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doi:10.15199/48.2019.01.55

# Analysis of transient states during the switching on operation of small hydropower plants - computer simulations using the EMTP-ATP program

**Abstract:** The paper presents phenomena occurring during the switching of a small hydropower plant equipped with an induction generator, to the MV grid. Computer simulations were carried out and several work options were considered. The influence of the moment of synchronization with the grid and the influence of capacitor banks to compensate for reactive power of the generator were checked. Obtained results by computer simulation were presented and analyzed.

***Streszczenie:*** *W pracy przedstawiono zjawiska występujące podczas załączania malej elektrowni wodnej wyposażonej w generator indukcyjny, do sieci SN. Przeprowadzono symulacje komputerowe oraz rozpatrzono kilka wariantów pracy. Sprawdzono wpływ momentu synchronizacji z siecią oraz wpływ baterii kondensatorów do kompensacji mocy biernej generatora. Przedstawiono oraz przeanalizowano otrzymane wyniki, uzyskane drogą symulacji komputerowej. (**Analiza stanów przejściowych podczas załączania do pracy małych elektrowni wodnych – symulacje komputerowe z wykorzystaniem programu EMTP-ATP)***

**Keywords:** modeling, small hydro power plant, transient states, induction generator
**Słowa kluczowe:** modelowanie, małe elektrownie wodne, stany nieustalone, generator indukcyjny

## Introduction

Electricity produced from renewable energy sources plays a greater role in the energy balance of our country from year to year. The disadvantage of these solutions is the need for the presence of appropriate atmospheric conditions, so that energy production is possible and profitable at all. The requirements for environmental protection imposed by the European Union enforce special interest in RES installations. 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 as generators, are used induction machines. Attachment of more and more scattered energy sources creates new problems that have not occurred so far. Therefore, this paper presents the analysis of hazards resulting from the inclusion of induction generators operating in small hydroelectric power stations [4]. The basis of the analysis were computer simulations carried out in the EMTP-ATP program.

## Power system and control of small hydropower plants

Each element of the power system should be designed in such a way that it does not pose a threat to the work of the system itself and the people who serve it. Therefore, it is necessary to install a number of electrical devices in them for safety during normal operation and in emergency situations. Usually, in the power plant building, an electrical switchboard is installed where all the necessary electrical devices are installed [2]. The single-line diagram of a hydroelectric plant with an asynchronous generator is shown in figure 1. Figure 1 shows only the main elements of the tested system.

An indispensable element of every hydropower plant working with an induction generator is reactive power compensation. Capacitor banks should be chosen so as to minimize the risk of self-ignition. For this purpose, it should be checked whether the maximum value of the capacitor current does not exceed 90% of the magnetizing current of the generator without load [5]. In the event that the above relationship is not met, the reactive power compensation can be carried out further. It should then be remembered to use a control system that will disconnect the capacitor banks when the generator island operation is detected.

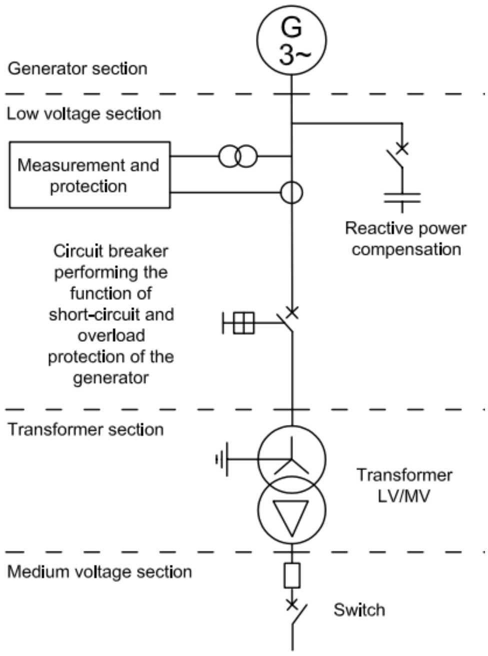



Fig. 1. One-line diagram of a hydroelectric plant with an induction generator

In order for the hydroelectric power plant to be connected to the power system, it must meet a number of requirements regarding protection automation. Each generator unit should be equipped with basic protection against external and internal faults, also against phase-to-phase and ground faults. Also, remember to protect the generator against motor operation and to install earth-fault protection. The generator should also be equipped with additional protection over and under voltage as well as over and under frequency [1]. They are particularly important from the point of view of island operation, when the frequency and voltage value are no longer maintained in the proper range by the power supply grid. Protection after detection of operation in an unauthorized frequency and voltage range gives a signal for opening the generator switch, which results in a definitive shutdown of the unit.

