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Analysis of the autonomous operation of an induction generator working in a small hydropower plant

Abstract: *The paper presents phenomena occurring during the transition of a small hydro power plant, equipped with an induction generator for island work. Computer simulations of power plant cooperation with the MV network were carried out and several work options were considered. The influence of capacitors for reactive power compensation, generator protection, regulation on the water turbine side and other system elements on the operation of the power plant was tested. Obtained results of the computer simulation were presented and discussed.*

Streszczenie: *W pracy przedstawiono zjawiska występujące podczas przejścia małej elektrowni wodnej, wyposażonej w generator indukcyjny na pracę wyspową. Przeprowadzono symulacje komputerowe współpracy elektrowni z siecią SN oraz rozpatrzono kilka wariantów pracy. Analizowano wpływ kondensatorów do kompensacji mocy biernej, zabezpieczeń generatora, regulacji od strony turbiny wodnej oraz pozostałych elementów systemu na pracę elektrowni. Przedstawiono oraz omówiono otrzymane wyniki, uzyskane drogą symulacji komputerowej.* ***(Analiza autonomicznej pracy generatora indukcyjnego pracującego w małej elektrowni wodnej).***

Key words: modeling, small hydropower plants, island work
Słowa kluczowe: modelowanie, małe elektrownie wodne, praca wyspowa

Introduction

Electricity produced from renewable energy sources plays a greater role in the energy balance of our country from year to year. Hydropower is one of the most commonly used renewable technologies not only in Poland, but also in the world. In small hydropower plants due to their simplicity, undoubtedly very good operating properties and the price usually induction machines are used as generators. Attachment of more and more dispersed energy sources creates new problems that have not been seen so far [1, 4, 7]. Therefore, this paper presents the analysis of hazards resulting from the transition of induction generators working in small hydropower plants for island work. The basis of the analysis were computer simulations carried out in the EMTP-ATP program [3, 9, 10].

Description of the test network

During the tests, a typical fragment of the power grid see figure 1. L1-L4 lines are medium voltage lines. Each length of MV line is 10 km. Two MV / LV, T1 and T2 stations have been connected to the L4 line. The T1 station was connected halfway along the line, the second T2 at the end of the line. The T2 station supplies five low voltage lines L421-L425. Each length of LV line is 1 km. The hydropower plant G is connected at the end of the L4 line with a TG transformer. The S2 switch performs the function of a generator switch installed in the electrical switchboard of the power plant, while the switch S1 presents a circuit breaker installed in the line field of the MV station. To compensate for the generator's reactive power, the CB capacitor bank was switched on using the S3 switch. Tables 1 to 8 show the parameters of the considered power grid.

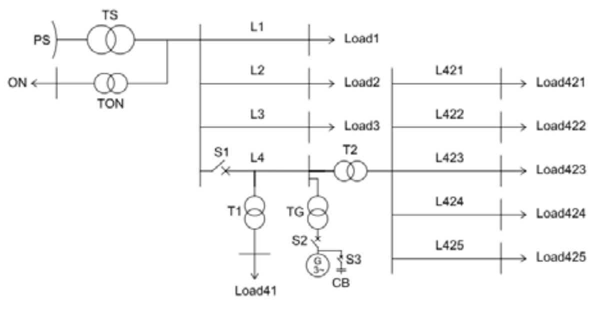

Fig. 1. The scheme of the considered network

Tab. 1. The parameters of the power system

S_{KQ}'' [GVA]	1,5
U_n [kV]	110

Tab. 2. Transformer parameters

	TS	TON	T1,2	TG
ϑ	115/16,5	15,75/0,42	15,75/0,42	15,75/0,69
S_n [MVA]	16	0,485	0,16	0,4
U_k [%]	12	4,5	4	4,5
ΔP_{Cu} [kW]	79,5	1,3	1,3	4,5
ΔP_{Fe} [kW]	9	0,45	0,21	0,61
I_0 [%]	0,5	1	1	0,35
Connection group	Yg/D	Yn/D	D/Yn	D/Yn

