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The Prediction Method of Prior Time for Precise Synchronization in the Case of Varying Slip Frequency

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Abstract

The paper describes a synchronization method to reduce the closing time and prevent the impact on the generator in case of varying slip frequency. The most important problem in synchronization is to close the circuit breaker at the moment voltage, frequency, phase of the generator, and the power system are in coincidence. The accuracy of sync-check according to phase angle is an important factor for precise synchronization. Also, considering the input time of the circuit breaker, it is necessary to generate the output signal of the circuit breaker at a time prior to when the difference of phase angle becomes zero. But in the case of varying slip frequency, the calculated prior angle has a large error. This paper suggested a precise prediction method of prior time in case of slip frequency changes linearly and nonlinearly. Then, by using MATLAB/Simulink simulation, it was proved that the novel prediction method of prior angle reduces the synchronization time and the impact induced on the generator.

Keywords

Synchronization; Sync-check; Slip frequency; Prior angle

1. Introduction

Synchronization is a process of matching a synchronous generator with a power system, which enables parallel operation of the power system [1, 2]. During this process, the voltage, frequency, and phase angle of the generator are matched to the power system. The two sources must have the same voltage magnitude, frequency, and phase angle relationship for safe parallel closing of the generator [3]. When paralleled, the synchronized generator and power system exchange power and load flows [4]. Precise synchronization will minimize the electrical and mechanical impact on the generator, provide rapid synchronous operation of the generator after parallel closing, and reduce its transient, thus minimizing the interference effects on the grid [5, 6].

For precise synchronization, following values of the power system and generator must be matched.

(a) Phase sequence (b) Voltage amplitude (c) Frequency (d) Phase angle

The problem of phase sequence in synchronization is important. If the phase sequence is not matched, a large surge current is applied during synchronization and could damage the stator and rotator of the generator. Also, if the voltage is not matched, the voltage difference will cause the balanced current to flow through the network [7].

This current represents a reactive and mechanical effect on the electrical equipment of the power system and results in the voltage drop in the power network. In addition, the frequency difference between the generator and

the power system will deliver a large mechanical impact on the stator and rotor of the generator.

Sync-check device is one that generates an input signal when the above values are matched [8].

The purpose of precise synchronization is to close the generator interconnection circuit breaker at zero phase angles to minimize power flow transients and prevent generator damage when the breaker is closed. When the generator is connected to the power system by synchronization, parameters are perfectly matched, the synchronization time is increased, and as a result, an increased amount of sources (water, coal) consumption.

The synchronization condition that can be used to enable fast connection to the power system without significant impact on the generator is presented in the following table [9].

The synchronization condition standards are given in the following table.

Table 1. Synchronization condition criteria

Parameter	IEEE standard	ABB suggestion
Phase angle difference	20°	15°
Frequency difference	0.3Hz	0.35Hz
Voltage difference	10%	2%

Phase sequence is very important for synchronization. In case of a mismatched phase sequence, the stator and rotator of the generator can be damaged by impact current.

Also, if the voltage is not matched, the voltage difference will cause the balanced current to flow into the power system. This current causes an electrical reaction and a voltage drop in the power system. The frequency difference between the generator and the power system produces a large mechanical impact on the stator and rotor of the generator.

As shown in the table, the sync-check device has to do well in measuring the synchronization parameters.

In general, voltage amplitude and frequency measurements are very accurate with the introduction of digitizing techniques.

In the case of phase angle, it can be estimated by various methods, such as zero-point detection, digital signal processing, etc., but the estimation of phase angle difference for varying frequency cases is not accurate.

Also, considering the operating time of the circuit breaker, it is necessary to generate the circuit breaker output signal at time prior to when the phase difference is zero, and in general, the circuit breaker can be closed by calculating the corresponding prior angle if the slip frequency (the frequency difference between the power system and the generator) is constant [10].

However, because the frequency of the generator and the power system is not always constant, and the frequency changes during the synchronization of the generator, most of the slip frequency is not constant, and the prior angle will change during the synchronization process, so accurate synchronization cannot be achieved.

