Identification of Out-of-Step Operation of Synchronous Machines Using High Resolution Spectrum Estimation Methods

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Abstract - **The out-of-step operation conditions of a synchronous machine may occur as a result of a power system three-phase fault. The mostly used methods of identification of loss of synchronism are not secure enough. In the paper a new method using high-resolution spectrum estimation method is presented. In the case of asynchronous operation of a synchronous machine the current waveform in the stator winding can be resolved into three components, which frequencies differ insignificantly. High-resolution subspace methods enable to estimate the frequencies and on this way to identify the asynchronous operation.**

Keywords: **Power System Control, Synchronous Machines, Out-Of-Step Operation, Spectrum Estimation, Subspace Methods.**

1. INTRODUCTION

The out-of step operation conditions (loss of synchronism) of a synchronous machine may occur as a result of a power system three-phase fault. Usually, the complex impedance measured at the machine terminals is compared with a proper characteristic on the complex impedance plane, to detect the asynchronous operation [1]. The other methods used for identification of out-of-step operations are based on the rate of change of apparent resistance augmentation [2], the equal area criterion [3], the observations of phase differences between sub-stations [4] or on the applications of neural networks [5]. Since the mostly used methods are not secure enough, it is suitable to search for new solutions.

When a fault occurs at the terminals of a synchronous generator, the power output of the machine is reduced as it is supplying a mainly inductive circuit. However, the input power to the generator from the turbine has not time to change during the short time of the fault and the rotor begin to gain speed to store the excess energy. If the fault persists long enough, the rotor angle will in-crease continuously and synchronism will be lost. In such case, the current waveforms in the stator winding contain three main components, which frequencies depend on the rotor slip. At the beginning of an asynchronous running, differences between the frequencies are small. Therefore, the identification of the components is rather difficult.

Estimation of the spectrum of discretely sampled processes is usually based on procedures employing the fast Fourier transform (FFT). This approach is computationally efficient and produces reasonable results for a large class of signal processes. In spite of the advantages there are several performance limitations of the FFT approach. The most prominent limitation is that of frequency resolution, i.e. the ability to distinguish the spectral responses of two or more signals. These procedures usually assume that only harmonics are present and the periodicity intervals are fixed, while periodicity intervals in the presence of interharmonics are variable and very long. It is very important to develop better tools of interharmonic estimation to avoid possible damages due to their influence. A second limitation is due to windowing of the data. Windowing manifests itself as "leakage" in the spectral domain. These two limitations are particularly troublesome when analyzing short data records. Short data records occur frequently in practice, because many measured processes are brief in duration or have slowly time-varying spectra that may be considered constant only for short record lengths. Windowing of data makes the implicit assumption that the unobserved data outside the window are zero. A smeared spectral estimate is a consequence. If more knowledge about a process is available, or if it is possible to make a more reasonable assumption, one can select a model for the process that is a good approximation. It is then usually possible to obtain a better spectral estimate.

To alleviate the limitations of the FFT approach, many new spectral estimation methods have been pro-posed during the last decades [6-9]. Advantages of the new methods depend strongly upon the signal-to-noise ratio (SNR). Even in those cases where improved spec-tral fidelity can be achieved, the computational effort of those alternative methods may be significantly higher than FFT processing.

The subspace frequency estimation methods rely on the property that the noise subspace eigenvectors of a Toeplitz autocorrelation matrix are orthogonal to the eigenvectors spanning the signal space. The model of the signal in this case is a sum of random sinusoids in the background of noise of a known covariance function. The eigenvectors spanning the noise space are the ones whose eigenvalues are the smallest and equal to the noise power. The earliest application of the property is the Pisarenko harmonic decomposition (PHD). The PHD method does not itself provide reliable frequency estimates. However, it has promoted a big interest in application of eigenanalysis to frequency estimation. The most important techniques, based on the concepts of subspaces are the MUSIC (MUltiple Signal Classification) and Min-Norm methods [8].

In the paper the frequencies of current components are estimated using the MUSIC method. Identification of current components which frequencies differ slightly can be applied as an indicator of generator out-of-step operation. To investigate the ability of the method several experiments were performed. Simulated current, current waveforms at the output of a simulated generator as well as current waveforms in a physical model of a power system were investigated.

