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# The Analysis of the Loss of Synchronism of a Synchronous Generator Using the Wavelet Coherence

***Abstract**. This paper proposes the usage of the wavelet coherence to analyse the phenomenon of the loss of synchronism by a synchronous generator due to a short-circuit in the transmission electrical power network. On the basis of the simulation studies and the use of the wavelet coherence, the relationships between various electrical and mechanical quantities were investigated.*

***Streszczenie.** Artykuł proponuje wykorzystanie koherencji falkowej do analizy zjawiska utraty synchronizmu przez generator synchroniczny na skutek wystąpienia zwarcia w sieci przesyłowej. Na podstawie badań symulacyjnych oraz użycia koherencji falkowej zbadano związki pomiędzy różnymi wielkościami elektrycznymi i mechanicznymi. **(Analiza utraty synchronizmu generatora synchronicznego z wykorzystaniem koherencji falkowej)**.*

**Keywords:** synchronous generator, loss of synchronism, wavelet coherence, power system stability.
**Słowa kluczowe:** generator synchroniczny, utrata synchronizmu, koherencja falkowa, stabilność systemu elektroenergetycznego.

## Introduction

Despite the growing interest in the renewable energy sources, a large number of the synchronous generators is still operating in the electric power system. The phenomenon of loss of synchronism is one of the considerable dangers in their work. The risk of this action may be associated with the appearance of a short-circuit in the network near the power plant. If the generator does not stay in a stable state, a transient state may occur and therefore delivering a certain amount of the power to the grid will be impossible.

The wavelet transform (WT) is one of the leading tools for analysing waveforms in transient states (nonstationary signals). This transform may be performed as a continuous (CWT) or discrete (DWT) version. With a CWT usage, the wavelet coherence can be applied. This calculation is helpful to study the interaction between two different time series and their evolution over a time or frequency. Moreover, it is also possible to effectively identify the regions with common dependencies of both signals.

The purpose of this article is to present the analysis of the loss of synchronism of a synchronous generator with the usage of the wavelet coherence. The Author's objective is to highlight the features of this approach and to point out that it can be comfortably used for the further studies in this field.

The paper is organized as follows: the initial part presents the related work research and the basic information about the loss of synchronism. Next, the materials and methods used are introduced. The main chapter is devoted to the results of the wavelet coherence analysis for the presented test system. The final part focuses on the main conclusions and summaries this study.

## Related work review

The classical problem of losing synchronism of a synchronous generator is well described in many sources. However, some new concepts and papers dealing with this issue have been recently published.

The paper [1] deals with evaluating resiliency of power generators against an earthquake to maintain synchronism. The author of [2] proposes to use the instability tolerant synchronous generator to enhance power stability. The article [3] explores the usage of the machine learning for predicting the probable loss of synchronism.

The work [4] presents real time detection and the control of loss of synchronism by usage of Energy Function Criterion and Phase Sequence Exchange Technique. The paper [5] focuses on the technique based on the auto / cross – correlation and instantaneous powers to identify sudden disturbances of various electrical signals in the case of the asynchronous operation.

In the article [6] an enhancement of power system stability by real-time prediction of instability and early activation of steam turbine fast valving is discussed. The authors of [7] present transient stability enhancement through individual machine equal area criterion framework using an Optimal Power Flow.

The research [8] highlights the factors of influence and countermeasures in case of the transient stability of generator groups. The paper [9] presents Wide Area Network for power swing detection based on deploying the intrinsic characteristics of GOOSE or R-GOOSE Multicast protocols with the loss of synchronism simulation in IEEE 39 Bus test system.

The work [10] deals with the field-circuit analysis of loss of synchronism during abnormal operating states of turbogenerator. The authors of [11] propose an emergency control in which a series breaking resistor is used to save from the loss of synchronism after a three-phase short circuit in the transmission line near the power plant. The authors of [12] propose the new algorithm based on acceleration power curve fitting to predict generator's out-of-step condition.

The work [13] describes the Faster-Than-Real-Time Analysis for prediction out-of-step condition. The authors of the paper [14] present the possibility of detecting the loss of synchronism by using real time load angle measurements.

Some papers are also devoted to the application of the wavelet transform. The authors of [15] were using DWT to protect synchronous generator from the loss of excitation. The article [16] describes the usage of DWT for power swings and fault detection. The work [17] describes usage of synchrosqueezed wavelet for oscillation localization. The paper [18] presents the method based on wavelet and multilayer perceptron neural network to predict transient stability status after a disturbance.

