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AN IDENTIFICATION OF ACTIVE POWER IMBALANCE USING WAVELET TRANSFORM

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ABSTRACT
Wavelet transform has been successfully adopted in many power system fields such as power system protection, power quality and transients analysis. Typical applications include power system protection, analysis of power system transients, power quality detection and classification, etc. Development of modern computer, communication and information technologies enables design of a new class of wide area monitoring, protection and control systems. Important function of these systems is identification of the initiating disturbance event. This paper is aimed at presenting the wavelet transform usage in identification, estimation and localisation active power imbalance.

KEY WORDS
Wavelet, power system, wide area, signal, analysis

1. Introduction

Early identification and location disturbance is very important, primarily in the frame of modern power system management and control, especially in Wide Area Monitoring Protection and Control (WAMPC) systems. Recently, a number of major blackouts happened around the world [1]. Analyses of these blackouts reveal that some disturbances could have been prevented thus minimizing disturbance propagation. This spurred an interest in finding tools, systems and solutions that could help in prevented widespread outages during blackout. Generally, disturbance propagation involves a combination of cascading events: line tripping by dynamic line loading, equipment tripping by over-excitation, loss of synchronism due to angular instability, voltage instability due to inadequate reactive power. This may lead to system separation into islands with substantial imbalance of power resulting in frequency deviation and eventual collapse of power supply. The likelihood of cascading deterioration of system performance due to a low-probability event increases when grid is already under stress due to pre-existing conditions (i.e. grid congestions, tight operating margins, inadequate reactive power support close to the loads). Although the complexity of the blackouts has been extensively studied, many questions still remain unanswered. Traditional approach to prevention and mitigation of power failures is increase in transmission capacities, which requires high initial investments. Todays, development of modern computer, communication and information technologies enables design of a new class of WAMPC systems. Purpose of WAMPC systems is to protect the transmission system against the spreading of disturbance and blackout.
The subject of this paper is the identification, estimation and localisation active power imbalance based on wavelet transformation.
This paper first presents, in Section 2, power system response during disturbances. Brief interdiction of disturbance classification and identification and wavelet transform are then provided in Section 3 and Section 4, respectively. Practical application (simulation and analysis) results estimate active power imbalance using wavelet transforms are presents in Section 5. Conclusions are given in Section 6.

2. Power System Response during Disturbances

Power systems are subject to a wide range of disturbances, from small to large, and must be able to adjust to the changing conditions without losing stability. Power system has a number of monitoring, protection and control devices to ensure that the system response to any change in system parameters is controlled and its' stability is maintained [2]. If the system is unstable it will result in progressive increase in angular separation of generator rotors, progressive decrease of bus voltages, or system frequency deviation.
Qualitative analysis of the effect of sudden application at *t=0* of a small load change $P_{k\Delta}$ at node *k* is analyzed in [3]. Impact of a sudden active power imbalance $P_{k\Delta}(0+)$ is shared among generators during the power system response according to different criteria, before the system settles to a new steady state condition. If these criteria are

different for machines, the impact is followed by oscillatory power swings to reflect the transition from the initial sharing of the impact to the final sharing (adjustment) reached at steady state. These oscillations are also reflected in power flows in the tie lines.

In general, there are three criteria of power impact distribution. Immediately after the impact, the power balance is maintained due to the source of electric energy supplied by the generators from their magnetic fields. Impact $P_{k\Delta}(0+)$ is distributed among generators according to synchronizing power coefficients $P_{Sik}(t)$. Thus the machines electrically close to the point of impact will pick up the greater share of the load regardless of their size. In other words the higher transfer susceptance and the lower the initial angle, the greater the share of the impact "picked up" by machine. Due to the sudden increase in its output $P_{i\Delta}(t)$ (the share of the imposed imbalance) machine i will start to decelerate. The incremental differential equation governing the motion of machine i is given by swing equation:

$$\frac{2H_i}{\omega_0}\frac{d\omega_{i\Delta}}{dt} + P_{i\Delta} = 0 \tag{1}$$

Expressing $P_{i\Delta}$ as a function of $P_{k\Delta}(0+)$, (1) becomes:

$$\frac{1}{\omega_0}\frac{d\omega_{i\Delta}}{dt} = -\frac{P_{Sik}}{2H_i}\frac{P_{k\Delta}(0^+)}{\sum_{j=1}^{n} P_{Sjk}} \tag{2}$$