In the traditional synchronization methods, for the correct solving of this problem, it empirical equation was used according to each case. Therefore, in the synchronization, many problems are suggested, such as large electrical and mechanical impact, long synchronization time, etc. Therefore, this paper proposes a prior angle prediction method in case of slip frequency varies and a phase measuring method that can evaluate the phase angle difference correctly using beat-voltage when frequencies are different.

2. Sync-check Method

2.1 Phase angle difference measuring method using beat voltage

When paralleling the generator to the power system, the synchronization closing conditions are as follows.

$$U_S = U_G, f_S = f_G, \delta = 0 \tag{1}$$

Where

U_S is the power system voltage.

U_G is the generator voltage.

f_S is the power system frequency.

f_G is generator frequency.

δ is relative phase angle between generator and power system.

As you can see above, it can be known that the voltage and frequency of generator are same with power system's ones.

To check automatically that these conditions are satisfied, the beat voltage method is used.

The beat voltage is time varying amplitude voltage by vector difference of two ac voltage that has different frequency each other.

The curve of the beat voltage versus frequency difference is shown in Figure 1.

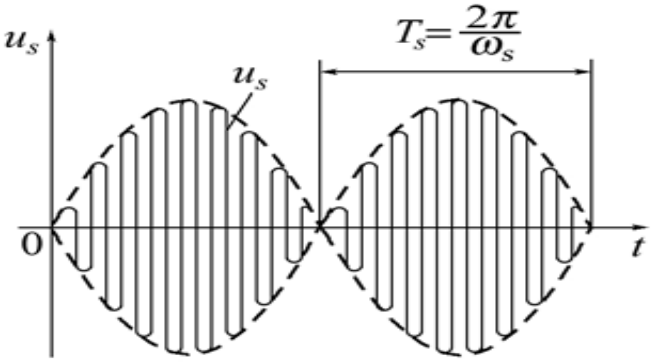

Figure 1. Beat voltage curve.

The figure shows the changing of beat voltage according to time.

The beat voltage that generated by power system and generator is following.

$$u_{\mathrm{B}} = u_{\mathrm{S}} - u_{\mathrm{G}} = U_{\mathrm{S}m} \sin \omega_{\mathrm{S}} t - U_{\mathrm{S}m} \sin \omega_{\mathrm{S}} t \tag{2}$$

The rms value of the beat voltage can be expressed as

$$U_{\mathrm{B}} = \sqrt{\frac{1}{T} \int_0^{2\pi} (u_{\mathrm{S}} - u_{\mathrm{G}})^2 \, dt} \tag{3}$$

In the one chip computer to calculate beat voltage, convert above equation to following discrete equation.

$$U_{\mathrm{B}} = \sqrt{\sum_{i=0}^{N-1} (u_{\mathrm{S}i} - u_{\mathrm{G}i})^2 / N} \tag{4}$$

Where

u_{Si} is AD conversion value of i time power system voltage.

u_{Gi} is AD conversion value of i time generator voltage.

n is the Sampling number of one cycle.

When the amplitude and phase angle of two sources are matched the beat voltage value is zero.

And the beat frequency increases according to reduce the frequency difference of two sources.

Beat cycle is as follow.

$$T_{\mathrm{B}} = \frac{1}{|f_{\mathrm{S}} - f_{\mathrm{G}}|} = \frac{1}{df} = \frac{2\pi}{\omega_s} \tag{5}$$

In practice, select the threshold according to voltage, frequency, and phase angle then if that values are satisfied, parallel closing is occurred.

The beat voltage is maximum value when $\delta = 180°$ and is minimum when $\delta = 0°$.
The maximum value is sum of two voltage and minimum is its difference.
Thus,

$$\left|U_{\mathrm{S}} - U_{\mathrm{G}}\right| \le U_{\mathrm{B}} \le \left|U_{\mathrm{S}} + U_{\mathrm{G}}\right| \tag{6}$$

Based on the rms value of the beat voltage, the phase difference can be calculated as follows.
Equation (3) can be expressed as follows.