The work [19] deals also with the usage of wavelet transform and acoustic signals for fault detection in a brushless synchronous generator. The work [20] presents the application of CWT to detect faults in salient pole synchronous generators. The number of works devoted to this topic is significant, which means that it is still an important and current problem in the electrical power engineering.

In the above mentioned papers different ideas are considered. However these articles do not focus on the wavelet coherence.

The novelty of this paper is the use of the wavelet coherence for analysing the loss of synchronism of a synchronous generator. The main contributions of this paper are: (1) the usage of the wavelet coherence to study the relationships between selected quantities during the loss of synchronism process, (2) to fill in the study gaps in the topic of loss of synchronism with the usage of the wavelet coherence.

## The basic information about the loss of synchronism of a synchronous generator

During a normal operation, a synchronous generator is connected (after the synchronization process) to the external grid, usually represented as an infinite bus (IB). However, in the meantime, both small and large disturbances can occur in the transmission power network. Large disturbances are particularly dangerous, as they can lead to the loss of synchronism. The examples of such disorders are switching off strongly loaded transmission line and permanent or transient short-circuits.

The phenomenon of the loss of synchronism will be explained on the basis of the example of a single-machine infinite bus model (Fig. 1). In this network, a synchronous generator (G) is connected to the infinite bus (IB) by a step-up transformer (T) and a transmission line (L).

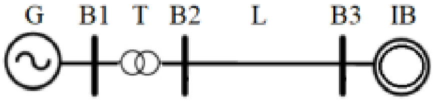

Fig.1. Single machine infinite bus network. Own work

Output electrical active power is a nonlinear function of the rotor angle $\delta$ and can be described by the formula (1) [21]:

$$P = \frac{EU}{X}\sin\delta \tag{1}$$

where: $P$ – active power, $E$ – electromotive force, $U$ – network voltage (at infinite bus), $X$ – reactance of transmission line, $\delta$ – power angle (angle between $E$ and $U$) or also rotor angle.

The stability of a synchronous generator can be assessed using the Equal Area Condition (EAC) (Fig. 2). Fig. 2 presents $P_e(\delta)$ characteristics before, during and after a transient fault. Two cases can be distinguished: (a) the stability is maintained and (b) the stability is not maintained and the synchronism is lost.

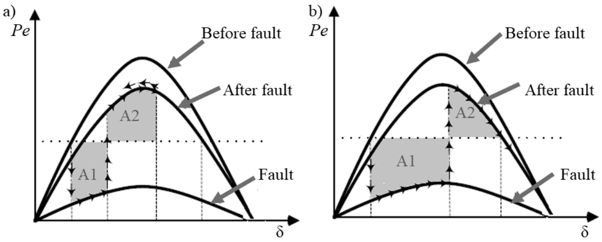

Fig.2. Equal Area Condition example. Own work, based on [13]

In case (a) after a large disturbance (for example: three phase fault), the acceleration filed (marked as A1 in the Fig.2) is smaller than the breaking filed (marked as A2 in the Fig.2). As a result, the $\delta$ angle returns to a new stable position and the stability is maintained. In case (b), after a large disturbance, the acceleration filed (A1) is now greater than the breaking field (A2). The considered system (Fig. 1) is stable after a large disturbance only if the acceleration area (A1) is lower than the breaking area (A2) (in the given conditions such as type of fault, fault duration etc.). The area A1 can be considered as a work necessary to the synchronism lost, while the area A2 – as a work necessary to maintain synchronism. If, in given conditions, the acceleration area A1 is greater than the possible breaking area A2 – the generator loses the synchronism. Just before the loss of synchronism, the rotor has the excess kinetic energy and the power angle increases.

The mathematical description is as follows: the dynamics of the rotor angle $\delta$ and the rotor electrical speed $\omega$ are given by formulas (2) and (3):

$$\frac{d\delta}{dt} = \omega - \omega_b \tag{2}$$

where: $\omega_b$ – base electrical frequency (at the infinite bus).

$$M\,\frac{d(\omega-\omega_b)}{dt} = T_m - T_e \approx P_m - P_e \tag{3}$$

where: $M$ – moment of inertia, $T_m$ – mechanical torque, $T_e$ – electrical torque, $P_m$ – mechanical power, $P_e$ – electrical power.