Therefore, after the initial impact various machines will be retarded at different rates, each according to its size Hi and electrical location given by synchronizing powers P_{Sik}. If the system maintains synchronous operation there will be an overall (system) deceleration during this transient period. Angle δ of the "center of inertia" and angular frequency ω of the center of inertia, according to:

$$\overline{\delta} = \frac{\sum_{i=1}^{n} H_i \delta_i}{\sum_{i=1}^{n} H_i}, \quad \overline{\omega} = \frac{\sum_{i=1}^{n} H_i \omega_i}{\sum_{i=1}^{n} H_i}$$

Than, swing equation of the center of inertia is described by:

$$\frac{1}{\omega_0}\frac{d\,\overline{\omega}_\Delta}{dt} = \frac{-P_{k\Delta}(0^+)}{\sum_{i=1}^{n} 2H_i} \tag{3}$$

Hence, while the system as a whole is retarding at the constant rate $d\omega_{i\Delta}/dt$, the individual machines are retarding at different rates $\left(d\overline{\omega}_\Delta / dt\right)$. Synchronizing forces tend to pull them toward the mean system retardation and if synchronism is maintained the mean value of the generator decelerations is the deceleration of the center of inertia.

After the initial transient period (no more than a few seconds) generator decelerations will acquire the same retardation given by (4). At the end of this transient period (at $t=t_1$) the various machines will share the increase in load $P_{k\Delta}(0+)$ only as a function of their inertia constants according to:

$$P_{i\Delta}(t_1) = \frac{H_i}{\sum_{j=1}^{n} H_j} P_{k\Delta}(0^+) \tag{4}$$

From the above qualitative analysis, the following characteristics of swing dynamics could be summarized:

- Immediately after the onset of the power unbalance $P_{k\Delta}(0^+)$ machines share the impact according to their electric proximity to the point of impact, as expressed by the synchronizing power coefficients $P_{Sik}(t)$.
- After a brief transient period ($t \le t_1$), the same machines share the same impact according to entirely different criteria expressed by (4), namely according to their inertia.

Finally, if the governors were active, the speed deviations would level off after a few seconds to a constant value and the oscillations would eventually decay. The impact would be then shared among generators according to their governor characteristics.

3. Disturbance Classification and Identification

Disturbances can be caused by a single event or by multiple events. Multiple events occur when the first event is so sever that it triggers subsequent events, usually due to the protection or control actions. Classification of disturbances account in [4] is based on the classification criteria for different types of stability. According to the proposed classification the basic features of single event disturbances are:

- Type and location in networks of the initiating event.
- Magnitude of change of the main system variable (small or large changes).
- Characteristics of the parameter oscillations (fast or slow transients and damping characteristics).
- Time frame of disturbances (short or long term).

Accurate and fast automatic identification of type and location of the initiating event could help achieve early alerting of the operators, clear understanding of the ongoing disturbance, and ultimately triggering early corrective emergency control actions. Generally, the objectives of disturbance identification are:

- Detect the onset in time of the disturbance.
- Classify the type of disturbance.
- Estimate the intensity and damping of the disturbance.
- Estimate the end time of the disturbance.

- Estimate the type and location of the initial event.

4. Wavelet Transform

Wavelet analysis is a relatively new signal processing tool and is applied recently by many researchers in power systems due to its strong capability of time and frequency domain analysis [5][6][7][8]. The Wavelet transform is a mathematical tool, like the Fourier transform for signal analysis. A wavelet is an oscillatory waveform of effectively limited duration that as average value of zero. Similarly, wavelet analysis is the breaking up of a signal into shifted and scaled versions of the original (or mother) wavelet. Figure 1 shows the wavelet.