Tab. 3. Parameters of MV overhead lines

R_1 [Ω/km]	0,44
R_0 [Ω/km]	0,59
L_1 [H/km]	0,0012
L_0 [H/km]	0,0049
C_1 [F/km]	$9{,}73 \times 10^{-9}$
C_0 [F/km]	$4{,}37 \times 10^{-9}$

Tab. 4. Cable line parameters

R_1 [Ω/km]	0,35
R_0 [Ω/km]	0,35
L_1 [H/km]	0,0006
L_0 [H/km]	0,0018
C_1 [F/km]	$0{,}23 \times 10^{-6}$
C_0 [F/km]	$0{,}076 \times 10^{-6}$

Tab. 5. Parameter of a low voltage overhead line

R_1 [Ω/km]	0,3033

Tab. 6. Receivers parameters

Load1 [MVA]	2-j0,4
Load2 [MVA]	2-j0,4
Load3 [MVA]	2-j0,4
ON [MVA]	0,3-j0,06
Load41 [MVA]	0,125-j0,06
Load421 [MVA]	0,025-j0,025
Load422 [MVA]	0,025-j0,019
Load423 [MVA]	0,025-j0,012
Load424 [MVA]	0,025-j0,012
Load425 [MVA]	0,025-j0,008

Tab. 7. Parameters of an induction motor operating as a generator in a tested hydropower plant

Rated Power P_N [kW]	260
Rated voltage U_N [kV]	0,4/0,69
Rated current I_N [A]	474/275
Rotational speed [rpm]	990
Power factor *cosφ* [-]	0,82
Efficiency *η* [%]	96,6
The multiplicity of the inrush current	6,5
Moment of Interia *J* [kgm^2]	17,102

Tab. 8. Settings of additional protections of the induction generator [2]

Protection function	Setting	Delay time [ms]
Undervoltage protection	0,8 U_n	100
Overvoltage protection	1,15 U_n	100
Underfrequency protection	47,5 Hz	100
Overfrequency protection	51,5 Hz	100

Working of a network without a hydropower plant

Let us assume that, due to a lightning strike into the MV line, its emergency disconnection from the system takes place. The disconnection occurs at time *t* = 2.5s. Figure 2 shows the voltage waveform on one of the loads supplied from the LV network. Analyzing the presented course, it can be noticed that the voltage value immediately drops to zero after disconnecting the power supply in the form of a power system. It should also be noted that the voltage at each point of the network in question falls within the permissible range.

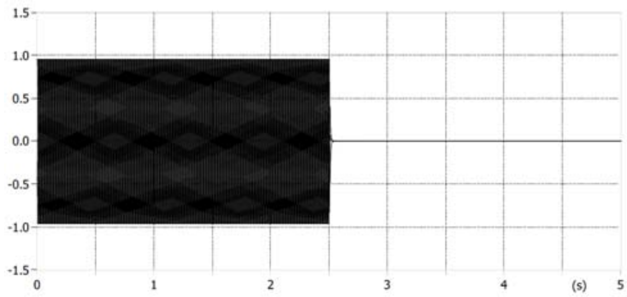

Fig. 2. The voltage sequence on one of the loads supplied from the low voltage network in relation to the rated voltage

Working of a network with a hydropower plant

The following course of events was considered. The power plant starts and after reaching the speed close to the synchronous speed, it takes it to the grid at time *t* = 1.4s using the S2 switch. At time *t* = 2.5s the circuit breaker S1 opens, which causes the line, load and hydropower plant to become an island isolated from the system. The opening of the S1 switch occurred, for example, as a result of a lightning strike into the MV line.

The first case is work without generator reactive power compensation. It was assumed that the system does not have any control and regulation systems on the turbine side, the generator is not equipped with reactive power compensation and the load on the island is comparable to the power of the hydroelectric generator.