$$\begin{aligned} U_{\mathrm{B}}^2 &= \frac{1}{T}\int_0^{2\pi}\left(U_{\mathrm{Sm}}\sin\omega_{\mathrm{S}}t - U_{\mathrm{Gm}}\sin\omega_{\mathrm{G}}t\right)^2 dt = \\ &\frac{1}{\omega_{\mathrm{S}}T}\int_0^{2\pi}\left(U_{\mathrm{Sm}}\sin\omega_{\mathrm{S}}t - U_{\mathrm{Gm}}\sin\omega_{\mathrm{G}}t\right)^2 d(\omega_{\mathrm{S}}t) = \\ &\frac{1}{2\pi}\int_0^{2\pi}\left(U_{\mathrm{Sm}}^2\sin^2\omega_{\mathrm{S}}t + U_{\mathrm{Gm}}^2\sin^2\omega_{\mathrm{G}}t - 2U_{\mathrm{Sm}}U_{\mathrm{Gm}}\sin\omega_{\mathrm{S}}t\sin\omega_{\mathrm{G}}t\right)d(\omega_{\mathrm{S}}t) \end{aligned} \tag{7}$$

In the above equation, assume

$$\omega_{\mathrm{G}}t = (\omega_{\mathrm{S}} + \Delta\omega)t = \omega_{\mathrm{S}}t + \Delta\omega t = \omega_{\mathrm{S}}t + \delta \tag{8}$$

Where
δ is phase angle difference during one cycle by frequency difference between power system and generator.
From equations (7, 8) obtain following equation.

$$\begin{aligned} U_{\mathrm{B}}^2 &= \frac{1}{2\pi}\int_0^{2\pi}U_{\mathrm{Sm}}^2\sin^2\omega_{\mathrm{S}}t\,d(\omega_{\mathrm{S}}t) + \frac{1}{2\pi}\int_0^{2\pi}U_{\mathrm{Gm}}^2\sin^2(\omega_{\mathrm{S}}t+\delta)d(\omega_{\mathrm{S}}t) - \\ &-\frac{1}{2\pi}\int_0^{2\pi}2U_{\mathrm{Sm}}U_{\mathrm{Gm}}\sin\omega_{\mathrm{S}}t\sin(\omega_{\mathrm{S}}t+\delta)\,d(\omega_{\mathrm{S}}t) \end{aligned} \tag{9}$$

The integral result of the above equation is as follows.

$$U_{\mathrm{B}}^2 = \frac{1}{2}U_{\mathrm{Sm}}^2 + \frac{1}{2}U_{\mathrm{Gm}}^2 - U_{\mathrm{Sm}}U_{\mathrm{Gm}}\cos\delta \tag{10}$$

Considering that the rms value of the voltage signal is $1/\sqrt{2}$ of the amplitude, Eq. 10 can be expressed as

$$U_{\mathrm{B}}^2 = U_{\mathrm{S}}^2 + U_{\mathrm{G}}^2 - 2U_{\mathrm{S}}U_{\mathrm{G}}\cos\delta \tag{11}$$

From the above equation, the phase angle is expressed as

$$\delta = \arccos\left(\frac{U_{\mathrm{S}}^2 + U_{\mathrm{G}}^2 - U_{\mathrm{B}}^2}{2U_{\mathrm{S}}U_{\mathrm{G}}}\right) \tag{12}$$

From above equation it can be calculated the phase angle difference between generator and power system by using power system voltage, generator voltage and beat voltage. The result calculated from equation (12) was validated against PMU measurements with $< 1°$ error.

2.2 Prior angle prediction method when the slip frequency is changing linearly

In the process, the frequency of the power system is constant and the frequency of the generator is tracked to the system frequency, the slip frequency is changed linearly.

The precise synchronous check device can calculate the ideal prior angle using the following equation.

$$\delta_s = \omega_{si} t_{DC} + \frac{1}{2} \frac{\Delta\omega_{si}}{\Delta t} t_{DC}^2 \tag{13}$$

Where

δ_s is prior angle.

ω_{si} is slip frequency of i time.

In the above equation, slip frequency ω_{si} can be calculated using the following equation.

$$\omega_{si} = \frac{\Delta\delta_i}{\Delta t} = \frac{\delta_i - \delta_{i-1}}{2\tau_x} \tag{14}$$

Where

$\delta_i - \delta_{i-1}$ is the angular difference between the current and the previous calculation points.

