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AC/DC/AC converter in a small hydroelectric power plant

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Abstract. The article discusses application of AC/DC/AC converter cooperating with an induction generator in small hydroelectric power plants. The induction generator works with power grid or a separated group of receivers, enabling to generate power even at low speeds of the turbine. The article provides also results of the investigation concerning the functioning of the generator coupled with AC/DC/AC converter in steady and transient states during start-up and voltage decay.

Key words: induction generator, AC/DC/AC converter, hydroelectric power plant.

1. Introduction

Over 700 electricity producers in Poland generate electricity in small hydroelectric power plants, many of them using up to several dozen generators with power of 20–500 kW. In most cases, these generators are induction machines connected directly to a power grid. Transfer of electric energy to the grid is possible only at a sufficiently high water level and in the presence of voltage in the grid. The direct connection gives rise to a number of issues related to frequently occurring switching processes, high starting-up currents, changeable power output, limited possibilities of controlling the transferred power, deterioration of power quality in the nodes of the grid close to the generator, and the necessity of the compensation of reactive power. In particular, the first two mentioned phenomena can be the causes of voltage dips and flickers. Also, cyclic power variations lead to the worsening of power supply conditions, or even to instability of the power supply system. All in all, the notable increase in the power obtained from these largely unpredictable sources in the past decade had serious repercussions for power engineering systems – especially considering countries whose total power production heavily relies on such sources – in terms of degeneration of power quality or even malfunctioning of certain elements of the system. Furthermore, the generators lack the functionality of electrical control of the transmitted power, being fitted with protective systems only. This means that the adjustment of a power output can be performed on the part of a turbine (by controlling the water flow), and to a limited extent.

In order to reduce or eliminate the adverse effects of hydroelectric plants on the electric network, the up-to-date generators are designed to have various power electronics converters [1, 2]. The introduction of such converters together with additional energy storage devices can significantly improve the cooperation of hydroelectric plants with power grid. Furthermore, it enables uninterrupted supply of power the local recipients so called “island” in the case of blackouts.

The efficiency of a converter is directly related to the average switching frequency, and in consequence – to the control method [3, 4]. Insofar as the generator can admit certain current signal deformation, in a power electronics converter any current and voltage distortions transmitted into the electric network are unacceptable. As far as the efficiency is concerned, nonlinear control methods may be advantageous (lower switching frequency at comparable output parameters, i.e. torque and current) [4]. In the case of the grid converter, linear current controllers seem to be more suitable since, at the constant frequency modulation, output current filter can be designed more easily [1]. In the presented paper, a turbine coupled with an induction squirrel cage generator is analyzed. Additional system of converters extends the range of applicability of the generators (i.e. electric energy production) over low water level (i.e. ow turbine speed) cases [2]. The AC/DC/AC converter comprises two parts: the DC/AC inverter, cooperating directly with the generator, and the AC/DC converter whose function is to transmit power into the grid, allowing for the regulation of power factor [5].

2. Concept of converter control

The design of the generator control system is dictated by the function performed by the generator (i.e. either connected to the power grid, or working as a “power island”). At a low turbine power output it can be assumed that the turbine, at any velocity of the shaft, always works to generate maximum power which later can be efficiently utilized. Therefore, there are no limitations whatsoever concerning the maximum power that can be transmitted into the power grid. Converter control design meeting the above assumptions is presented in Fig. 1. The DC/AC inverter connects the generator with the DC link represented by the capacitor C. In order to ensure the maximum use of water and turbine power, at specified angular velocity ω_m of the shaft the turbine output power can be determined relying on $P_w = f(\omega_m)$ relation. Next, the set torque M^* which provides the generator's maximum power output at the angular velocity ω_m is calculated. If the turbine's power curve is unknown, the maximum torque can be established by means of a step-by-step algorithm. The AC/DC

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converter transmits the power from the DC link circuit into the three-phase network. The master control of this converter is the capacitor voltage regulation system [1, 2, 6, 7]. Such a feedback is organized for two reasons:

- to provide appropriate voltage which will enable shaping sine wave current transmitted into the power grid under specified conditions (grid voltage, current, and choke's inductance).
- to protect the converter against overvoltage in the cases when there is a difference between the transmitted power and the power received from the DC link.