The rotor kinetic acceleration ($E_1$) energy and deceleration energy ($E_2$) are given by formulas (4) and (5) respectively:

$$E_1 = \int_{\delta_0}^{\delta_c}(P_m - P_e)dt = A_1 \tag{4}$$

where: $\delta_0$ – rotor angle before fault, $\delta_c$ – rotor angle after fault, $A_1$ – acceleration area

$$E_2 = \int_{\delta_0}^{\delta_c}(P_e - P_m)dt = A_2 \tag{5}$$

where: $A_2$ – breaking area.

At the moment of the loss of synchronism and during an asynchronous operation, the slip of the rotor (7) can be large.

$$\Delta\omega = \frac{d\delta}{dt} = \frac{d\delta^{'}}{dt} \tag{7}$$

where: $\Delta\omega$ – slip of the rotor

The further and detailed information about this phenomenon can be found in [22].

## Materials and methods

The research was divided into two parts: (1) the simulation of the generator synchronism loss in the test network and (2) the use of wavelet coherence to analyse selected waveforms from the simulation. In both cases the appropriate computer programs were used. The OpenModelica package [23] (with OpenIPSL libraries [24]) was used to simulate the electrical power system transient states, while the Matlab Wavelet Toolbox was used for the wavelet analysis.

IEEE 9 Bus test system was selected for the proposed studies (Fig. 3). This system consists of: 3 synchronous generators, 6 transmission lines, 3 two-winding transformers and 3 *PQ* loads. The use of the well-known test power system for research allows for their easier verification and comparison to other results of scientific research.

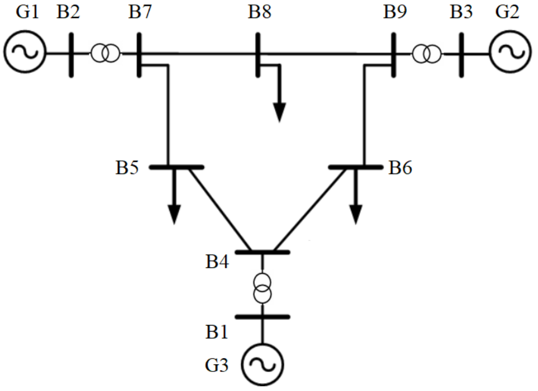

Fig.3. IEEE 9 Bus test power system

The wavelet can be represented as the mathematical function that has a number of features that are key to the analysis of signals, in both the time and frequency domains. The characteristics of wavelets are: a finite signal strength, the mean value equalling to zero and a finite frequency range. The name of these functions refers to their oscillations, which are similar to the real waves in the nature. With the usage of the wavelets there is a possibility to analyse a given signal looking for its similarity to the shifted and rescaled versions of the original wavelet called the mother wavelet.

The CWT for a time series with equal intervals can be expressed by the formula (8). This equation is a convolution of the examined time series with the scaled and shifted wavelet function.

$$W_m(s) = \frac{\sigma_t}{\sqrt{s}} \sum_{n=0}^{N-1} x_n \varphi * \left[\frac{(n-m)\sigma_t}{s}\right] \tag{8}$$

where: $\sigma_t$ - equal interval between samples, $s$ - scale factor, $N$ - the number of time series samples, $x_n$ - $n$-th element of the time series (where $n$ =1,2,3…N), $\varphi$ - wavelet function, $m$ - offset factor, * - complex number conjugation.

In order to study the potential interrelationships between the two signals, the wavelet coherence was used. It is the transformation based on CWT and these areas (in the time-frequency domain) where both tested signals show common changes can be detected. The wavelet coherence of two signals is described by the formula (9).

$$R_n^2(s) = \frac{\left|S(s^{-1}W_n^{XY}(s))\right|^2}{S(s^{-1}\left|W_n^X(s)^2\right|)\cdot S(s^{-1}\left|W_n^Y(s)\right|^2)} \tag{9}$$

where: $R_n^2(s)$ - coherence factor, $S$ - smooth operator, $s$ - scale factor, $W_n^X$, $W_n^Y$ - continuous wavelet transforms of signals, expressed as a convolution of the $n$-th signal sample with scaled and normalized wavelet, $W_n^{XY}$ - cross wavelet transform of $x_n$ and $y_n$ samples

The coherence coefficient can take the values ranged from 0 to 1. The closer its value is to 1, the more the two tested signals are correlated with each other. If the coherence coefficient is close to 0, then the coherence is very weak. Graphically, it can be visualized using colours – warm colours (yellow, red) represent strong coherence, while cold colours (blue, purple) represent weak coherence.