2. CURRENT WAVEFORMS IN THE STATOR WINDINGS

If the machine running in parallel with others is disturbed from its synchronous-state conditions, the rotor winding and the stator winding fluxes rotate with different velocities. The stator winding flux generates an electromotive force (e.m.f.) in the rotor winding which angular velocity depends on the rotor slip. The current in the rotor winding, caused by the e.m.f., produces a pulsating magnetomotive force (m.m.f.), which can be resolved into two "rotating" m.m.f.s of constant and equal amplitude revolving in opposite directions. These m.m.f.s are assumed to set up corresponding gap fluxes. The angular velocities of the fluxes are equal to the angular frequencies of the alternating components of the rotor winding current.

$$\omega_f = s \cdot \omega_s ; \omega_b = -s \cdot \omega_s \qquad (1)$$

where:

ω_f - angular velocity of the forward field component,

ω_b - angular velocity of the backward field component,

ω_s - angular velocity of the rotating stator field,

s - rotor slip.

The angular velocity of the rotor ω_r is described as:

$$\omega_r = (1-s)\,\omega_s \qquad (2)$$

The field components cut the stator conductors at velocities depending on the velocities of the components and velocity of the rotor. Hence, in the stator windings are induced corresponding e.m.f.s. causing currents components to flow. The angular frequencies of the components are: ω_s and $(1-2s)\,\omega_s$. Direct current in rotor windings produces m.m.f.s, which set up corresponding gap fluxes. The fluxes rotate with the angular velocity ω_r, cut the stator conductors at sleep speed, induce corresponding e.m.f.s and cause an other component of the stator currents.

3. SUBSPACE METHODS

The recent methods of spectrum estimation are based on the linear algebraic concepts of subspaces and so have been called "subspace methods" [6, 8, 9]. Their resolution is theoretically independent of the SNR. The model of the signal in this case is a sum of random sinusoids in the background of noise of a known covariance function. Pisarenko first observed that the zeros of the Z-transform of the eigenvector, corresponding to the minimum eigenvalue of the covariance matrix, lie on the unit circle, and their angular positions correspond to the frequencies of the sinusoids. In a later development it was shown that the eigenvectors might be divided into two groups, namely, the eigenvectors spanning the signal space and eigenvectors spanning the orthogonal noise space. The eigenvectors spanning the noise space are the ones whose eigenvalues are the smallest and equal to the noise power. The most important techniques, based on the Pisarenko's approach of separating the data into signal and noise subspaces are the Min-Norm and MUSIC (Multiple Signal Classification) methods.

We assume that the data consists of p complex sinusoids in complex white Gaussian noise.

$$\mathbf{x}[n] = \sum_{i=1}^{p} A_i \exp(j2\pi f_i n + \Phi_i) + z[n] \qquad (3)$$

for $n = 0,1,\ldots,N-1$

$z[n]$ is complex white Gaussian noise with zero- mean and variance σ_0^2.

The $N \times N$ autocorrelation matrix for $N > p$ has the form:

$$\mathbf{R}_{xx} = \sum_{i=1}^{p} \mathbf{P_i e_i e_i^H} + \sigma_0^2 \mathbf{I} = \mathbf{R}_{ss} + \mathbf{R}_{zz} \qquad (4)$$

$\mathbf{R}_{xx}$ is the sum of a signal autocorrelation matrix $\mathbf{R}_{ss}$ and a noise autocorrelation matrix $\mathbf{R}_{zz}$.

The frequency information is contained in the matrix $\mathbf{R}_{ss}$. The decomposition of the matrix $\mathbf{R}_{xx}$ bases on the eigenvectors and eigenvalues. The eigenvectors corresponding to the *p* largest eigenvalues contain information about signal parameters. To extract the information we can use the orthogonality of the eigenvectors. It is said that eigenvectors containing the information about signal span the signal subspace and the remaining span the noise subspace. The signal vectors are orthogonal to all vectors in the noise subspace. The earliest application of the property is the Pisarenko Harmonic Decomposition (PHD). Because of difficulties with practical applications of the PHD method we investigated two other subspace methods: Min-Norm and MUSIC.

The MUSIC method involves projection of the signal vector:

$$\mathbf{s}_i = \begin{bmatrix} 1 & e^{j\omega_i} & \ldots & e^{j(N-1)\omega_i} \end{bmatrix} \qquad (5)$$

onto the entire noise subspace, where N - is the number of the signal sample.

We consider a random sequence $\mathbf{x}$ made up of p independent signals in noise.

$$\mathbf{x} = \sum_{i=1}^{p} A_i \mathbf{s}_i + \eta \; ; \quad A_i = |A_i| e^{j\phi_i} \qquad (6)$$

It is a general model used in all "subspace methods".

