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Dynamic Parameter Estimation of Inter-area Oscillations in a Power System by a Combination of Kalman-Filtering and Wavelet Transformation Techniques

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Abstract: Within this paper two techniques for online estimation of frequency and damping ratio of inter-area oscillations in a power system are compared. The techniques are the Kalman filtering technique and the wavelet transformation in combination with the random decrement technique. First, the two methods are compared regarding the accuracy of frequency estimation and the accuracy of damping estimation by use of a test system with known parameters. Second the capability of detecting changes in the frequency or in the damping ratio is investigated. Subsequently a combined approach consisting of the Kalman filtering technique as well as the wavelet transformation is developed to overcome the drawbacks of both methods. The usability of the developed method is finally shown on basis of measurement data of the European power system

Keywords: Inter-area oscillations, power system stability, wide area monitoring, Kalman filtering techniques, wavelet transformation, random decrement technique

1 INTRODUCTION

The European energy system is undergoing an enormous change. Liberalization of the European energy market leads to a higher market coupling between the European countries and hence to an increase of the inner-continental trading of electric energy. Furthermore, the European Union has the ambitious goal to raise the share of renewable energy sources in the total energy consumption to 20 % by the year 2020. This results in a growing share of electricity production from renewables like wind and photovoltaics with fluctuant generation characteristics. The balancing of these fluctuations leads to higher energy exchanges between the connected countries.

As a consequence the inner European power flows increase and therefore mainly the load of the interconnectors between the different countries is rising. Hence, the grid is more and more operated at its stability limits.

An additional challenge in a widespread interconnected power system are the so called inter-area oscillations. These oscillations lead to additional unintended power flows and an increasing load on the tie-lines. Inter-area oscillations not only occur after disturbances in the grid, but also during ambient conditions. In the European power system (see Fig. 1) four dominant oscillation modes in a frequency spectrum of 0.1-2 Hz are known. The damping of these modes is usually sufficient. However, depending on the specific load situation and the corresponding use of power plants the damping can reach lower values. In case of additional utility outage the damping can even be negative which leads to an unstable operation. Hence, in order to provide sufficient measures to prevent stability problems, the main parameters of these oscillations, frequency and damping ratio, have to be known for the transmission system operator in online operation.

Various studies have shown different approaches for online estimation methods, such as (Korba, 2007). However, the two most promising methods are the Kalman filtering technique (KFT), which is already in commercial use, and the newer wavelet transformation technique in combination with the random decrement technique (WTRD). Within this paper these two methods are compared and a combination of the two methods for better accuracy and change detection is presented.

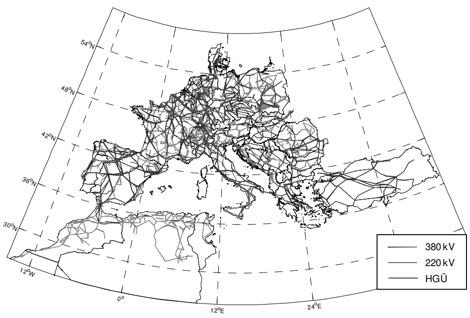

Fig. 1. Extension of the continental European power system

First chapter 2 gives a short overview on inter-area oscillations and the dynamic parameters which are estimated by the considered methods.

In the following, chapter 3 and 4 explain the concept of the Kalman filtering technique and the wavelet transformation technique for estimation of frequency and damping ratio in an electrical interconnected system.

In chapter 5, the differences of the two methods are depicted and discussed.

Finally, a combined method consisting of both methods is presented in chapter 6.

2 INTER-AREA OSCILLATIONS

Inter-area oscillations are excited in normal operation by different power imbalances. These power imbalances can be modelled as Gaussian noise and occur mainly due to the fluctuant demand of the consumers in the power system. The considered inter-area oscillations within the European power system are damped electro mechanical oscillations in the frequency range from 0.1 Hz to 2 Hz (Lehner *et al.*, 2010). A damped oscillation can be described by the frequency and the damping ratio. This is displayed in Fig. 2 for the velocity of the rotor angle of a generator with frequency $f = 0.2$ Hz and the damping ratios $\zeta_1 = 5\ \%$ (a) and $\zeta_2 = 3\ \%$ (b).