$2\tau_x$ is the time between two computing points.

t_{DC} is the time until closing the breaker by generating the output signal of the synchronous check device, and can be expressed as follows.

$$t_{DC} = t_{DL} + t_C \tag{15}$$

t_{DL} is operation time of the breaker.

t_C is operation time of the output relay of the synchronous check device.

Because ω_s variation between the two adjacent calculation points are very small $\Delta\omega_{si}$ can be calculated once through a few calculation points.

Thus, $\Delta\omega_{si}$ of the equation (13) can be expressed as follows.

$$\frac{\Delta\omega_{si}}{\Delta t} = \frac{\omega_i - \omega_{i-n}}{2\tau_x n} \tag{16}$$

ω_i, ω_{i-n} is value of ω calculated in the current and n^{th} previous calculation points.

Using equation (13) can calculate the nest prior angle δ_s.

The value and δ_i angle of the current calculation point are compared using following equation.

$$\left|(2\pi - \delta_i) - \delta_s\right| \le \varepsilon \tag{17}$$

ε is permission error

If above equation is satisfied, it generates closing signal immediately.

In the condition like following equations calculate for next points continuously until δ_i satisfies equation (17).

$$\left|(2\pi - \delta_i) - \delta_s\right| > \varepsilon \tag{18}$$

or

$$(2\pi - \delta_i) > \delta_s \tag{19}$$

If the calculation $\delta_e(t)$ curve is same as A of Figure 2 a) and corresponding ω_s is constant (straight line A'), $\Delta\omega_{si} = 0$ and this is same as prior angle test of general synchronous method.

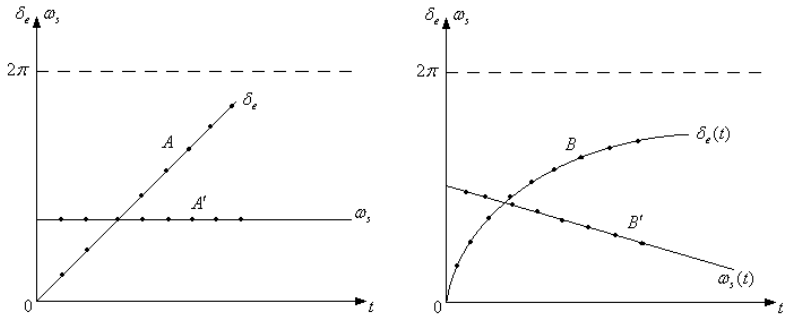

Figure 2. Curve of $\delta_e(t)$. (a) when ω_s is constant, (b) when $\omega_s(t)$ is varied

If in the calculation $\delta_e(t)$ curve is the same as B of Fig 2 (b) and corresponding $\omega_s(t)$ is straight line B' (ω_s is changed on uniform velocity), this means that paralleling synchronous motion is accelerated on uniform velocity. Generator frequency is approached to the system frequency gradually. In that time, using equation (13) can calculate the best prior angle by considering the accelerator of the generator.

If it compares the best prior angle δ_s and δ_i of current calculation point, the following case can also appear. Thus

$$(2\pi - \delta_i) < \delta_s \tag{20}$$

Figure 3 shows the phase difference change curve when the closing time doesn't match.

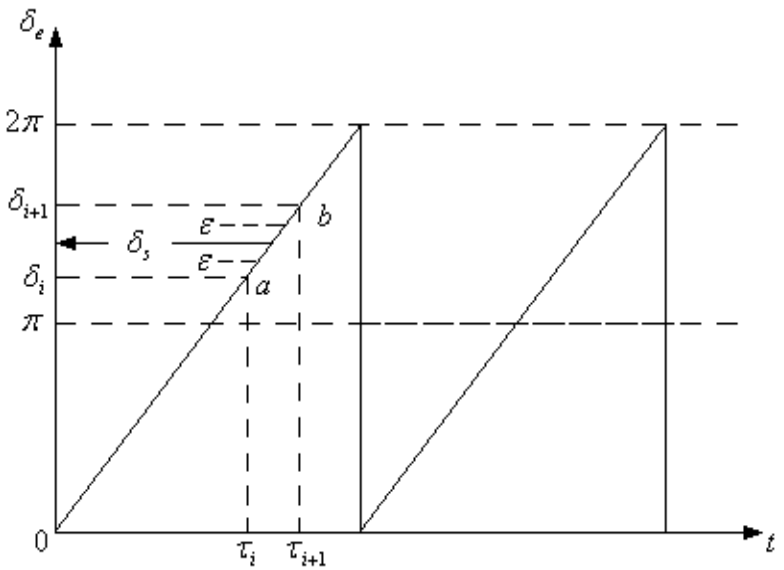

Figure 3. Curve of phase angle difference when the closing time doesn't match.