$N-p$ smallest eigenvalues of the correlation matrix (matrix dimension $N > p+1$) correspond to the noise subspace and p largest (all greater than σ_0^2) correspond to the signal subspace.

We define the matrices of eigenvectors:

$$\mathbf{E}_{signal} = \begin{bmatrix} \mathbf{e}_1 & \mathbf{e}_2 & \cdots & \mathbf{e}_p \end{bmatrix} \tag{7}$$

$$\mathbf{E}_{noise} = \begin{bmatrix} \mathbf{e}_{p+1} & \mathbf{e}_{p+2} & \cdots & \mathbf{e}_N \end{bmatrix} \tag{8}$$

$\mathbf{E}_{noise}$ can be used to form a projection matrix $\mathbf{P}_X$ for the noise subspace

$$\mathbf{P}_{noise} = \mathbf{E}_{noise}\mathbf{E}_{noise}^{*T} = \mathbf{I} - \mathbf{P}_{signal} \tag{9}$$

The squared magnitude of the projection of an auxiliary vector w (defined as in (5)) onto the noise subspace is given by:

$$\mathbf{w}^{*T}\mathbf{P}_{noise}\mathbf{w} = \mathbf{w}^{*T}\mathbf{E}_{noise}\mathbf{E}_{noise}^{*T}\mathbf{w} \tag{10}$$

The MUSIC pseudospectrum is defined as:

$$\widehat{P}\left(e^{j\omega}\right) = \left[\mathbf{w}^{*T}\mathbf{E}_{noise}\mathbf{E}_{noise}^{*T}\mathbf{w}\right]^{-1} \tag{11}$$

and it exhibits sharp peaks at the signal frequencies where $\mathbf{w} = \mathbf{s}_i$

4. SIMULATION OF THE FAULT OPERATIONS OF A SYNCHRONOUS GENERATOR

In the recent years, simulation programs for complex electrical circuits and control systems have been improved essentially. The EMTP-ATP (Electromagnetic Transients Program - Alternative Transients Program) as a FORTRAN based and to MS-DOS/WINDOWS adapted program serves for modelling complex 1- or 3-phase networks occurring in drive, control and energy systems.

In the paper we show investigation results of a fault operation of a synchronous generator powered by hydraulic turbine combined to a PID governor system and excitation system. Excitation system implements IEEE type 1 synchronous machine voltage regulator combined to an exciter.

Generator data: salient-pole synchronous generator: Nominal power 200MVA, nominal voltage 13800 V, nominal frequency 50 Hz.

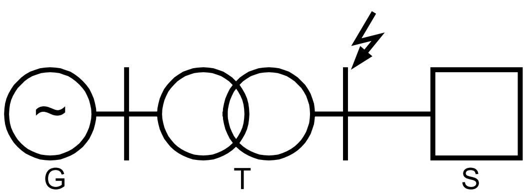

Fig. 1. Modelled power system.

Reactances: $X_d = 1{,}305$, $X_d^{'} = 0{,}296$, $X_d^{''} = 0{,}252$, $X_q = 0{,}474$, $X_q^{''} = 0{,}243$ (p.u.)

Block transformer: 210 MVA, 13,8 kV/230 kV, dY, $R_1 = 0{,}0027$, $L_1 = 0{,}08$ (p.u.)

System: 10 GVA, 230 kV, sampling frequency: 200 Hz

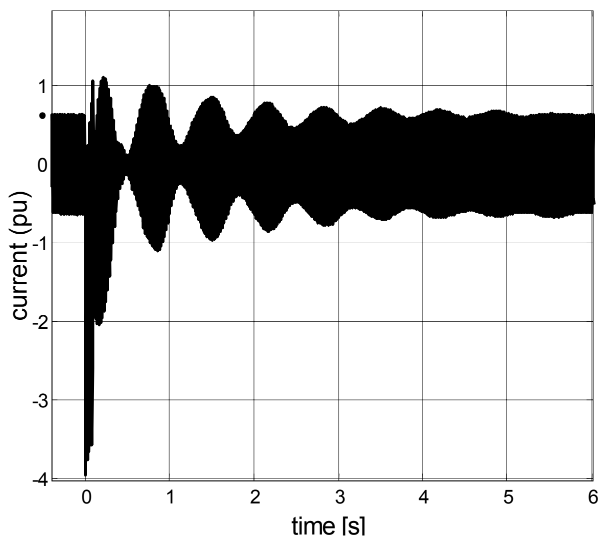

Fig. 2. Current waveform at the generator output. Duration of the fault 100 ms.