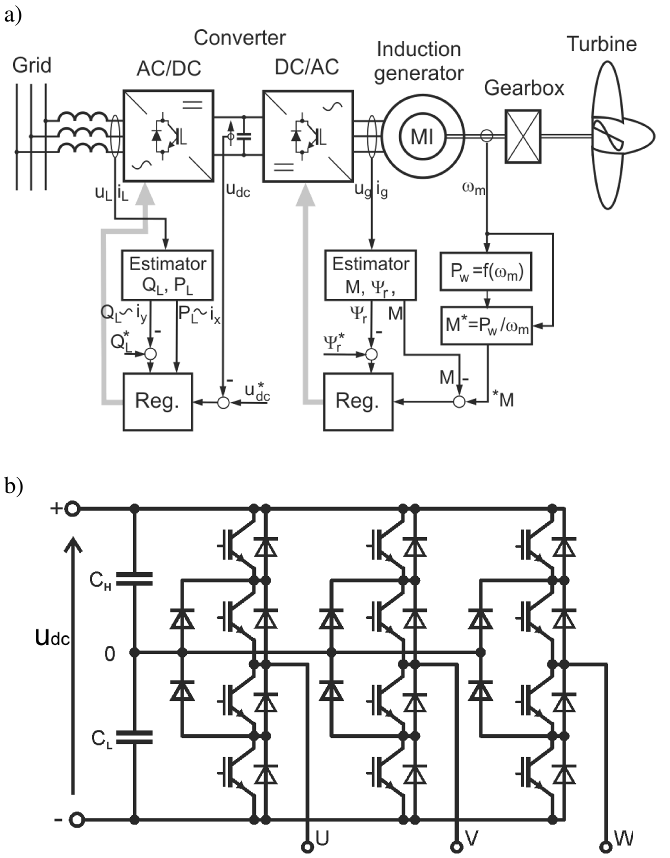

Fig. 1. Control diagram of AC/DC/AC converter used for cooperation between generator and power grid (a), and the three-level structure of the converter (b)

Internal control loops in the induction generator are the same as in a squirrel-cage motor. Figure 1a presents the system for direct control of torque and flux DTC with the sectors divided into 12 parts [8]. The torque and flux are regulated in two separate paths. There are no particular requirements as to the dynamics of the controlled quantities. The generator works at a constant flux value. The set torque value is a variable parameter, but the change rate of M^* is limited by the change rates of the turbine angular velocity ω_m. Thus, the dynamics of set power and torque changes is several orders of magnitude smaller than the time constants of torque control (several milliseconds) possible to achieve in DTC approach. Internal control systems in the converter connecting the generator to the grid were practically realized by means of DPC 3×2 method [9], with two paths of power control in rotating with the grid angular frequency coordinate system xy. Voltage error U_{dc} on the capacitor determines the amplitude