If we suggest to be constant in rotational speed of the generator to be parallel except the closing time, then consider the point a, δ_i is already approached to δ_s, but doesn't satisfy equation (17) and it is corresponded to equation (18) and equation (19).

Considering point b, δ_{i+1} isn't yet satisfied equation (17) and it corresponds to equation (18) and equation (19). This would result in a mismatch in the closing time.

To avoid this situation, it can predict δ_{i+1} of the next moment when calculating δ_i the current moment simultaneously.

We expect that the best closing prior angle δ_s is between the current calculation point and the next prediction point, take the positive in time, and derive the time needed for $\delta_i - \delta_s$. Like this, the closing signal is generated at the prior angle δ_s moment correctly.

Therefore, if the voltage and frequency of the generator to be operated in parallel satisfy the synchronization condition, find the beat closing prior angle δ_s and generate the closing signal in time, so it was achieved fast synchronization is achieved.

Since the closing time of the circuit breaker has dispersion, the allowable slip frequency and acceleration of the synchronization process within the set allowable closing error angle must be determined by calculation.

2.3 Prior angle prediction method when slip frequency is changing nonlinearly

During the generator frequency is tracking to the power system frequency, the slip frequency will change according to the control characteristics of the governor.

The change is irregular and it is difficult to represent as a function.

Therefore, the prior angle prediction was carried out using neural network.

The neural network can generate into function the irregular input-output relation characteristics by learning training dataset and complicated formulation is not required.

Learned neural network generates valid output signal with respect to untrained dataset.

The prior angle prediction method using neural network is as follows.

The prediction was carried out using Matlab 2015a on core i5-8350U computer.

To make predictions using neural network, first, it determines the input signal and output signal then prepare training dataset according to it.

The input signal can be selected the factors that have a significant effect on the output signal.

Input signals is selected generator frequency f_G, power system frequency f_S, sampling time t_{sp}, circuit breaker input time t_{in} and phase angle difference δ of present time.

Table 2. Input dataset of neural network

f_G(Hz)	60.195	60.197	60.200	60.203	60.206	60.208	60.3
f_S(Hz)				60			
t_{sp}(ms)				20			
t_{in}(s)				0.4			
δ(˚)	80.079	117.743	86.354	112.042	112.919	97.821	108.1

The output signal is selected as the phase angle difference between two sources after circuit breaker input time.

Next, the training parameters were set.

Based on characteristic of dataset it is used the RNN (recurrent neural network).

The important problems in prediction using neural network are to select type of network, number of hidden layer, number of neuron, activation function and learning type well.

So RNN which can predict characteristic of time series dataset is used.

The neural network for prediction consists of three layers including one input layer, one hidden layer and one

output layer. The number of units in each layer is 5, 10 and 1. The activation function of the hidden layer is used the rectified linear function and output layer is used the 'tanh'. The training function is used 'trainlm' and epoch is defined 100. The result of the above neural network was the most accurate, as the number of layers, nodes and training functions of the neural network were varied.

The following picture shows the configured neural network and learning rate.

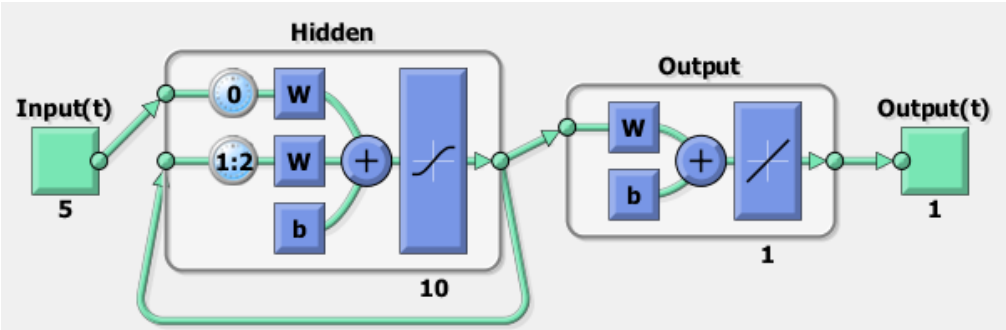

Figure 4. Recurrent neural network for prediction of prior angle.