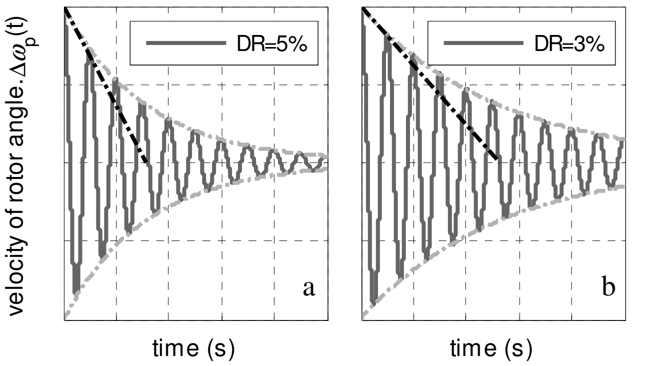

Fig. 2 Two decaying oscillations with damping ratio of 5 % (a) and 3 % (b).

By knowing the poles $s_i = \sigma_i + j\omega_i$ of a system, the frequencies f_i and the damping ratio ζ_i can be calculated with (1) and (2) (Wang, 1997).

$$f_i = \frac{\omega_i}{2\pi} \tag{1}$$

$$\zeta_i = \frac{\sigma_i}{\sqrt{\sigma_i^2 + \omega_i^2}} \tag{2}$$

In the following, two methods are considered for estimating these two values.

3 KALMAN FILTERING TECHNIQUE

The Kalman filtering technique is well known and used for many applications. The feasibility of KFT for estimation of frequency and damping ratios of inter-area oscillations is shown by (Korba and Uhlen, 2010) for oscillation modes of the Scandinavian power grid. Hereinafter the general principle of KFT for estimation of frequency and damping ratio is presented.

The general principle of the Kalman filtering technique is depicted in Fig. 3.

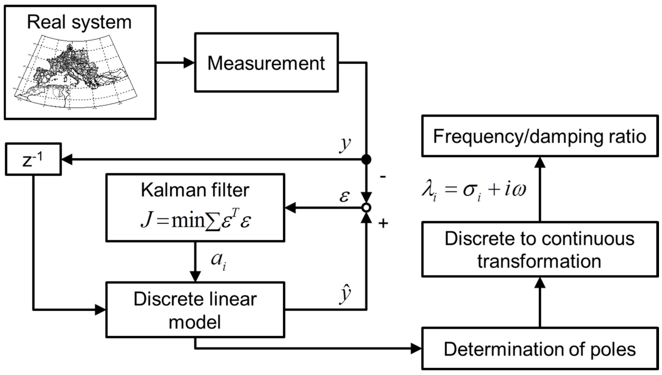

Fig. 3. Principle scheme of the Kalman filtering technique

Measurements like frequency, power flows or phase angles of the real system are used to estimate the frequency and the damping ratio of the present oscillations modes. The KFT is based on a discrete linear model of order n. The order defines the number of past measurements values which are used as input. With the KFT, the parameter of this model is getting adjusted in a way that the error between the output of the model and the measured signal of the real system defined in (3) is minimized.

$$\varepsilon(k) = \hat{y}(k \mid k-1) - y(k) \tag{3}$$

Thereby $\hat{y}(k \mid k-1)$ gives the prediction of $y(k)$ with use of the n prior measured values up to the time step $(k-1)$. The further equations of the used Kalman filter are explained more detailed in (Korba *et al.*, 2003). The poles of the adjusted model contain the information of frequency and damping ratio of the real system. The poles can be found by solving the characteristic equation of the adjusted model.

Transformation of the obtained poles from the discrete time domain into the continuous time domain with (4) provides the continuous poles of the system.

$$s_i = \ln(z_i) \cdot f_S = \sigma_i + j\omega_i \tag{4}$$

Thereby defines f_S the sample frequency of the measurements. Based on the gained continuous poles the frequencies f_i and the corresponding damping ratios ζ_i can be calculated by use of (1) and (2). These steps are executed continuously during online operation.