It is possible to determine the phase coherence – formula (10) – which informs about the mutual phase relations between the oscillations of both signals as a function of frequency.

$$\phi_{x,y} = \tan^{-1}\left(\frac{\mathrm{Im}(W_n^{XY})}{\mathrm{Re}(W_n^{XY})}\right) \tag{10}$$

where: $\varphi_{x,y}$ - the phase of coherence contained in the interval $[-\pi,\pi]$, Re, Im – respectively the real and the imaginary part of the expression $W_n^{XY}$

The values are displayed graphically in the form of the arrows, which indicate how the two signals oscillate with each other at a certain frequency. The arrows directed to the right mean that the signals are in the phase with each other. While the arrows directed to the left mean that signals are out of phase. The direction up means that the first signal leads the second by 90 degrees, while arrows directed down mean the opposite situation.

The further and detailed information about the wavelets and the wavelet coherence can be found in [25,26].

## The analysis of the loss of synchronism using the wavelet coherence

For the purposes of the study, it was assumed that the loss of synchronism was caused by a large disturbance such as short-circuit. A three-phase transient fault was modelled in the test system at the node B8 (Fig. 3). The total duration of the simulation was 5.00 seconds, with the short-circuit lasting from 2.00 to 2.05 seconds. Each of the waveforms obtained from the simulation consisted of 500 intervals points.

As a result of the simulations, the following values were obtained for each generator: the active and reactive power, the rotor angle, the rotor speed, the d-axis and q-axis transient voltage, the filed voltage, the terminal voltage, the d-axis current and q-axis current, the derivative of rotor angle and the derivative of rotor speed. For the remaining elements of the system, the following parameters were determined: the bus voltage magnitude, the bus voltage angle, the active and reactive power flows in the lines, the currents in lines. Below there are some example waveforms from the simulation: the terminal voltage of generator 1 (Fig. 4) and the rotor angle of generator 1 (Fig. 5).

Due to the large number of the obtained waveforms obtained, only the selected ones are presented in this paper. Since these waveforms are nonstationary signals, the wavelet coherence is a suitable tool for their further analysis. Each magnitude-squared wavelet coherence was computed with the analytic Morlet wavelet. The results are shown in Fig.6-11. The horizontal axis shows the time of the simulation while the vertical axis shows the period. Next to the each plot there is a colour scale, indicating the level of the coherence.