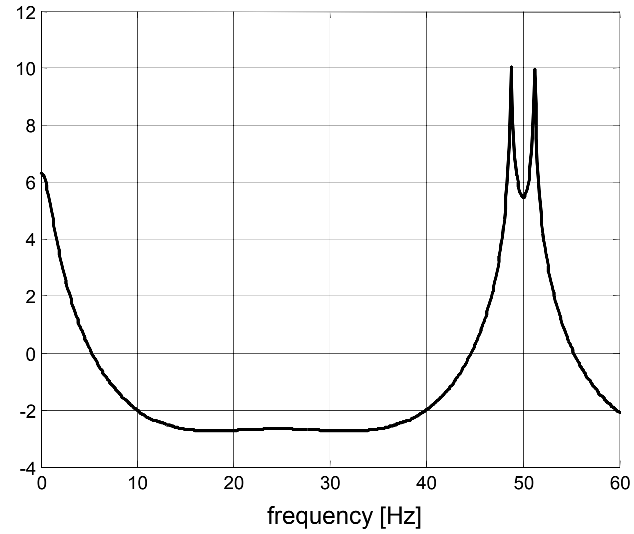

Fig. 3. Current spectrum of the signal in Fig. 2, for t=2 s after the fault incipience. Detected signal components with frequencies: 48,73 and 51,27 Hz.

Under normal steady state conditions a three-phase to ground fault at the transformer output was simulated (Fig. 1). The fault was switched on at t=0. After the fault was cleared out-of-step operation conditions occurred. In Fig. 2 the current waveform at the generator output for the short-circuit duration of 100 ms is shown. Time-frequency distribution of the waveform has been calculated applying the MUSIC method and the window of 40 samples (0,2 s).

On this way a three-dimensional spectrum has been obtained. In the paper, only some cross sections of the spectrum are shown to demonstrate the high resolution of the method.

MUSIC spectrum of the stator current 2 or 4 seconds after the fault incipience is shown in Fig. 3 and Fig. 4, respectively. The difference between the frequencies of the two current components are for t=4 seconds smaller than estimated for t=2 seconds.

Decrease of the frequency differences of the signal components over the time confirms the trend towards the retrieval of the generator from the out-of-step state. In the case when the fault duration was extended to 300 ms, an additional component can be detected. In Fig. 5 the current waveform at the generator output for the short-circuit duration of 300 ms is shown and in Fig. 6 the rotor speed during the fault.

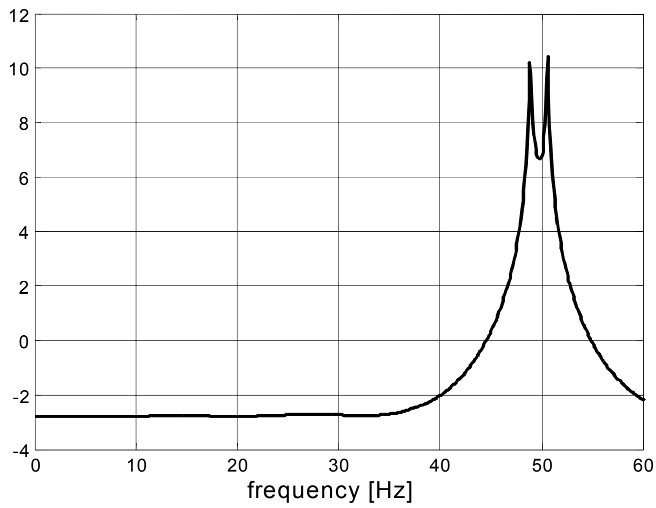

Fig. 4. Stator current spectrum of the signal in Fig. 2, for t=4 s after fault incipience. Detected signal components with frequencies: 48,83 and 50,68 Hz.