4 WAVELET TRANSFORMATION

Another method for estimating the frequency and the damping ratio of occurring oscillations modes is the wavelet transformation in combination with the so called random decrement technique. In the following a short introduction is given. A deeper view on WTRD is given in (Jukka Turunen, 2011).

Using the WTRD for online estimation, the signal $y(t)$ has to be analyzed stepwise with a sliding time window. The length of the window defines the size of data analyzed in each step.

Estimation of the frequency and the damping ratio in each step consists of the parts depicted below.

1) Frequency estimation of dominant oscillation modes
2) Determination of wavelet coefficients of corresponding frequencies
3) Generation of an impulse response by use of the random decrement technique
4) Wavelet transformation of the created impulse response

These steps are displayed in Fig. 4 and explained hereinafter.

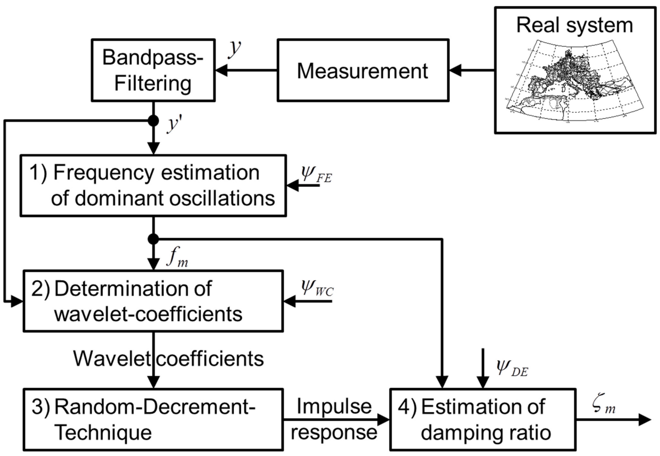

Fig. 4. General principle of the wavelet transformation technique

By use of a bandpass filter the measured signal is filtered first to shed the steady components and high frequency effects. An example of a real signal (a) and the bandpass filtered signal (b) is displayed in Fig. 5.

4.1 Estimation of frequency

The wavelet coefficients of the filtered signal are calculated by wavelet transformation (see Fig. 5c). For this step usually a complex wavelet function ψ_{FE} is used for better frequency resolution (Turunen *et al.*, 2010). Averaging the magnitude of the calculated wavelet coefficients provides the dominant frequencies of the considered signal and time window. This is displayed in Fig. 6. Each peak corresponds thereby to a dominant oscillation mode. In Fig. 6 the dominant peak at $f = 0.134\ Hz$ can be seen.

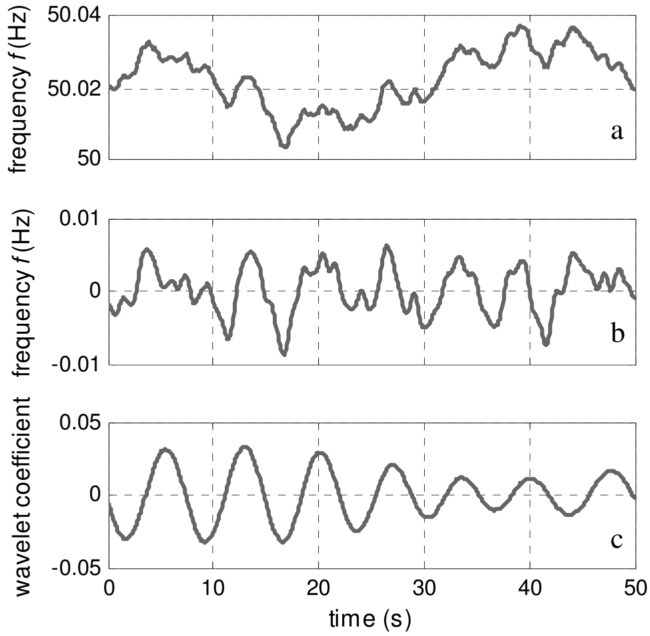

Fig. 5 Frequency signal (a), corresponding bandpass filtered signal (b) and wavelet transformed signal (c) for the oscillation mode with the frequency $f = 0.134$ Hz