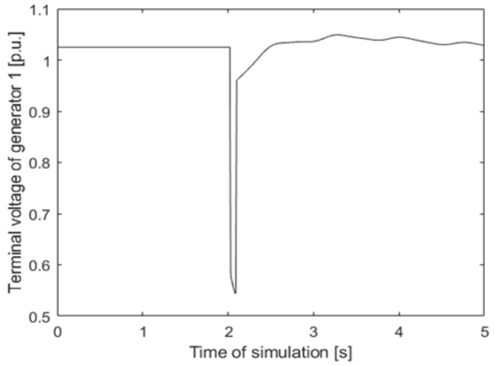

Fig.4. Terminal voltage of generator 1. Own work

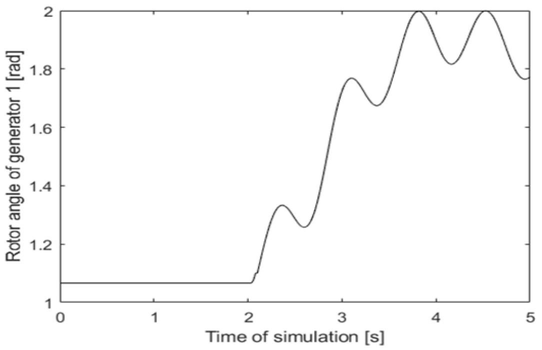

Fig.5. Rotor angle of generator 1. Own work

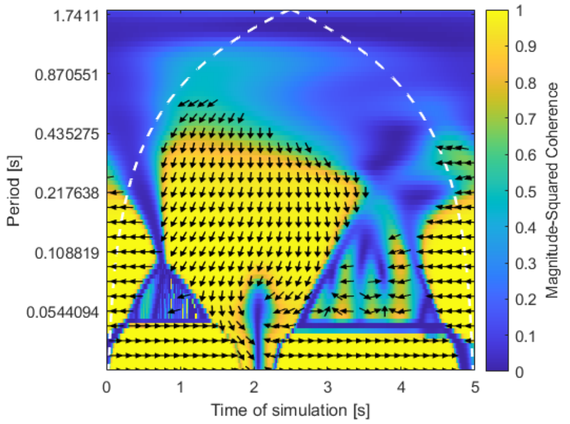

Fig.6. Wavelet coherence of B7 voltage magnitude and generator 1 rotor speed. Own work

Figure 6 shows the wavelet coherence between voltage at Bus 7 and the rotor speed of a generator G1. It can be observed that both values are highly coherent during most time of the simulations (yellow colour).

The moment of the three-phase short-circuit occurrence – at 2.0 second is the exception. Then, for some periods, the coherence is almost 0 (dark blue colour). After the short-circuit is cleared, the coherence is not so high again. However, due to the loss of generator synchronism, the phase relationships between the observed values changed. The arrows are directed to the left (on the small part of the yellow plane).

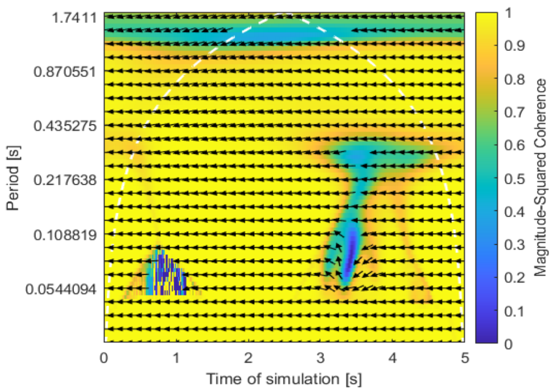

Fig.7. Wavelet coherence of generator 1 derivative of rotor speed and active power in line 7-8. Own work

Figure 7 presents the wavelet coherence between the derivative of the rotor speed of generator 1 and the active power flowing from Bus 7 to Bus 8 (Line 7-8). It can be observed that these both values the have high coherence during the most time of the simulation. The exception can be observed for some periods between 3.0 and 4.0 seconds. At the same time, the phase relationships are almost constant (arrows always directed to the left).

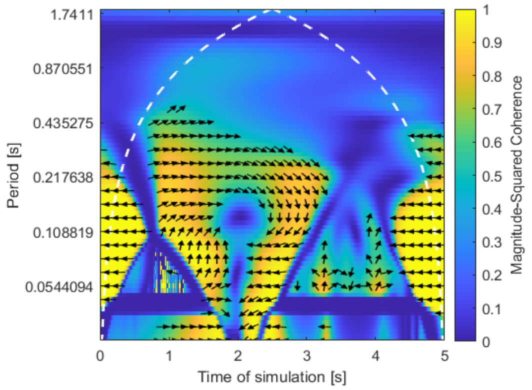

Fig.8. Wavelet coherence of generator 1 rotor angle delta and its terminal voltage. Own work

Figure 8 highlights the wavelet coherence between the delta angle of the generator 1 rotor and the terminal voltage of the generator 1. From the observations it can be noticed that both values are not strongly coherent. There is no coherence between them during short-circuit time. Moreover, in the periods with the high coherence (yellow stripes) the arrows are changing their direction. Before the fault, the arrows are directed to the left, then up and to the right. After the fault, the arrows are again directed mostly only to the left.

Figure 9 presents the wavelet coherence between the delta angle of the generator 1 rotor and the active power flowing from Bus 7 to Bus 8 (Line 7-8). It can be observed that during the most periods of the simulation there is a significance or very high coherence between them. The exceptions can be noticed during the short-circuit and periods after losing the synchronism. Mostly, arrows are directed to the right. This is the confirmation of the formula (1).