**Modeling of electrical machines in the EMTP-ATP program**

To enable the analysis of phenomena occurring during the cooperation of the induction generator with the system, the parameters of the engine should be described using the Park transformation [7].

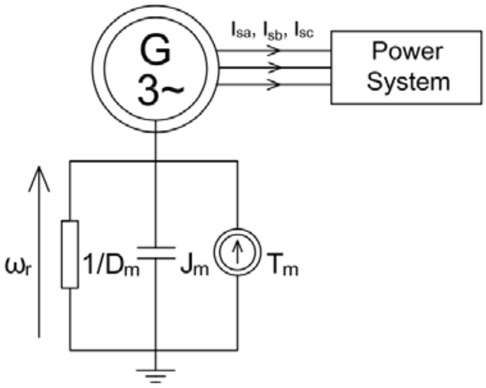



Fig. 2. Diagram of electrical mapping of a mechanical part of an induction machine [6]

Figure 2 shows the model of the mechanical part of the induction machine. The mechanical part is represented by an equivalent electrical circuit, which in the simplest case consists of a power source, a capacitor and a resistor. The current source represents the load moment on the machine shaft. Depending on the motor or generator operation, it may take negative or positive values. The capacitor is the electrical representation of the moment of inertia of the system, and the resistor reflects the losses associated with the friction of the machine. The generated voltage represents the angular velocity of the rotor.

**Findings**

During the tests, a typical SN grid was used (fig. 3) consisting of four overhead lines. The exact parameters of the analyzed grid are given in [3], while the parameters of the induction motor operating as a generator in the power plant are shown in table 1. The hydroelectric power plant was connected to one of the overhead lines by means of a TG transformer. The W2 switch performs the function of a generator switch installed in the electrical switchboard of the power plant, while the switch W1 presents a circuit breaker installed in the line field of the MV station. To compensate for the reactive power of the generator, a BK capacitor battery was applied by means of the W3 breaker.

Tab. 1. Parameters of the generator of the tested hydropower plant.

| Parameter | Unit | Value |
|---|---|---|
| Rated power | [kW] | 260 |
| Rated voltage | [kV] | 0,4/0,69 |
| Current | [A] | 474/275 |
| Rotation velocity | [$min^{-1}$] | 990 |
| Power factor | [-] | 0,82 |
| Efficiency | [%] | 96,6 |
| The multiplicity of the inrush current | [-] | 6,5 |
| Moment of inertia | [$kgm^2$] | 17,102 |

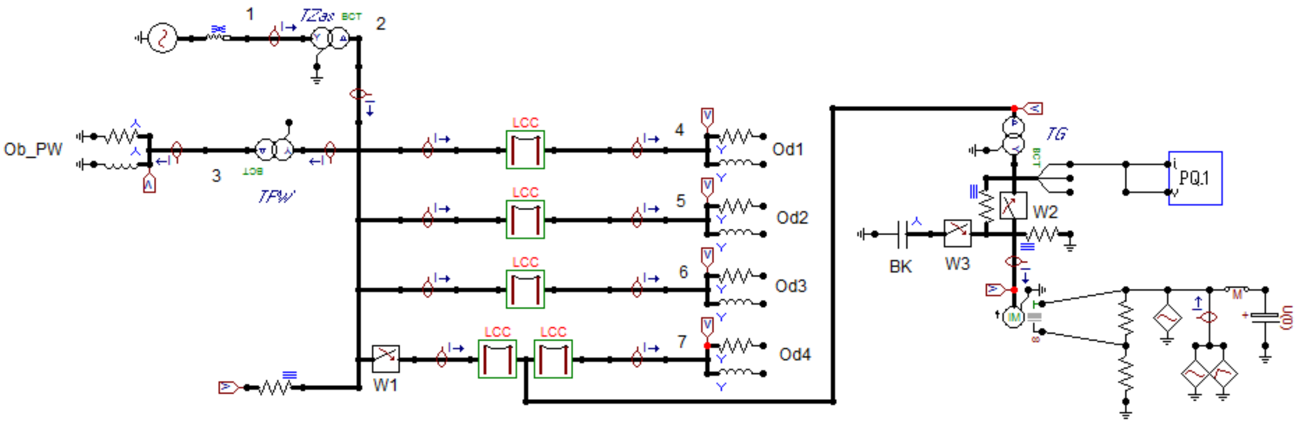
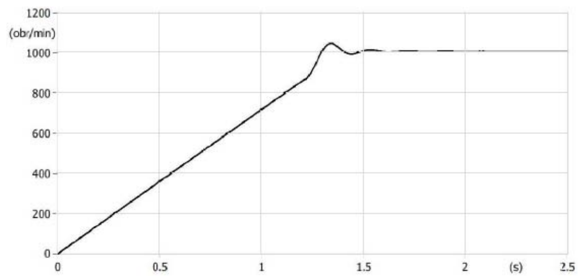