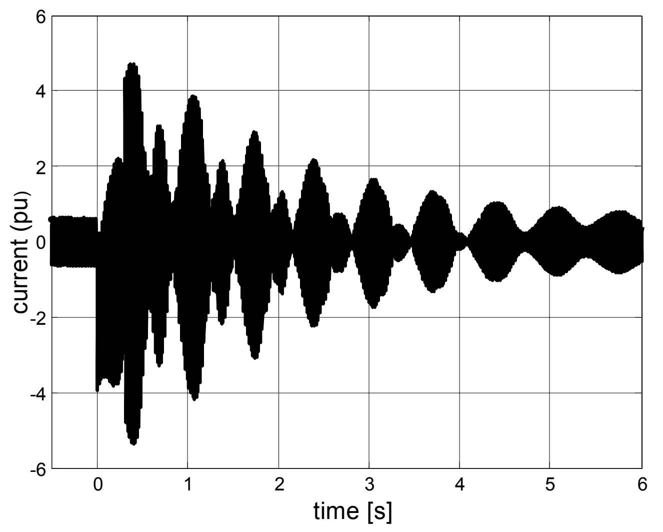

Fig. 5 Current waveform at the generator output. Duration of the fault 300 ms.

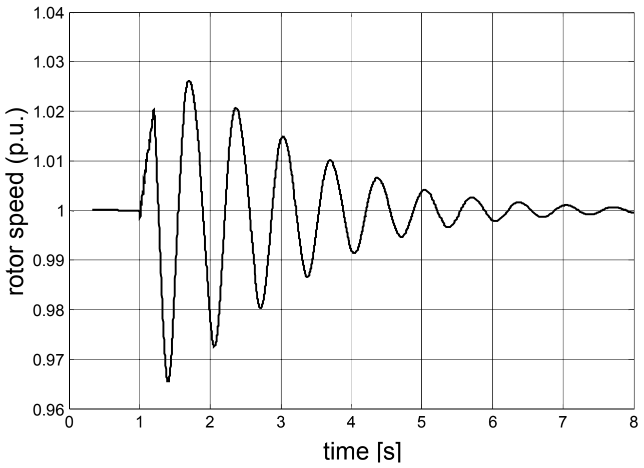

Fig. 6 Rotor speed of the generator during fault (p.u.)

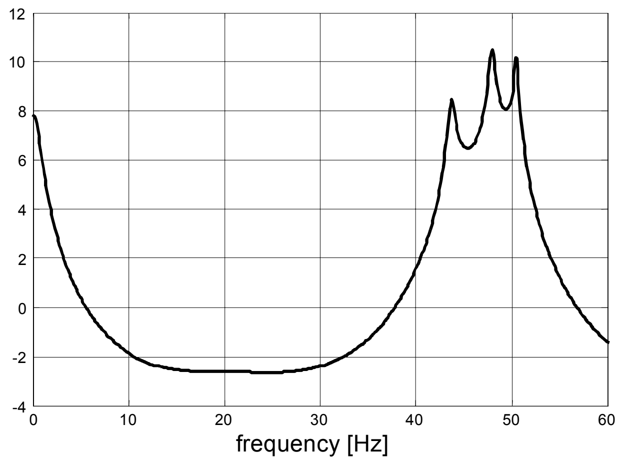

Fig. 7. Stator current spectrum of the signal in Fig. 5, for t=2 s after fault incipience. Detected signal components with frequencies: 43.75, 47.95 and 50.49 Hz.

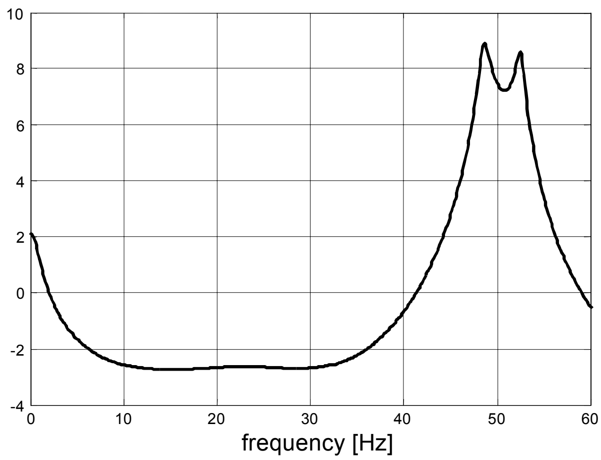

Fig. 8. Stator current spectrum of the signal in Fig. 5 for t=4 s after fault incipience. Detected signal components with frequencies: 48.63 and 52.54 Hz.

At the beginning of the asynchronous running three current frequency components have been detected (Fig. 7). Afterwards the components with the smallest frequency disappeared (Fig. 8).

