keeps the implementation simple.

Fig. 9 and Fig. 10 both show the output voltage and the output current of the PMSM at the top and the output voltage and current at the output of the ZSI at the bottom. The output voltage of the PMSM is the AC-input voltage of the ZSI.

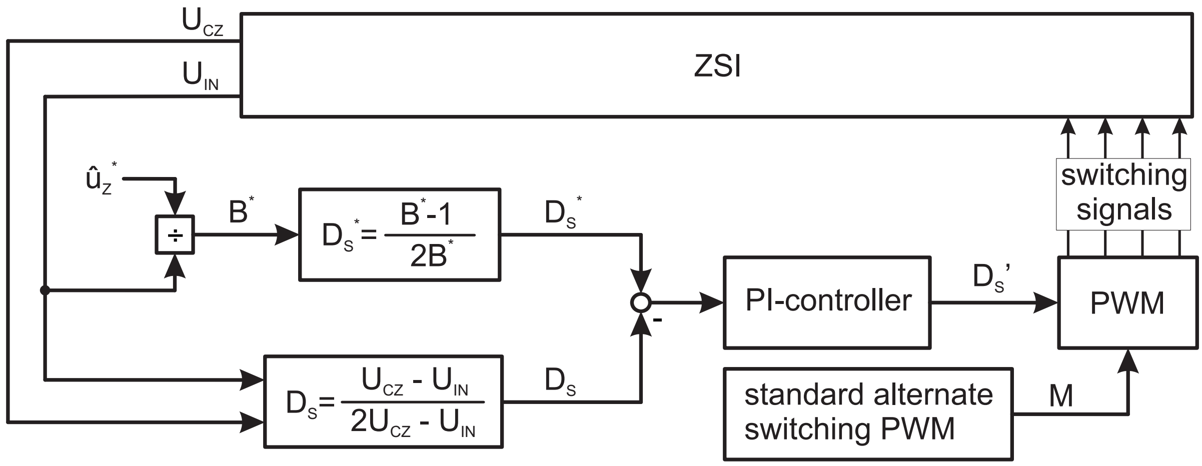

Fig. 8 Control structure for controlling the output of the Z-Source inverter

The output power at Fig. 9 is 50 W, the output power of Fig. 10 is 600 W. It can be seen that the frequency and the amplitude of the machine voltage decreases as the load increases. At a load of 50 W the shaft turns with a velocity of 2060 1/min which corresponds to a frequency of 103 Hz. The AC-input voltage has a value of 206 V RMS so only low boosting is required. As the load is increased to 600 W the speed of the machine drops to 1410 1/min. The frequency is now 72 Hz and the output voltage of the PMSM is only 144 V RMS. Considering the ratio of $\frac{U_{OUT}}{U_{PMSM}}$, a boosting factor of 1.57 is obtained. In both cases the output voltage has a constant value of 230 V RMS and a constant frequency of 50 Hz. Thus, the output values are constant regardless of the values at the input of the inverter.

The power characteristic of the ZSI when increasing the output load from no-load to 600 W shows a power consumption of 45 W at no-load. At the maximum output power of 600 W the ZSI takes a total power of 774 W from the mechanical part of the system. Fig. 11 shows the corresponding efficiency curve. The efficiency reaches a maximum level of 80 % and is practically constant in a wide range of power. A further analysis of the efficiency of the ZSI is given in [9].

It is not possible to obtain more than 600 W from the turbine at this configuration. As mentioned before, the operation point is located on the right side of the performance curve. To increase the power the operating point has to move along the curve to the maximum power point. Once the system slips over the summit, the deliverable power goes back. Due to smaller input voltages the current requirement becomes higher though. Higher current consumption leads to a higher torque at the shaft. This reduces the speed of the machine even more. Operating on the left side of the curve is therefore unstable and not possible. Once the input voltage falls below 100 V, due to the reduced speed of the PMSM, the control is programmed to shut down the operation.

It can be seen in Fig. 4 that the maximum available power of the medium size turbine is 885 W. The maximum output power is 600 W. This results in a maximum overall efficiency of the system of 89 %.

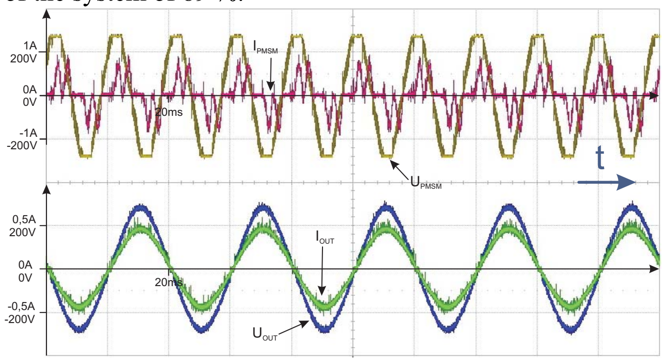

Fig. 9 Input current and voltage for the ZSI are shown at the top, output voltage and current are shown at the bottom at a load of 50W

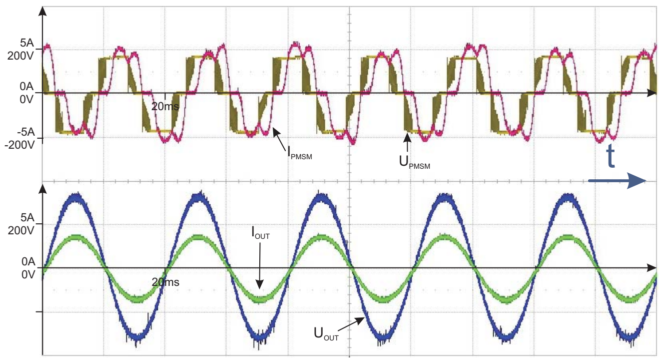

Fig. 10 Input current and voltage for the ZSI are shown at the top, output voltage and current are shown at the bottom at a load of 600W