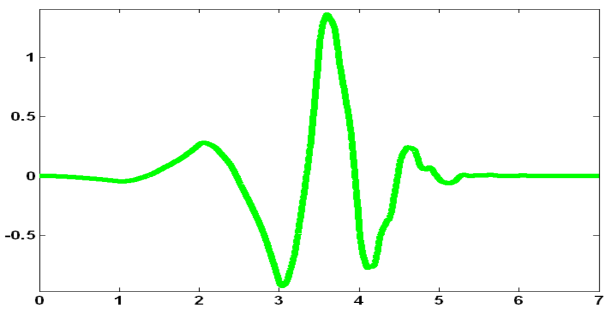


Figure 1. Wavelet (db4)

The wavelet transform of a time dependent signal *f(t)* consists of a set coefficients $W_s(a,b)$. These coefficients measure the similarity between the signal *f(t)* and a set of functions $\psi_{a,b}(t)$. All the functions $\psi_{a,b}(t)$ are derived from a 'mother wavelet' as follow:

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right), \quad a > 0 \qquad (5)$$

Where a represent a time dilatation and b a time translation. The Continuous Wavelet Transformation (CWT) of a time domain signal is defined by:

$$CWT_f(a,b) = (f, \psi_{a,b}) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\overline{\psi}\left(\frac{t-b}{a}\right)dt \qquad (6)$$

where: $\psi(t)$ is the basis wavelet function (or mother wavelet), that can be real or complex, a is the dilatation scale parameter, b is the time scale parameter, $\psi\left(\frac{t-b}{a}\right)$ are the daughter wavelet function. The application of wavelet transform in engineering areas usually requires a discrete wavelet transform Discrete Wavelet Transformation (DWT). A square integrable signal *f(t)* is decomposable into different time-frequency scales. In wavelet analysis, such a signal can be represented by a linear combination of two parameter wavelet functions:

$$f(t) = \sum_{k=-\infty}^{\infty} a_{j_0}(k)\varphi(t-k) + \sum_{j=j_0}^{\infty}\sum_{k=-\infty}^{\infty} d_j(k) 2^{j/2}\psi(2^j t - k) \qquad (7)$$

The wavelet functions $\varphi(t)$ and $\psi(t)$ are localized in time. Parameters *k* and *j* perform translation and time scaling of the original functions. The functions $\varphi(t)$ and $\psi(t)$ are usually chosen so that the functions on the right side of (6) form an orthonormal basis. Then decomposition and reconstruction are efficient using orthogonal projection. The $a_j(k)$ and $d_j(k)$ terms are referred to as approximation and detail coefficients, respectively (coefficients of low-pass and high-pass filters). These coefficients can be order according fallowing relations:

$$\begin{aligned} a(k) &= \sqrt{2}\int_{-\infty}^{+\infty} \varphi(t)\cdot\varphi(2t-k)dt \\ d(k) &= \sqrt{2}\int_{-\infty}^{+\infty} \psi(t)\cdot\varphi(2t-k)dt \end{aligned} \qquad (8)$$

They reflect a range from local to global characteristics of the original signal *f(t)* because their associated functions have different time-frequency scales. A very useful implementation of DWT, called multiresolution analysis, is demonstrated in Figure 2.

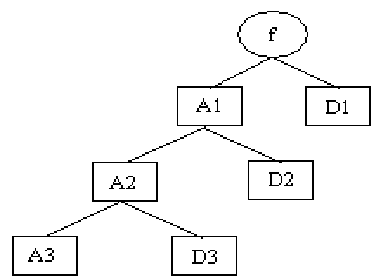


Figure 2. Wavelet multiresolution analysis

The original sampled signal *f* is passed through a highpass filter (D) and a lowpass filter (A). Then the outputs from both filters are decimated by 2 to obtain the detail coefficients and the approximation coefficients at level 1 (A1 and D1). The approximation coefficients are then sent to the second stage to repeat the procedure. Finally, the signal is decomposed at the expected level.