5. INVESTIGATIONS AT A PHYSICAL MODEL OF POWER SYSTEM

Further investigations were carried out on a physical model of a power system at the Saarland University. The system consists of modelled 160 MVA synchronous generator with transformer, connected to 100 km 220 kV transmission line and 100 MW load

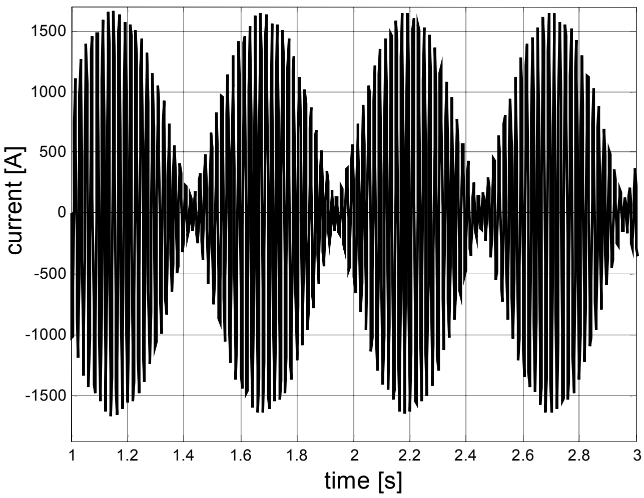

Fig. 9 Current waveform at the generator output, recorded at the physical model..

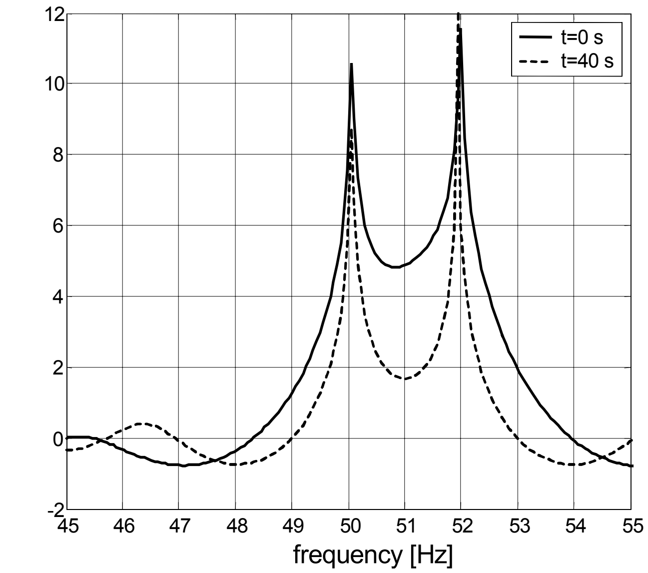

Fig. 10 Stator current spectrum of the signal in Fig. 8. **Solid line** – at the beginning of the asynchronous running: detected components 50, 52 Hz; **Dash line** – after 40 s of the asynchronous running: detected components 50, 51,8 Hz.

The transmission line is connected at the other terminal to the external power system. Three-phase short circuit occurred at the line side of the transformer causing the asynchronous running of the generator. The current waveforms were recorded with the sampling frequency equal to 500 Hz

A section of the waveform is shown in Fig. 9. The asynchronous running of the generator lasted very long, so that it was necessary to switch off the generator. Current waveforms were recorded over 40 seconds and have been analysed for the begin and for the end of the record using sampling window equal to 100 ms. At the beginning of the asynchronous running two signal components with frequencies 50 Hz and 52 Hz have been detected. After 40 seconds the frequencies of the components were 50 Hz and 51,8 Hz (Fig. 10). Decrease of the frequency difference confirms, that the generator is leaving the out-of-step state.

6. CONCLUSIONS

When the synchronous running of a synchronous machine is lost, a current in the stator winding can be resolved into two or three components with different frequencies depending on the rotor slip. At the beginning of an asynchronous running, differences between the frequencies are small. For identification of the asynchronous operation, the frequencies of the current components are estimated. The appearance of additional current frequency components can be used as indicator of out-of-step operation of a synchronous machine. Decrease of the frequency differences of the detected current components over the time indicates that the generator is leaving the out-of-step state. Because of very small differences between the frequencies of the components, high-resolution spectrum estimation methods are needed. Therefore, subspace methods have been applied. Extensive investigations confirm the validity of the proposed method.

ACKNOWLEDGEMENT

This work was partly supported by the ***North Atlantic Treaty Organization*** (Advanced Science Fellowship for Dr. Z. Leonowicz).

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