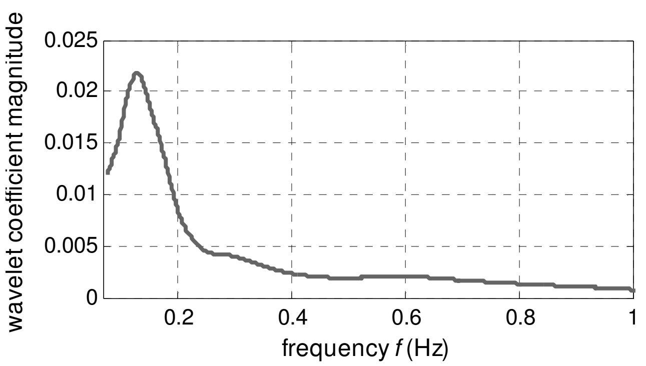

Fig. 6 Mean value of the wavelet coefficient magnitude for a measured frequency signal in Algeria

4.2 Damping estimation

After determination of the dominant frequencies a real mother wavelet ψ_{WC} is used to extract the wavelet coefficients of the corresponding modes. For each extracted time series of wavelet coefficients an impulse response is created by use of the random decrement (RD) technique.

In the fourth step the obtained impulse response is wavelet transformed. The attained wavelet coefficients C_{ir} are used to calculate the damping ratio with (5).

$$\zeta_m = -\frac{100}{2\pi f_m T_d} \ln \frac{\left| C_{ir}\left(T_{sp} + \frac{T_d}{2}\right)\right|}{\left| C_{ir}\left(T_{sp} - \frac{T_d}{2}\right)\right|} \tag{5}$$

Thereby two wavelet coefficients C_{ir} of the impulse response are taken into account at different time instants T_d of the damping calculation based on one instant of time T_{sp} within the impulse response.

5 COMPARISON

Within this chapter the presented methods are compared with respect to the following criteria:

- Accuracy of frequency estimation
- Accuracy of damping estimation
- Detection of change in frequency or damping

The results are displayed and discussed in the following.

5.1 Accuracy of frequency and damping ratio estimation

A 4th order linear time invariant (LTI) test system is used as a simple example for a power system with two dominant oscillations modes. The test system is excited with Gaussian noise. The poles of the LTI system describe the dominant modes of the system and are given by $s_1 = -0.05 \pm j2\pi f_1$ and $s_2 = -0.1 \pm j2\pi f_2$ with $f_1 = 0.5$ Hz, $\zeta_1 = 3.18$ % and $f_2 = 0.7$ Hz, $\zeta_2 = 1.14$ %.

100 simulations with different Gaussian noise are conducted to minimize the impact of the input. Average (AVG) and standard deviation (STD) are used to compare the two methods.

The results of the 100 simulations are summarized in Fig. 7

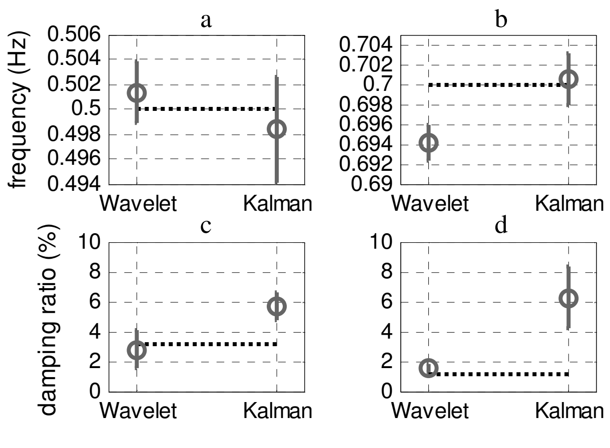

Fig. 7 Average and standard deviation of f_1 (a), f_2 (b), ζ_1 (c), and ζ_2 (d), each with the KFT and WTRD plus the nominal value (dotted line)

Regarding the accuracy of frequency estimation, the mean values of all sequences with both methods have very little deviations. However, considering the accuracy in the estimation of the damping ratio, WTRD leads to results with higher precision. The mean value of the damping ratio over the 100 simulated sequences by use of KFT has high deviations from the real value. These high deviations in the mean value area a result of a small number of estimations with maximal error more than 5 times the real value (Fig. 8). In low excited systems the KFT has problems estimating the damping ratio with high precision.