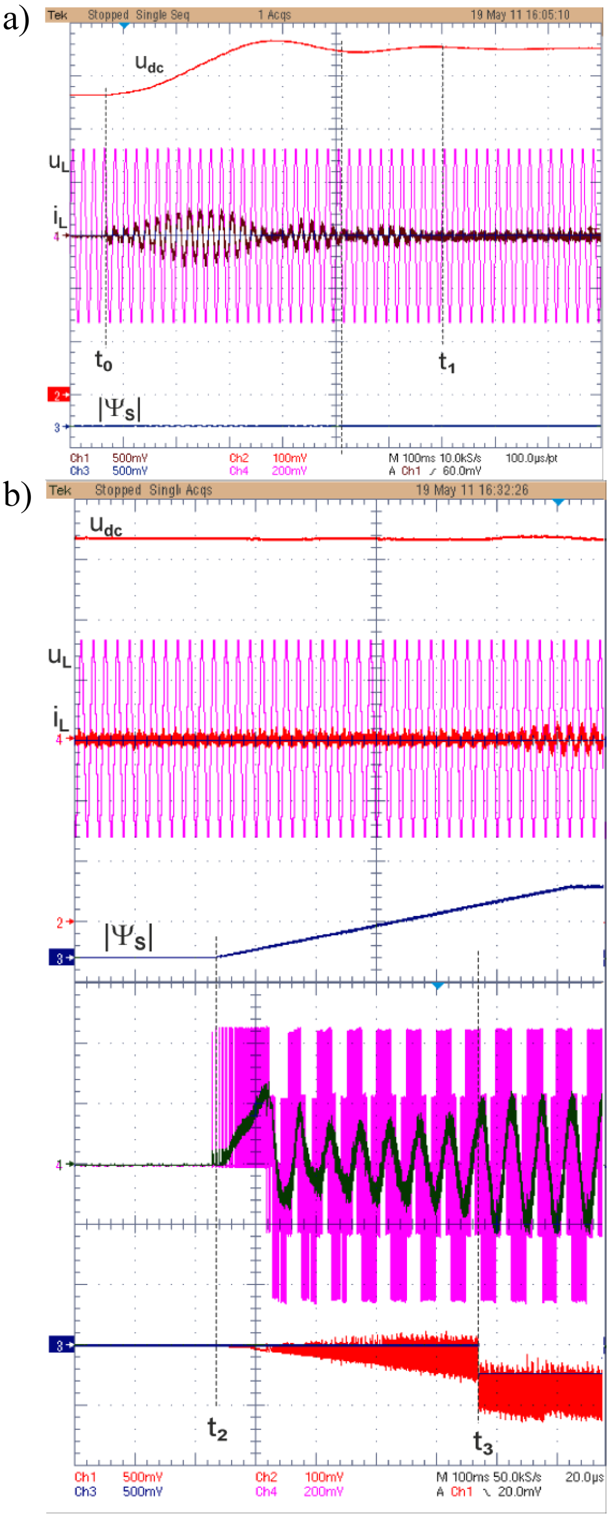

Fig. 2. Results of laboratory testing of start-up cycle when the system cooperates with power grid: DC link voltage U_{dc}, U_L voltage, single-phase AC/DC converter current i_L in the first stage of the start-up (a), and U_{dc}, U_L, i_L and the generator's flux module Ψ_s, as well as the current and phase voltage of the generator, along with the set and the actual torque in the second stage of the start-up (b). Scale: u (100 V/div), i (5 A/div)

and direction of the component proportional to the set value of active power P_L^*. The y-axis component is proportional to the reactive power Q_L^* generated into the grid. When the set value of Q_L^* equals zero, the current flowing into the grid remains in phase with the respective voltages present in the grid (and thus only active power is generated). Similarly as in the case of DC/AC inverter, high dynamics of current components control systems is not required, because changes of both the set (U_{dc}^*, P_L^*) and the controlled (U_{dc}) parameters are not abrupt. The PI-type U_{dc} voltage controller, operating at quasi-constant values, ensures static accuracy. Also, the internal power controllers were built with PI-type linear controllers (PWM) – for operating in the "power island" mode, and with DPC2x3 non-linear controllers (2- and 3-level comparators) for cooperation with power grid. The latter situation requires a specific switching sequence within the turbine-generator-converter-grid system. The proper functioning demands the AC/DC converter directly cooperating with the grid to be actuated first. Figure 2 shows results of laboratory tests related to turning on. In the first stage of the start-up, pre-charged to the voltage of about 560 V capacitor of the DC link circuit, after the turning on the control of AC/DC converter, is charged up in the t_0-t_1 interval to the set voltage U_{dc} equal 650 V. Next, in the second stage, in time t_2 the DC/AC converter is actuated, and in the $t_2 - t_4$ interval the generator is "excited". When the generator's flux reaches 0.8 of the nominal value (t_3), it is possible to apply load the set torque load M^* adequate to the current mode of work. The current and voltage of the same phase in the generator are presented in Fig. 4b. Their shape is independent of the control method used in the AC/DC converter.