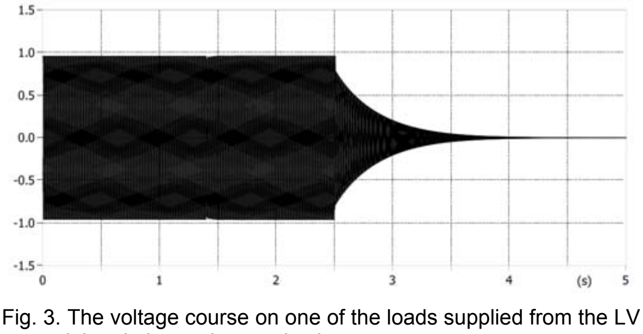

Fig. 3. The voltage course on one of the loads supplied from the LV network in relation to the rated voltage

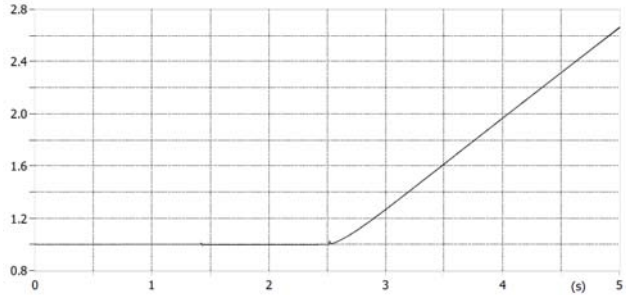

Fig. 4. The frequency waveform on one of the loads supplied from the LV network in relation to the rated frequency

The simplest case of a hydropower plant with an asynchronous generator is a system in which the generator does not have reactive power compensation. In this case, the demand for reactive power of both the receivers and the generator itself is covered by the network [5].

Figure 3 and figure 4 show the waveforms of voltage values and frequencies on one of the loads supplied from the LV network.

It can be noticed that when the generator is switched on to the grid (*t* = 1.4s), the voltage is temporarily reduced, which is not dangerous for the receivers being supplied. From the point of view of recipients, it is much more interesting what happens after separating the island of loads from the working hydropower plant. The lack of compensation of reactive power results in improper conditions for self-induction of the asynchronous generator, which in turn translates into a rapid increase in the frequency of the generated voltage. It was also observed that the voltage does not disappear almost stepwise as in the case of work without a hydropower plant, but gently decreases to zero. The reason for this is the presence of residual capacitance in the system. It should also be noted that the rate of voltage decay and the increase in frequency after the secretion of the island will be the greater, the greater the active power deficit in the separate network.

In the analyzed operating conditions of the generator, additional protection of a small hydropower plant would have been activated. An additional undervoltage protection of the generator would work at time *t* = 2.628s or 128 ms after the island emerged, at a voltage reduced to about 55% of the rated value and the frequency raised to about 52 Hz. However, additional overfrequency protection would work at time *t* = 2.693s, or 193 ms after the island emerged.

The second case is work with generator's reactive power compensation. It was assumed that the system does not have any control and regulation systems on the turbine side, the load on the island is comparable to the power of the hydroelectric generator and the generator is equipped with reactive power compensation. The generator's reactive power has been compensated to *cosφ* = 0.93 [6].

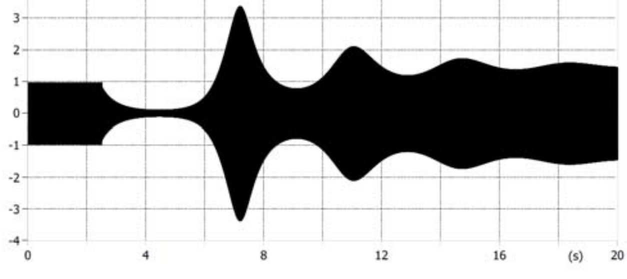

Fig. 5. The voltage course on one of the loads supplied from the low voltage network in relation to the rated voltage

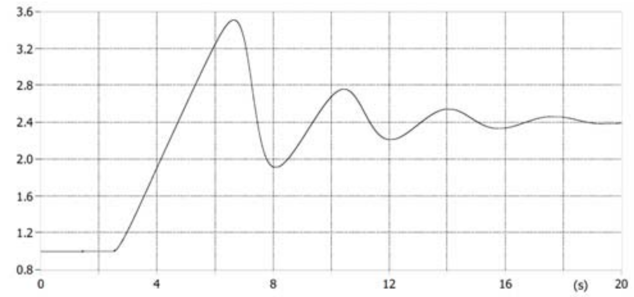

Fig. 6. The frequency waveform of voltage on one of the loads supplied from the low voltage network in relation to the rated frequency

Figure 5 and figure 6 show the waveforms of voltage values and frequencies on one of the loads supplied from the LV network. Analyzing the results of the research, it can be noticed that the reactive power deficit in the system under consideration results in improper conditions of self-excited generator. Significant voltage and frequency oscillations were noticed.