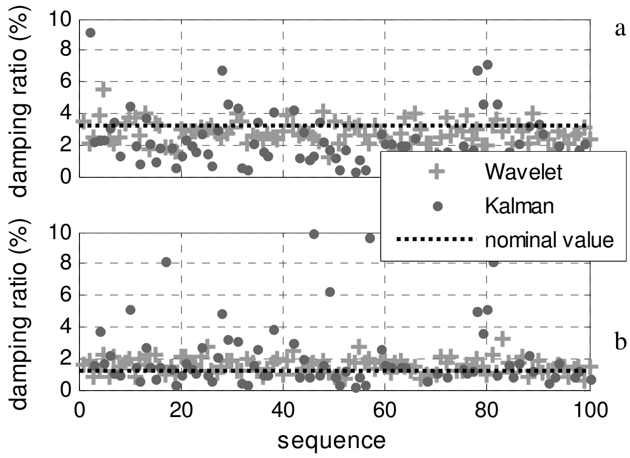

Fig. 8 Damping ratio estimation of ζ_1 (a) and ζ_2 (b) with the KFT and the WT

5.2 Determination of change in oscillation parameters

The capability of detecting changes in oscillation parameters is done by a synthetic model representing a power system with three regions. The regions are connected via three tie-lines and are excited by Gaussian noise. The structure of the synthetic power system is displayed in Fig. 9.

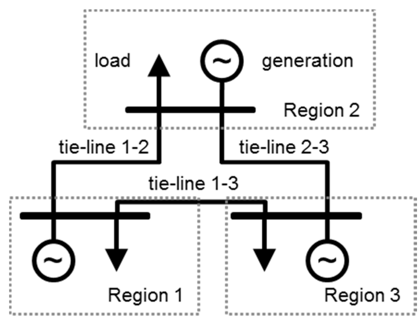

Fig. 9 Structure of the synthetic power system

At $t = 0\,s$ the tie-line 1-3 between region 1 and region 3 is disconnected. As a result of this the frequency of the dominant oscillation mode drops from $f_{3,1} = 0.507$ Hz to $f_{3,2} = 0.446$ Hz. First the WTRD is used to detect the changes in dynamic parameters. Within the study it became evident that the length of the used time window is the main parameter for gaining good detectability of changes in dynamic parameters. Hence, the time window length of the sliding window is changed from 30 to 120 seconds. In Fig. 10 the change of the frequency f_3 estimated with the WTRD under use of three different time window lengths is shown. With a short time window length the change can be detected in less than 20 s. However, the quality of frequency estimation diminishes significantly. The shorter the time window the higher is the influence of the current excitation. A longer time window averages effects due to excitation and therefore, the estimation is more accurate. An acceptable tradeoff between estimation quality and detection capability of frequency changes is reached at a time window length of 90 seconds. With this time window length the WTRD needs about 60 seconds to reach the end value of the frequency drop.

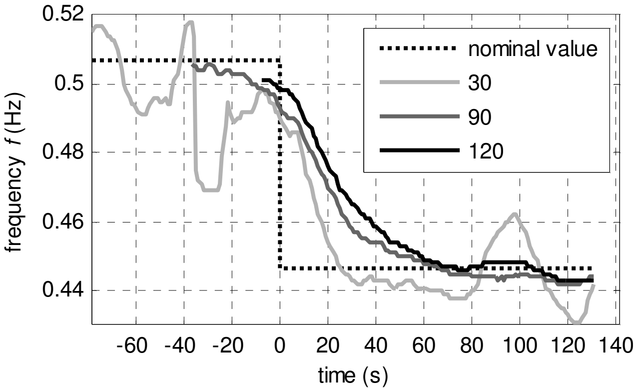

Fig. 10 Detection of a change in frequency due to line tripping with the WTRD technique using window lengths of 30, 90, and 120 seconds

The same system is analysed below with the KFT. In Fig. 11 the results of the KFT and the WTRD with a window length of 90 seconds are displayed.