3. "Power island" mode

The abovementioned "power island" mode (i.e. supplying power to separated load points) is much more complex from the point of view of the converter circuit design, and its practical implementation requires modifications in the control structure of the converter (Fig. 3). The irrevocable rule here is absolute balancing of the generated power and the power used within the "power island". Otherwise, when e.g. more power is generated than can be used, the overvoltage in local electrical network can damage appliances connected to it. Thus, this mode necessitates introduction of an energy storage device into the network, such as an accumulator. Due to a high control inertia of the power generated by the turbine, abrupt changes in the load values may require transferring power from or to the storage device. Then, if such possibility exists, the amount of energy delivered to the turbine should be adjusted (by regulating the stream of the flowing-through water) to the value corresponding to the actual load (this situation has been analyzed later in the article). The AC/DC converter cooperating with power grid shapes the sine wave voltage (with the use of PWM modulator). PWM provides means for effective filtration of the voltage supplied to the "power island".

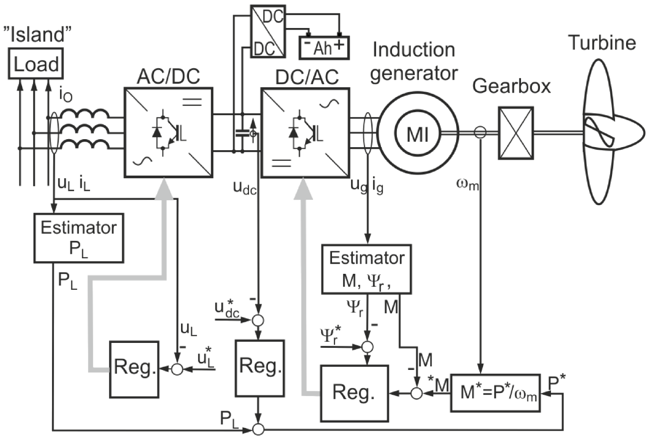

Fig. 3. Diagram of AC/DC/AC converter control for cooperation of the generator with local electrical network ("power island")

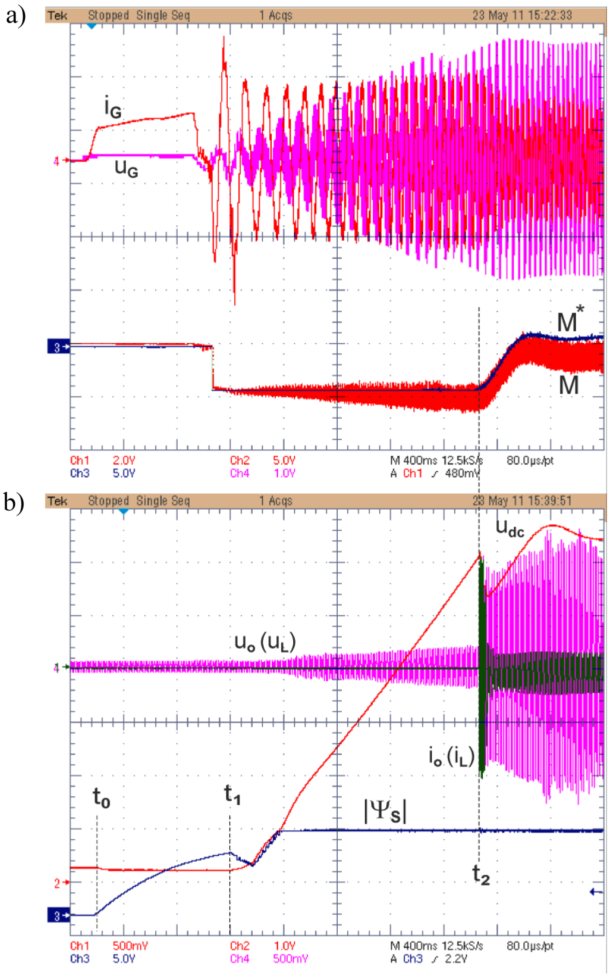

Fig. 4. Results of laboratory testing of the system start-up cycle when working in the "power island" mode: current i_G and phase voltage u_G of the generator, together with the set and the actual load torque of the generator (a), as well as current and voltage of the "island" load (AC/DC converter), U_{dc} voltage and generator's flux module Ψ_s (b). Scale: u (100 V/div), i (5 A/div).