The operation of a hydropower plant in the aforementioned conditions poses a threat, not only to the operation of devices installed in the network, but also to people in the vicinity of these devices. Therefore, the generator must be disconnected as soon as possible by its additional protections. An additional undervoltage protection would work at time t = 2.658s, or 158 ms after the island emerged, at a voltage reduced to about 61% of the rated value and the raised frequency to about 52.5 Hz. Additional overfrequency protection would work at time t = 2.710s, or 210 ms after the island emerged.

The mismatch between load and active power generation causes significant changes in generator operating conditions. The oscillation of voltages and frequencies will be stronger when the active power deficit increases, or milder in the case of excess active power generated. Such situations are presented in figure 7 and figure 8, when the active load of the island is 50% of the active power of the hydroelectric generator.

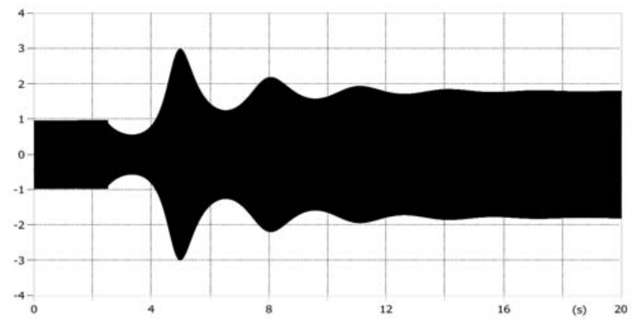

Fig. 7. The voltage course on one of the loads supplied from the low voltage network in relation to the rated voltage.

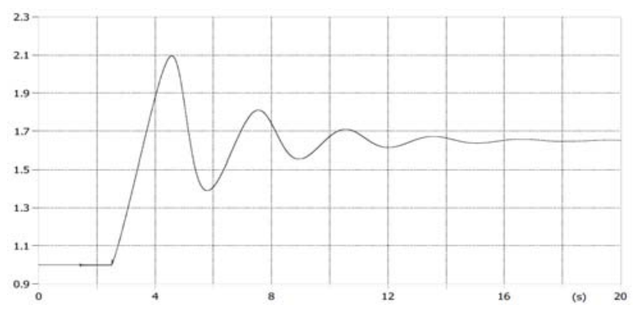

Fig. 8. The frequency waveform of voltage on one of the loads supplied from the low voltage network in relation to the rated frequency

The third case is operation with generator reactive power compensation and turbine side control. It was assumed that the hydro-set has a control and regulation system on the turbine side. This system, after detection of over-turns in one second, closes the water supply so that the increase in turnover does not exceed 115% of their nominal value [8]. The load on the island is comparable to the power of the hydroelectric generator and the generator is equipped with reactive power compensation. The generator's reactive power was compensated to *cosφ* = 0.93.

Figure 9 and figure 10 show the waveforms of voltage values and frequencies on one of the loads supplied from the LV network. Research shows that closing the water supply to the turbine effectively counteracts the emergence of dangerous voltages in the recipients and significantly limits the increase of rotor velocity (voltage frequency), but it should be noted that despite this, the frequency of generated voltage increases dangerously to around 120% the nominal value. Therefore, the power plant should be disconnected as soon as possible by its additional protections [4].

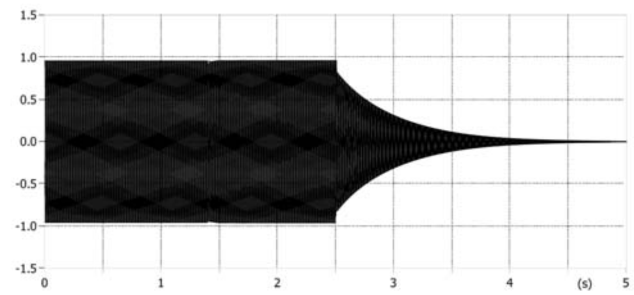

Fig. 9. The voltage course on one of the loads supplied from the low voltage network in relation to the rated voltage