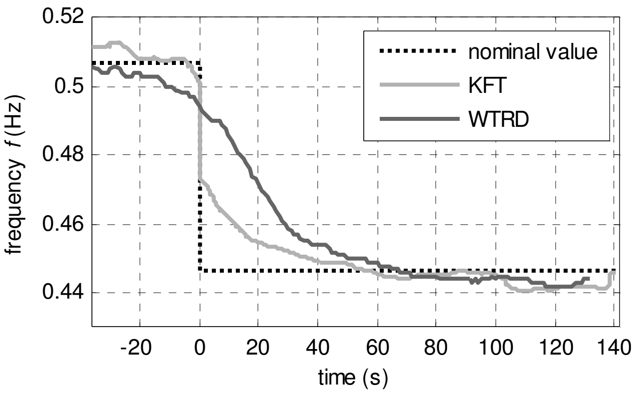

Fig. 11 Comparison of WTRD and KFT detecting a change in frequency

As one can see the Kalman filter detects the line tripping immediately after a change in the frequency of the dominant oscillation mode. Thus, compared with the WTRD, the KFT detects the change faster. Therefore, the KFT is more suitable in detecting changes

6 COMBINATION OF THE TWO TECHNIQUES

It could be seen, that both methods have high accuracy of frequency estimation. Drawback of the KFT is the small precision of damping ratio estimation regarding low excited systems. However, the KFT is more suitable to detect changes in dynamic parameters. Hence, in this chapter a combination of these two methods is presented to overcome the drawbacks of each method. Thus, accuracy of both methods regarding frequency estimation was similar and the KFT has better capabilities in detecting changes in the frequency, KFT is used for the frequency estimation. The obtained frequencies of the dominant oscillation modes are subsequently used for damping ratio estimation with the WTRD. The whole procedure is depicted in Fig. 12

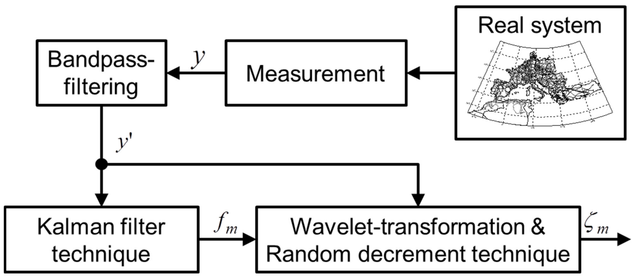

Fig. 12 Scheme of the coupling of KFT and WTRD

The example of the line tripping from chapter 5 is used to show the benefit of the coupled method. The results of the estimation of frequency and damping ratio are presented in Fig. 13. The estimation of the frequency follows the nominal value with a low delay. Also the estimation of the damping ratio detects the change, however, has still significant deviations from the nominal values $\zeta_{3,1} = 4.53\ \%$ and $\zeta_{3,2} = 1.63\ \%$.

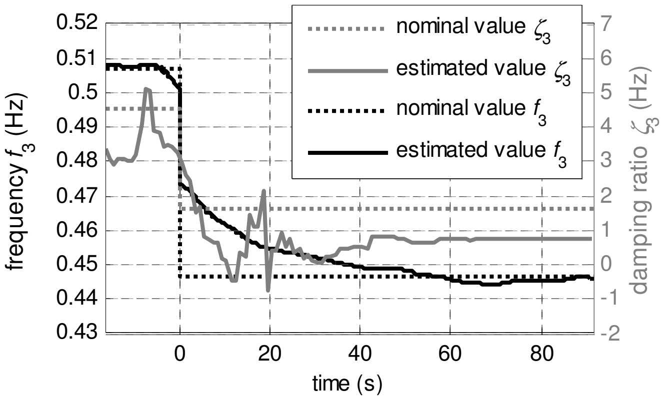

Fig. 13 Detection of change of dynamic parameters due to line tripping with use of a coupled method of KFT and WTRD

In the following example the developed method is applied to a real case of the European power system. At February 19th of 2011 an undamped oscillation could be seen in the frequency signal of Aalborg, Denmark (see Fig. 14a). The oscillation is clearly visible in the filtered signal in Fig. 14b.