The hidden layer of the neural network updates the weighting coefficients by repeating the training to obtain the output from the input data.

After the above neural network was constructed and trained, the following accuracy was achieved.

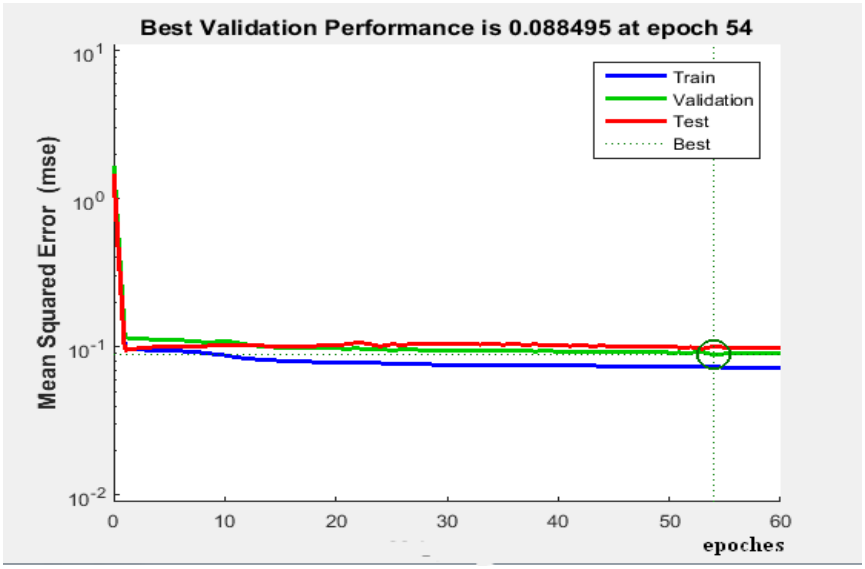

Figure 5. Graph of mean square error.

The accuracy of parameter estimation was evaluated with the mean square error between the actual and predicted parameters.

As shown in the figure, when the number of epochs is 54 the error is the smallest in which the mean error square is 0.088495.

Since the error satisfies the criteria, the above calculation results are used.

3. Simulation

MATLAB Simulink was used to compare the predicted values in above neural network and real phase angle after circuit breaker input time.

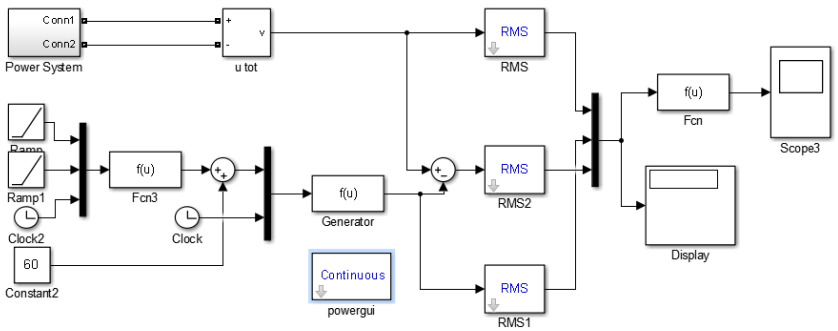

Figure 6. Simulation circuit of phase angle difference at synchronizing time.

The phase angles difference between generator and power system for varying frequency are as follow.