5. Arresting Frequency Collapse- Test System

Many systems try to detect a global frequency collapse by locally monitoring the frequency in various substations and shedding load locally if the frequency becomes too low. This unbalance between problem (global) and solution (local) is illustrated by the fact that in some countries the national transmission system operator has installed under-frequency relays in substations of regional utilities. This way of handling frequency collapse leads to sub-optimization of the systems installed to arrest frequency collapse: the shed load may not be enough or may be too much. Sub optimization is caused by the fact that adequate information is not available locally to properly arrest the frequency collapse. Based on the qualitative analysis of swing dynamics described in section 2, procedure of estimation active power imbalance in power system, are given below:

- From data samples of $\omega_i(t)$, recorded during the first swing at a generator bus, it is possible to determine first swing transient stability of the generator. Providing that transient stability is maintained, it is then possible to estimation, using a wavelet transform, of the frequency of center of inertia as well as the machine share of the unbalance impact $P_{i\Delta}(t)$.
- Providing that information regarding the total system inertia $\sum_{j=1}^{n} H_i$ and inertia of the generator H_i are known, it is further possible to calculate, from the estimated value of $P_{i\Delta}(t1)$, the amount of the total power unbalance in the system $P_{k\Delta}(0^+)$.
- After estimation the active power imbalance, analyzing signal of the voltage angle at load buses using wavelet transform, it is possible to determine the largest change of the angle at load bus. Compare this value it is possible estimate of area where is imbalance.

Simulation and analysis was done by using Two Area test system (P.Kundur) presented on Figure 3, using Power System Analysis Toolbox (PSAT) and Matlab Wavelet Toolbox. Total generation in system are 2960.30/903.05 [MW/MVar], load is 2870.7/-367.5 [MW/MVar] and losses 86.6/1270.5 [MW/MVar]. The completely power flow results give in Table 1. Table 2 presents value of inertia all generators.

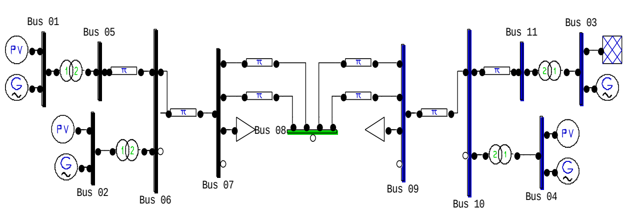


Figure 3. Two Area test system

When a disturbance occurs in a power system creating an imbalance between the mechanical power being supplied to a generator by its turbine and the electrical power being supplied to the power system, this imbalance is translated into a change in the kinetic energy of the rotor. In other words the generators begin to speed or slow down. Normally various damping phenomena within the power system will act so that the system will attain a new steady state operating point.

After simulation connection new nominal 100 MW load at bus 7, the individual machine speed deviation are plotted in Figure 4. In this case, governors are active, the speed deviation would level to a constant value and the oscillations would decay.

Table 1. Load Flow Results

Bus	V [kV]	Phase [rad]	P gen [MW]	Q gen [MVar]	P load [MW]	Q load [MVar]
Bus 01	20.6	0.38764	735	207.48	0	0
Bus 02	20.2	0.20755	735	272.59	0	0
Bus 03	20.6	-0.1186	755.30	194.32	0	0
Bus 04	20.2	-0.3065	735	228.65	0	0
Bus 05	230.8	0.26884	0	0	0	0
Bus 06	223.7	0.08252	0	0	0	0
Bus 07	219.2	-0.073	0	0	1015.35	-105
Bus 08	213.9	-0.3326	0	0	0	0
Bus 09	222.4	-0.5860	0	0	1855.35	-262.5
Bus 10	225.3	-0.4306	0	0	0	0
Bus 11	231.3	-0.2404	0	0	0	0

Table 2. The Machine Inertia

G1	G2	G3	G4
6.5	6.5	6.175	6.175

Using of DWT multiresolution analysis, the original sampled signal $\omega_i(t)$ is passed through a highpass filter (D) and a lowpass filter (A). In this case, for the analysis is using db 8 wavelet. Figure 5 present the centre of inertia and low frequency (approximation) component of the signal $\omega_i(t)$ all machines. Analyzing this low frequency signal, it is possible to estimate the value $d\omega_{i\Delta}/dt$, $P_{i\Delta}(t_1)$ and the total power unbalance in the system $P_{k\Delta}(0^+)$.