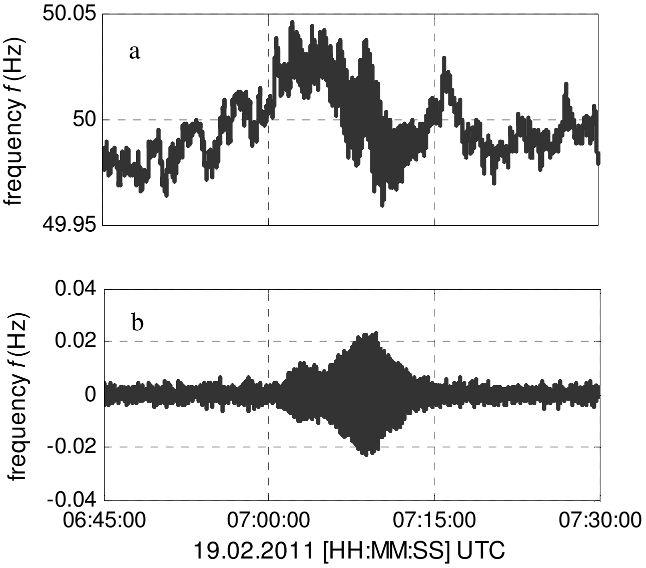

Fig. 14 Undamped oscillations in the frequency measurements of Aalborg, Denmark (a) and the filtered signal (b)

This measured frequency signal of Aalborg, Denmark is used for estimating the frequency and the damping ratio for this interval with the developed combination of KFT and WTRD. The result of the estimation is shown for the oscillation mode of 0.26 Hz in Fig. 15. It can be seen that the frequency drops from 0.282 Hz at 6:45, reaching its minimal value of 0.248 Hz at 7:07, recovering to 0.27 Hz at 7:30. The same behaviour can be noticed for the damping ratio. At the beginning of the observation the oscillation is well damped with a damping ratio above 6 %. Coming closer to 7:00 the damping ratio decreases until it is even negative shortly after 7:00, reaching its lowest value of -1 % around 7:02. In the following the damping ratio stays around zero for another 7 minutes until it recovers in the end to a stable value over 5 %.

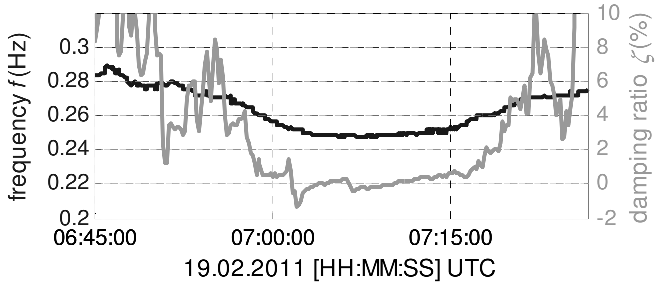

Fig. 15 Estimated frequency and damping ratio by the combined method

7 CONCLUSIONS

In this contribution two methods for estimation of frequency and damping ratio of oscillations modes within a power system are compared. The both considered methods are the model based Kalman filtering technique and the signal based wavelet transformation in combination with the random decrement technique. Comparison of the methods is done by two test systems. Thereby the test systems represent power systems with known dynamic parameters of the dominant oscillation modes. Accuracy of frequency and damping ratio estimation as well as capability of detecting changes in dynamic parameters are compared. Thereby the drawback of the Kalman filtering technique, the inaccuracy in estimating damping ratios of low excited systems is revealed. However, it is shown that the Kalman filtering technique has a better capability of detecting changes in the frequency of the observed oscillation modes. Hence, a combination of the two methods is developed. Finally the viability of the developed method is shown at a real case of the European power system.

In additional work the accuracy in estimating the damping ratio can be extended. Further, the frequency resolution for detecting oscillation modes with small difference in its frequencies has to be improved.

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