The role of a DC voltage controller in the DC link is taken over by the DC/AC converter control system cooperating with the generator. The converter provides only the power necessary to cover the demands of the “island” (P_L) and to preserve the required own voltage U^*_{dc}. In this way, the worked out set power P^* signal determines the expected load torque M^* of the turbine. The start-up process in the “power island” mode is presented in Fig. 4. Both of the converters are turned on, with initially excited constant flux in the generator by the DC/AC converter ($t_0 - t_1$ interval). Generator excitation should be carried out at the zero velocity of the turbine due to the low voltage (24 V) of the battery which in the first stage of the start-up supplies the DC/AC inverter. After reaching 0.8 of the nominal flux value, initial torque load is applied to the generator, which allows for quicker increase of the U_{dc} voltage. When the voltage rises to the set value of 600 V, the control system of the AC/DC converter is switched on (t_2).

4. Generator in switching between grid/”power island”/grid modes

The load within “power island” are directly connected to the output of the AC/DC converter (Fig. 5). This allows for practically uninterrupted supply of power to these points (Fig. 6) whenever voltage decay occurs in the grid. During the “power island” mode the U_L voltage is shaped in the AC/DC converter with the $C_F L_F$ filter, and preserves the required THD $< 8\%$. In time intervals $t_0 - t_1$ (Fig. 6a) and $t_3 - t_4$ (Fig. 6b) the generator, working with the power grid, receives maximum torque load resulting from the actual power of the turbine. Any voltage decay during the cooperation with the grid (Fig. 6a) in time t_1 causes instantaneous locking of the AC/DC converter control and switching off the W switch in time $t_1 - t_2$. In time t_3, the AC/DC control with the PWM is re-initiated (Fig. 3). Finally, in time $t_3 - t_4$ during the “power island” mode the control system adjusts generator load (M^*) to the power demand of the load. It has to be mentioned that the load are not supplied in time $t_1 - t_3$ which is necessary to switch on the W switch and to change the configuration of control from the one presented in Fig. 1a to the presented in Fig. 3. In the time interval when power is not being received from the DC circuit U_{dc} voltage is rising, and when it exceeds the value of 720 V, the power is transmitted through by the DC/DC converter to accumulators. The torque which is applied to the generator, after the change in control configuration, adjusts itself to the power of a load point within the “island”. As for the generator’s flux, it remains constant during the switching processes.