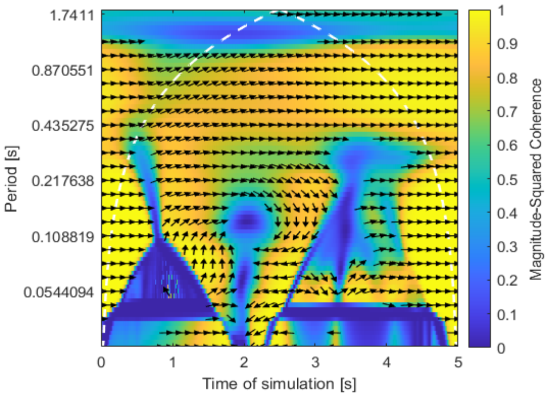

Fig.9. Wavelet coherence of generator 1 rotor angle delta and active power in line 7-8. Own work

Figure 10 shows the wavelet coherence between the rotor speeds of the generator 1 and the generator 2. The modelled short-circuit is midway between these two generators. Although after the loss the synchronism for some periods the coherence is almost zero, it can be seen that the arrows are almost all the time directed to the right – both speeds are in phase.

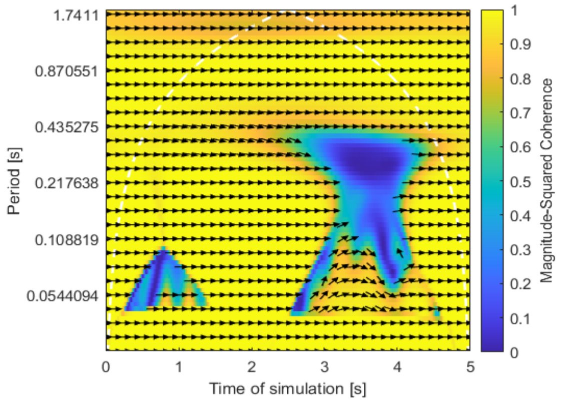

Fig.10. Wavelet coherence of rotor speeds from generator 1 and generator 2. Own work

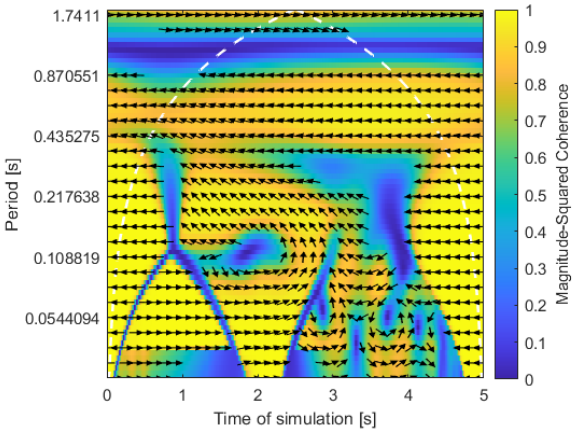

Fig.11. Wavelet coherence of rotor angles delta from generator 1 and generator 2. Own work

Figure 11 presents the wavelet coherence between the delta angles of the generator 1 and the generator 2 rotors. Most of the time, the arrows are directed to the left. In contrast to the cases from Fig. 6,8 and 9, during the short-circuit at Bus 8 (2.0 sec.), there is a very high coherence between the observed delta angles. This relationship decreases after clearing the short-circuit.

## Conclusions and summary

The objective of this paper was to present the analysis of the loss of synchronism of a synchronous generator with the usage of wavelet coherence. The presented research confirmed the usefulness of the wavelet coherence in order to investigate this type of phenomena. The applied method allows to extend or supplement the current view on the phenomenon of testing the stability of a synchronous generator. The use of the coloured scalograms enables to conduct the easy analysis of the variability of selected quantities before, during and after the disturbance in the tested power system. Moreover, it is easy to prepare the input data for creating scalograms – non-stationary waveforms can come from any suitable software such as OpenModelica. The simultaneous analysis of electrical and mechanical quantities is another advantage of the proposed approach. The proposed approach can be easily used by power system engineers to study the transient states in more depth. Moreover, the presented method can be also applied to extend dynamic stability studies (occurred by small disturbances).

It is worth emphasizing that the final results of the coherence plots may depend on the type of the used power system models. Moreover, the usage of the stability enhancement solutions can lead to the different wavelet scalograms. The wavelet coherence can successfully complement the traditional tools used for the loss of synchronism analysis.

The possible paths for the future research in this filed may be: the analysis of different kinds of short circuit types along with their duration and the location from the generator or combining the presented solution with other power system transients investigation methods. In general, the wavelet transform can be a promising extension of conventional simulations models to find additional information which may be overlooked [27, 28].

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