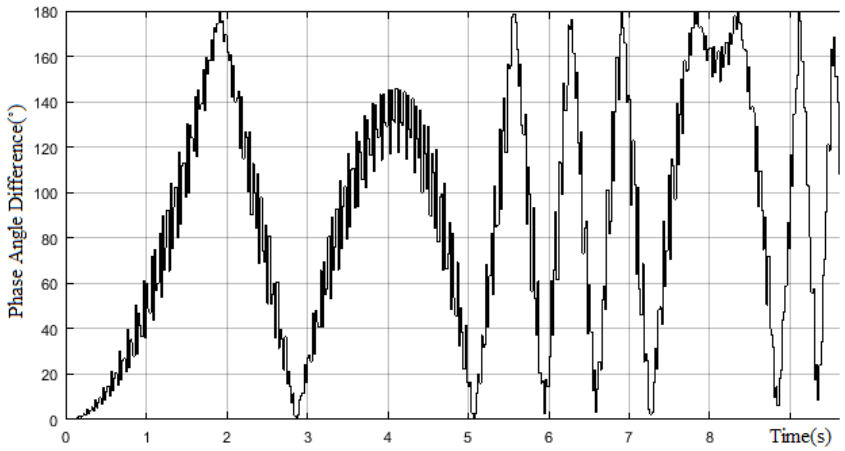

Figure 7. Graph of phase angle difference according to time during synchronization.

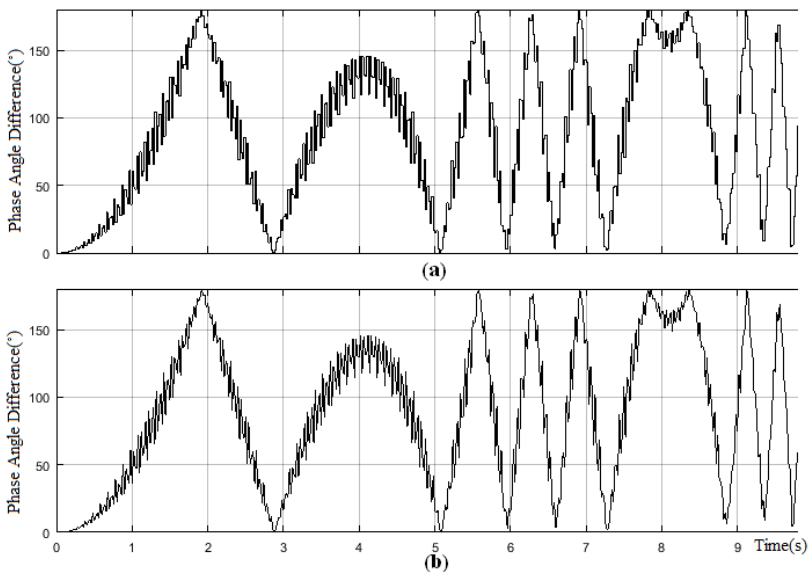

Figure 8. Graph of phase angle difference according to time during synchronization. (a) actual phase angle, (b) predicted phase angle).

The above graph values are tabulated as follows.

Table 3. Real phase angle and predicted phase angle according to time

Time(s)	0	0.2	0.4	0.6	0.8	1	1.2	1.4
Real value (˚)	0	1.787	7.524	18.124	35.214	60.074	89.783	109.7
Prior value (˚)	0	1.872	7.589	18.436	35.543	61.894	90.021	107.3

From Table 3, it can be seen that the difference between the actual and predicted phase angle difference is $\triangle \delta < 5^{\circ}$.

Through simulation result, it can be seen as follows.

(a) New synchronization method can reduce the synchronization time of generator.

In the traditional methods, because the predicted prior angle wasn't accurate it missed synchronization point, as a result the synchronization time is increased.

The new method can find the moment of parallel closing accurately, thus reduce the synchronization time.

(b) Novel synchronization method can reduce the impact induced to generator with 0.5 times compared to IEEE standard (20° phase tolerance).

4. Conclusion

In this paper, prior time prediction method of synchronization closing was considered in case of the slip frequency was varied linearly and nonlinearly.

Novel synchronization method could be reduced the impact induced to generator and closing time greatly.

Through simulation, accuracy of predicted phase angle was ascertained.

This method could be reclosed the generator after an accident rapidly because the synchronization time of the generator is short, thus can be increased the stability of the power system and restored the power supply to the users.

To prevent of generator damage during synchronization, various protections must be implemented.

The future work will improve the efficiency of neural network to become reliability and accuracy of prior angle prediction higher.

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