Fig. 3. The scheme of the considered grid in the EMTP-ATP program

Analyzing figure 4 and figure 5, it can be seen that the moment of synchronization of the generator with the grid plays a significant role in terms of current surges occurring at the moment of switching on. In power plants equipped with extensive control automatics, the switch-on takes place automatically. This is the most advantageous situation because the programmed algorithm is supervised over the moment of switching on. This case is illustrated in figures 4c and 5c, when the power plant is switched on at a speed close to the synchronous speed, which results in a relatively small and short-term current stroke. It is recommended to connect the generator to the grid when its speed differs from synchronous by less than ± 5% of the synchronous speed. Too early or too late synchronization results in a long and unstable transitional state. Too early causes repeated oscillations that occur when the synchronous speed is reached. However, the most dangerous situation is during the delayed synchronization. In addition to the highest and longest current impact (fig. 5b), there is also a rapid reduction of the rotational speed (fig. 4b), which can cause mechanical damage to the unit.

a)



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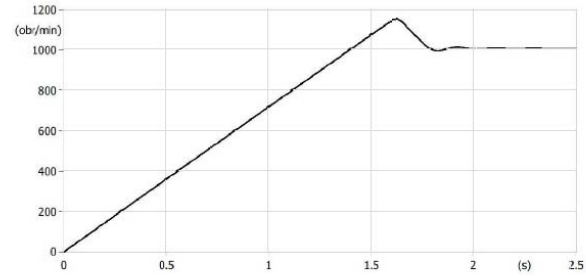


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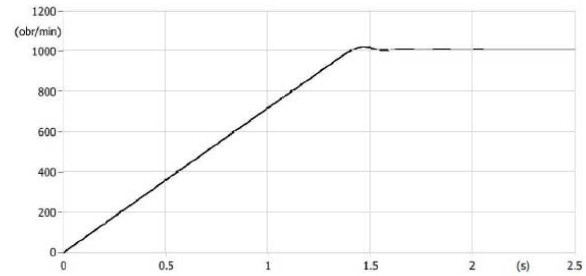
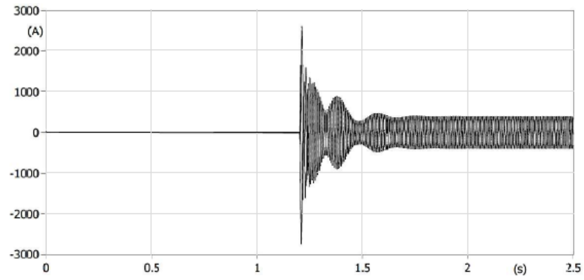



Fig. 4. The rotational speed of the generator depending on the moment of synchronization with the grid: a) synchronization at the speed of 870 rpm; b) synchronization at 1150 rpm; c) synchronization at 998 rpm

a)

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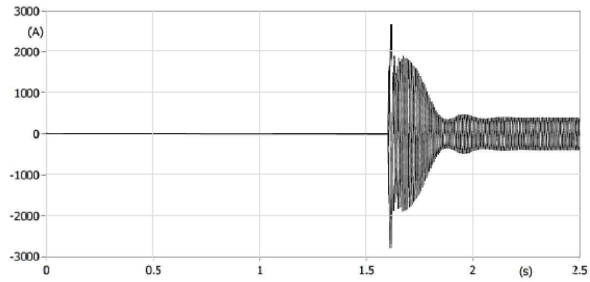