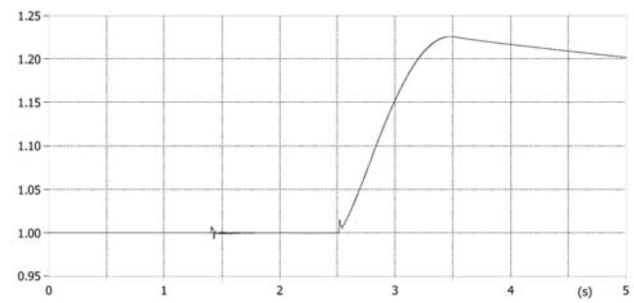

Fig. 10. The frequency waveform of voltage on one of the loads supplied from the low voltage network in relation to the rated frequency

In the analyzed operating conditions of the generator, additional protection of a small hydropower plant would have been activated. An additional undervoltage protection of the generator would work at time t = 2.656s, or 156 ms after the island emerged, at a voltage reduced to about 61% of the rated value and the frequency raised to about 52 Hz. However, an additional overfrequency protection would work at time t = 2.723s, that is 223 ms after the island emerged.

Working of a network with the connection of a hydropower plant with the cable line

In previous variants of the work, it was assumed that the MV / LV T1, T2 stations and the hydropower plant are connected to the MV overhead line. In this case, a cable line with the same cross-section was used, but with a length of 14 km. Until now, if the balance of active power in the system has been maintained, it was not possible to preserve the reactive power balance. In this case, the medium voltage cable line is the source of capacitive reactive power, which should have a significant influence on the reactive power balance in the system.

It was assumed that the system does not have any control and regulation systems on the turbine side, the generator is equipped with reactive power compensation and the active load of the island is comparable to the active power of the hydroelectric generator.

By analyzing figure 11 and figure 12, it can be noticed that at any time, both the voltage and frequency values do not exceed the permissible value. Operation of the power plant in such conditions does not pose a threat to receivers installed in the network. Therefore, additional protection of the power plant would not detach it after the island emerged.

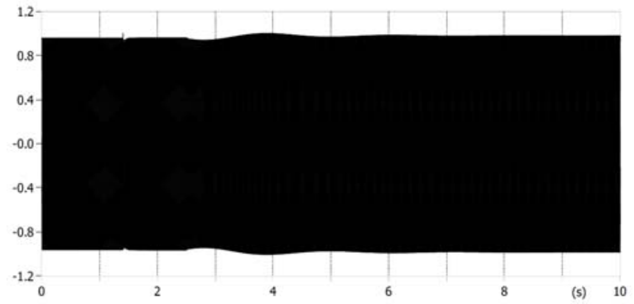

Fig. 11. The voltage sequence on one of the loads supplied from the low voltage network in relation to the rated voltage

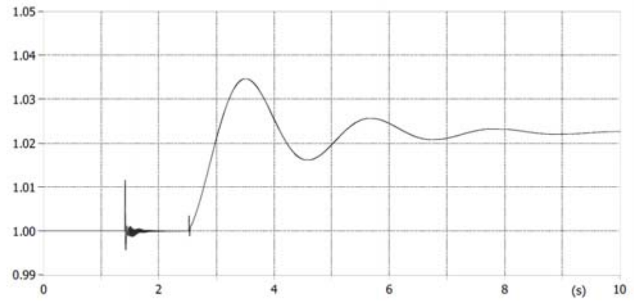

Fig. 12. Frequency waveform on one of the loads supplied from the LV network in relation to the rated frequency

Summary

When analyzing the conducted research, the following conclusions can be made:

1) The conditions of autonomous operation of the induction generator are very variable and depend on the active and reactive power load of the generator,

2) Any changes in the load on the island cause sudden changes in the parameters of electricity produced,

3) The generator should absolutely be equipped with additional overvoltage and undervoltage protection as well as over and underfrequency protection,

4) Appropriate balancing of active and reactive power in the island gives rise to relatively safe working conditions,

5) Generator operation in a network with the predominance of cable lines is dangerous from the point of view of uncontrolled self-stirring of the generator.

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