To test the dynamic behavior of the emulation in combination with the proposed ZSI, a sudden change of the load is performed at the output of the inverter. At first the load resistance was adjusted so that the consumed power was 200 W. In this operation point the shaft speed has a value of 1910 1/min. The load resistance was now reduced in order to reach an output power of 500 W. The results can be seen in Fig. 12. The output voltage and the output current are shown at the bottom of the figure, the DC Input voltage U_{IN} at the top.

The sudden increase of the load has a minor impact on the output voltage as the sinusoidal waveform is quickly restored. As the load is now increased the velocity of the PMSM reduces to 1590 1/min with the subsequent drop of U_{IN}.

Fig. 13 shows the same curves as Fig. 12 but the load is now decreased from 500 W to 200 W. When the load drops, the amplitude of the output voltage varies but comes back to a stable value very fast. By applying the reverse procedure the shaft speed increases to 1940 1/min causing the corresponding increase of U_{IN}.

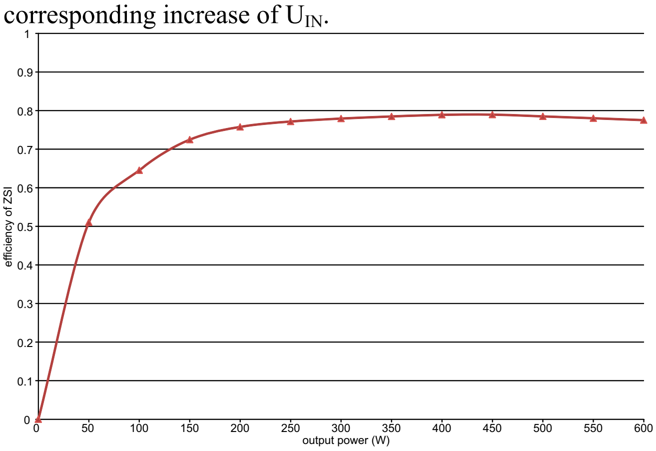

Fig. 11 Efficiency of the ZSI utilized in the proposed setup

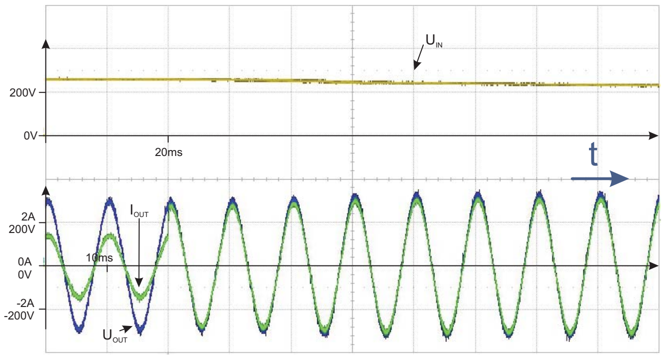

Fig. 12 Increasing the inverters load from 200 W to 500 W

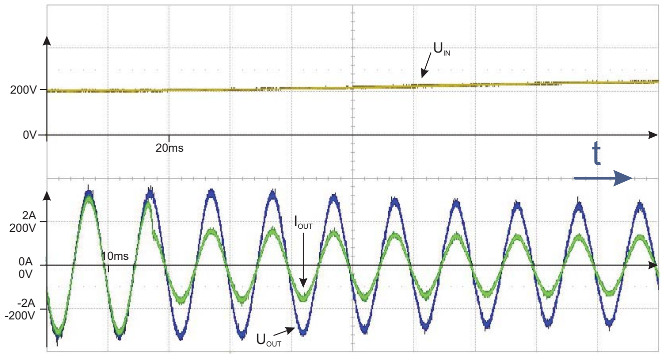

Fig. 13 Decreasing the inverters load from 500 W to 200 W

V. CONCLUSION

This paper introduces the combination of a small scale variable hydro turbine emulator and a Z-Source inverter. The system is used to emulate the behavior of a small hydro-turbine in the laboratory. Besides, it is able to scale the power speed characteristic according to water flow, hydraulic head and turbine type by considering the variations of the angular speed. The emulation is based on a reference curve gained by measurement on the river lab. An inverter - fed induction machine drive is controlled according to the performance curves of the turbine. The shaft power is converted to electric power utilizing a PMSM. Since the amplitude and the frequency of the output voltage of the PMSM vary with the shafts speed, a power electronics system converts the power to an appropriate format. So the generated power is fed into a ZSI. It converts the available output of the PMSM into a voltage with constant amplitude and frequency. A control scheme is also proposed that works in a wide range of load and keeps the output voltage stable for varying loads. The proposed setup is simple, robust and easy to implement as it works for various turbines and load configurations controlled by a simple dsPIC microcontroller.

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APPENDIX

TABLE 2
DATA OF THE UTILIZED PMSM

rated torque M_N	7,8 Nm
rated current I_N	5,1 A
rated speed n_N	3000 1/min
rated power P_N	2450 W
torque constant k_T	1,52 Nm/A
speed constant k_E (per 1000 1/min)	96 V