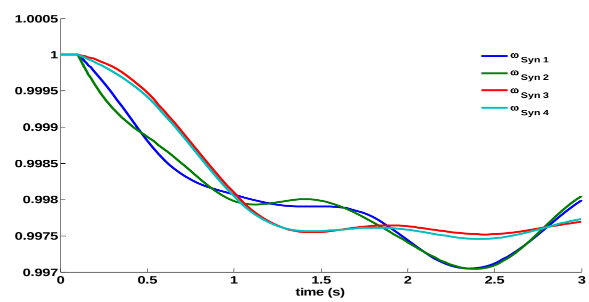


Figure 4. Machine speed deviation

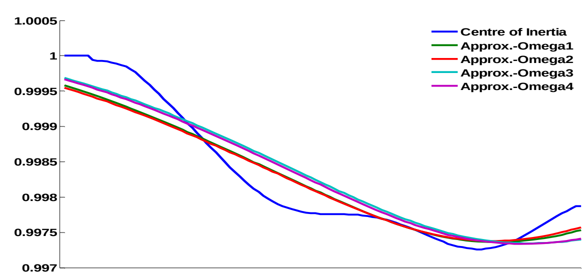


Figure 5. Centre of inertia and low frequency (approximation) component

Table 3.The Results of the Estimation

$d\omega_{1\Delta}/dt$ [Hz/s]	$d\omega_{2\Delta}/dt$ [Hz/s]	$d\omega_{3\Delta}/dt$ [Hz/s]	$d\omega_{4\Delta}/dt$ [Hz/s]
0.2	0.2	0.2	0.2

Table 4. The Results of The Estimation Machine Shar of the Unbalance Impact

$P_{1\Delta}$[MW]	$P_{2\Delta}$[MW]	$P_{3\Delta}$[MW]	$P_{4\Delta}$[MW]
27.21	27.21	25.85	25.85

The results of the estimation presents in the Table 3 and Table 4. The individual machine speed deviations are estimate in Table 3. The estimation mean deceleration is 0.2 Hz/s. The results machine share of the unbalance impact $P_{i\Delta}(t)$ it is present in Table IV. The test system estimate amount of the total power unbalance in the system $P_{k\Delta}(0^+)$ is 106.12 MW.

Figure 6 presents the relative voltage angles change at bus 7, bus 8 and bus 9 due to unbalance impact. The largest change of the voltage angle is on bus where the connections new load, in this case at bus 7.

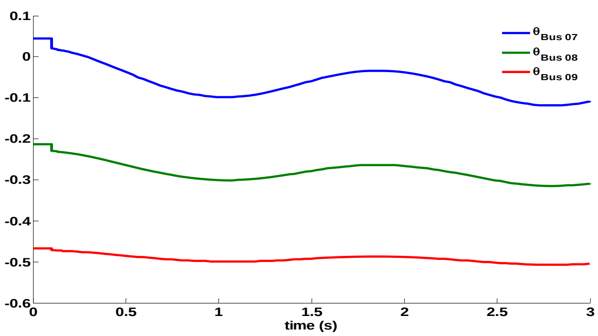
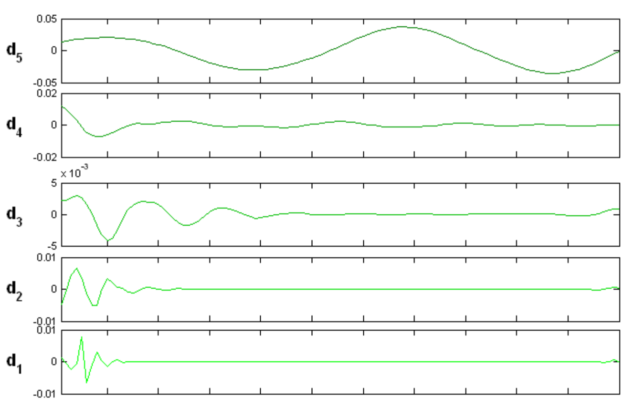