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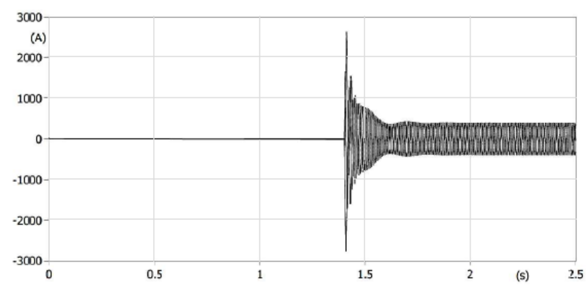
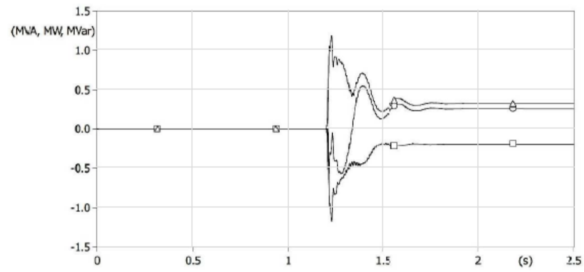



Fig. 5. Generator current depending on the moment of synchronization with the grid: a) synchronization at the speed of 870 rpm; b) synchronization at 1150 rpm; c) synchronization at 998 rpm

Figure 6 and figure 7 show the power and torque waveforms of the generator during synchronization. Too early synchronization results in significant active and reactive power consumption by the generator (fig. 6a). This means that the induction machine then works as a motor, which can be unambiguously determined by analyzing the course of the electric moment (fig. 7a). At the moment of switching on the generator, the electric torque takes negative values, after exceeding the synchronous speed, the generator operation occurs with the positive electrical torque and the positive active power sign of the generator. On the other hand, the delayed activation of the generator causes a significant reactive power consumption (fig. 6b), but there is no phenomenon of the transition of the induction machine from motor to generator operation, which could be observed in the previous case. The electrical torque always assumes positive values. In the first moments, the moment reaches high values which is caused by the need to brake the machine's rotor. As you can see, the best conditions for synchronization occur when the generator is switched on at a speed close to synchronous. This results in the lowest reactive power consumption and a gentle transition from motor to generator operation (fig. 6c and fig. 7c).

a)

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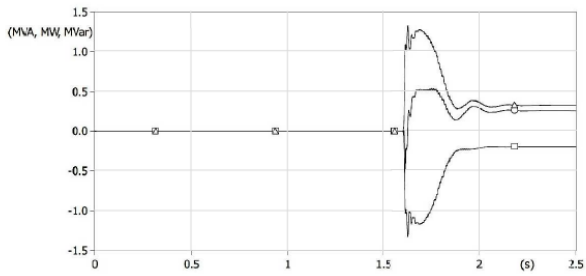


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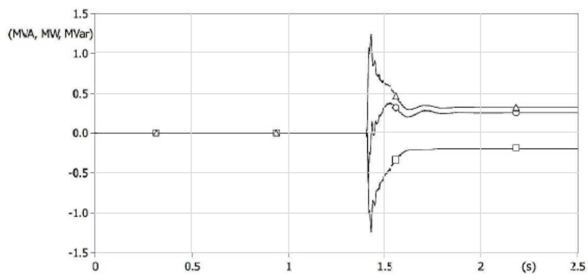
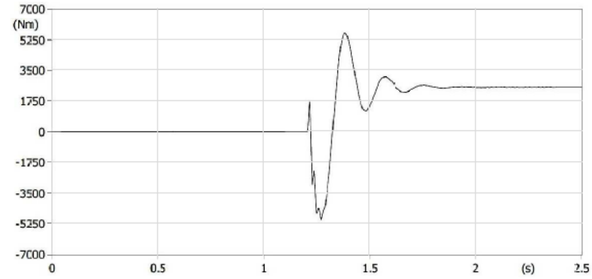



Fig. 6. Active (○), reactive (□) and apparent (△) power of the generator depending on the moment of synchronization with the grid: a) synchronization at the speed of 870 rpm; b) synchronization at 1150 rpm; c) synchronization at 998 rpm

Figure 8 shows the generator's voltage at the moment of connecting it to work on a rigid grid. As you can see at the moment of switching on, there is a transient state manifested by a short-term increase in voltage above the rated voltage of the generator (fig. 8b). Visible overvoltages are caused by the presence of a capacitor bank to compensate for the reactive power of the generator. It should be noted here that the capacitors were already connected to the generator when switched on. Figure 8c shows the situation when generator synchronization is carried out without connected capacitor banks, only switching on of the capacitors takes place at time t = 2s. This generates the generation of larger surges with a higher amplitude even when compared to the method of variant b).