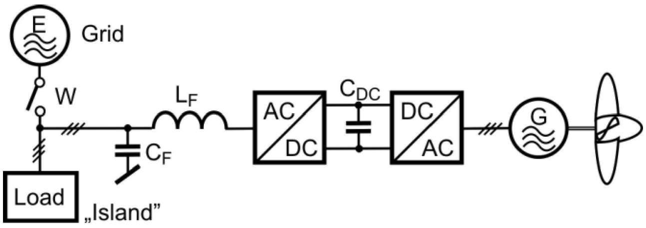

Fig. 5. Diagram of the grid-generator-“power island” system configuration

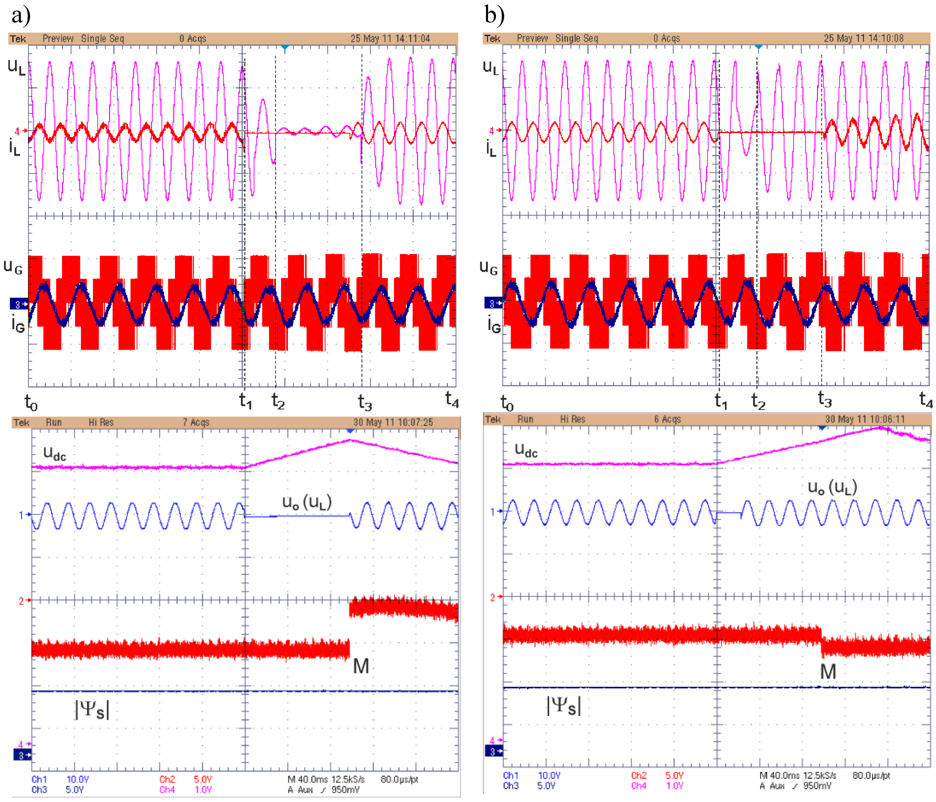

Fig. 6. Results of laboratory testing of the generator’s switching cycle between grid/“power island” modes (a), and “power island”/grid modes (b): voltage u_L and current i_L of a single-phase of the AC/DC converter, together with current i_G and phase voltage u_G of the generator, as well as DC link voltage, “power island” current, load torque and generator’s flux. Scale: u (100 V/div), i (5 A/div)

In the reverse process, that is switching from the "power island" mode to the cooperation with grid (Fig. 6b) after the voltage recovery in the grid, firstly synchronization of AC/DC converter control with the grid takes place ($t_0 - t_1$). In the following steps the PWM control of the AC/DC converter is locked (t_1), the W switch is switched on (t_2), and re-initiation of the converter control configuration according to the pattern presented in Fig. 1a occurs (t_3). During the switch from "power island" mode to the grid cooperation mode the power is not supplied to the load only in the time necessary to switch on the W switch ($t_1 - t_2$), because as soon as the power in the grid is back it can readily supply power up load. Next, after switching on the AC/DC converter control (t$_3$), the load is supplied from the generator. Similarly as in the switch from the grid to "power island" mode, U_{dc} voltage rises until it exceeds 720 V, and then the power is transmitted by the DC/DC converter to accumulators. The torque which is applied to the generator, after the change in control configuration, adjusts itself to the value adequate to the condition of maximum transmitted power into the grid. Again, the generator's flux remains constant during the switching.

5. Conclusions

The induction generator working with AC/DC/AC converter can be coupled with either power grid or a separated group of load. The intermediating converter eliminates the main drawbacks prevailing in a direct connection of the generator to the grid. It allows for lower start-up currents, as well as supports the "power island" mode, and makes it possible to control the amount and characteristics (active and reactive power) of power transmitted into the grid. Another important advantage of the presented solution is the capability of generating power at arbitrarily low angular velocity of the turbine (insofar as the power generated by the turbine is sufficient to cover the generator's and the converters' own losses). The structure of the AC/DC/AC converter and its control ensures only minimum interruption in power supply to the load during the switching processes.

Appendix

Laboratory setup

The experimental results are obtained using a commercial induction machine:

Table 1
IM parameters

Rated power	20 kW
Rated speed	145 rad/s
Rated voltage	230 V
Rated current	40 A

The AC/DC/AC converter used in the laboratory set-up was built in the Bialystok University of Technology. The control system was realized on the floating-point processor ADSP-21262.

Table 2
Laboratory set-up parameters

Nominal line voltage	230 V
Rated power AC/DCAC converter	20 kW
Power devices	IGBT 75A/1200V
Converter configuration	2 × 3-level converter
Grid filter inductance L_F	11.3 mH
Grid filter Capacity C_F	2 μF
DC link capacitor C_{DC}	8.25 mF
Nominal/max. DC link voltage	650/750 V
Switching frequency	10 kHz

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