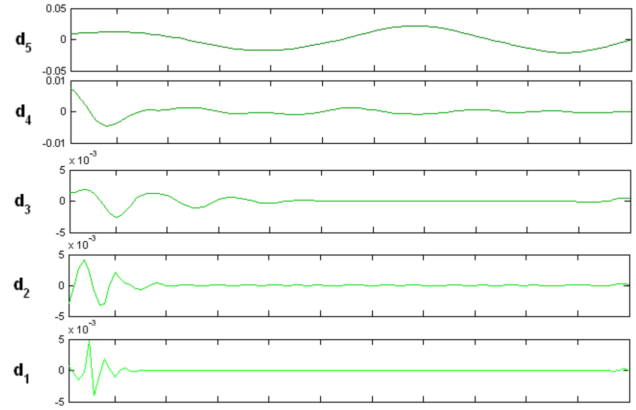
Figure 6. The relative voltage angles change at bus 7, bus 8 and bus 9 of the unbalance impact

As stated before, the Daubiches mother wavelet of order 8 (db8) is selected to analysis this signals. Using DWT multiresolution analysis, this signal is decomposed on approximations and details coefficients at the five level. Figure 7 presents high frequency component (D) or detail coefficients on voltage angle at a) bus 7, b) bus 8 and c) bus 9.

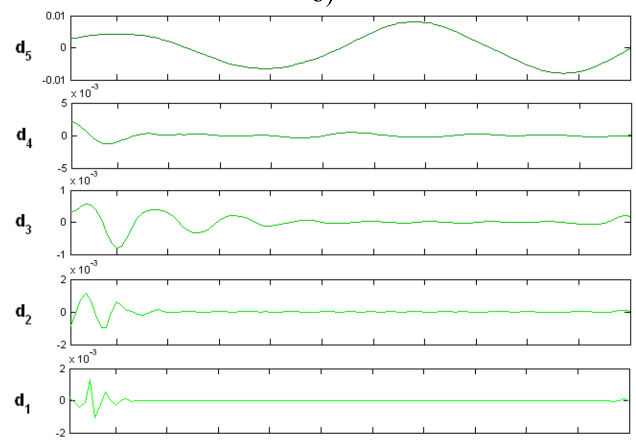
As far as the detection and the localization are concerned the first inner decomposition level of the signal (d1) is normally adequate to detect and localize any disturbance in the signal [9]. However other coarser resolution levels are used to extract more features which can help in the estimation process.



a)



b)



c)

Figure 7. High frequency component (D) on voltage angle at a) bus 7, b) bus 8 and c) bus 9

The magnitude of the coefficient line indicates the nature or intensity of the disturbance. The wavelet coefficients value of the detail is different and they are biggest on signal that is near the location the imbalance. Compare this value is possible estimate the location the disturbance. In this case, value of the wavelet coefficients is biggest at high component on signal voltage angle at bus 7. The details from level 1 to 5 are shown and the instant of the occurrence of the disturbance can easily be detected from the Wavelet analysis.

6. Conclusion

The probability of future power system blackouts is very low but their impact will be very devastating. The technological infrastructure for improvements in system monitoring, protection and control is already available in the form of broadband communication networks, high precision synchronized GPS devices and real-time monitoring systems. Hence, there is a great potential for new development of Wide- Area Monitoring Protection and Control systems, which could protect power systems against different sets of blackout-inducing contingencies. This paper is presented the wavelet transform as a relatively new signal processing tool and its possibility usage in detection and estimation active power imbalance. Because of its own advantages concerning standard mathematical signal processing tools, it is expect to use wavelet transform in modern WAMPC system, especially in modern wide area monitoring system.

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