a)

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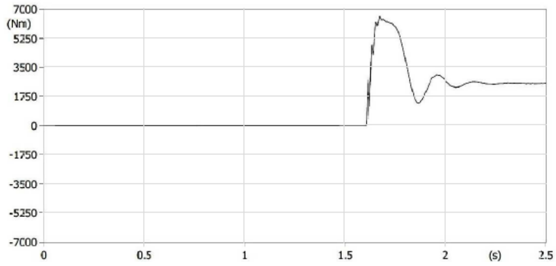


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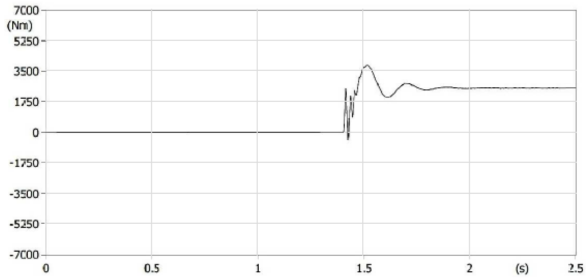
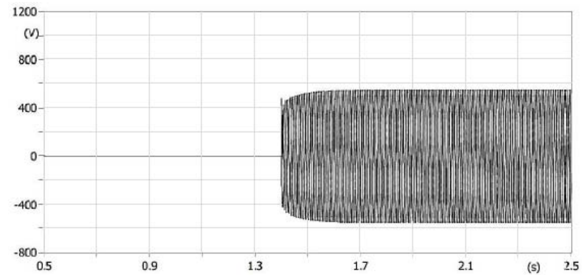



Fig. 7. Electric moment (in the gap) of the generator depending on the moment of synchronization with the grid: a) synchronization at the speed of 870 rpm; b) synchronization at 1150 rpm; c) synchronization at 998 rpm

a)

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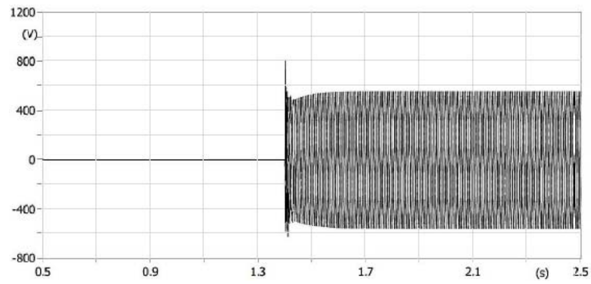


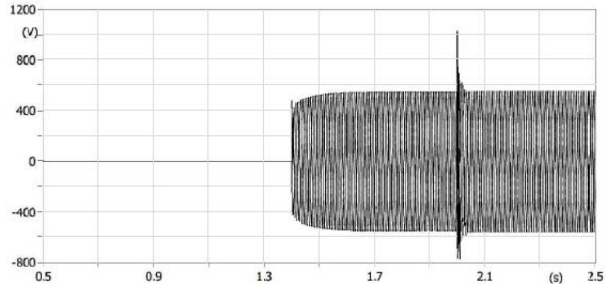


Fig. 8. The generator's voltage during switching on the grid: a) without compensation of reactive power; b) with a connected battery for reactive power compensation; c) without reactive power compensation - the capacitor battery is switched on after synchronization with the grid

The resulting surges can affect the operation of devices installed in the hydropower plant itself, but also transfer to other devices and loads supplied from the same part of the power grid.

## Conclusions

Simulations of switching small hydropower plants equipped with an induction generator were carried out. Particular attention was paid to the moment of connecting the generator to the grid and consequences resulting from incorrect synchronization with the grid. The influence of capacitor banks connected to the generator's terminals to compensate for reactive power was also considered. As you can see on the waveforms, the correct synchronization is crucial from the point of view of the generator's correct and safe operation. Too early or late, it results in the formation of transient states manifesting in the form of significant current surges. It can also be noted that too early synchronization causes the generator to temporarily switch over to the engine operation, which is related to the momentary power consumption of the generator. The undoubted influence of the capacitor bank has also been proved, resulting in the occurrence of overvoltage when the generator is switched on to the grid or when the capacitor batteries are switched on.

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