ASSESSMENT OF TRANSIENTS IN POWER SYSTEM WITH WIND GENERATORS BY APPLICATION OF PRONY METHOD

Przemyslaw JANIK, Tadeusz ŁOBOS, Jacek REZMER
Wroclaw University of Technology
Poland
przemyslaw.janik@pwr.wroc.pl, jacek.rezmer@pwr.wroc.pl, tadeusz.lobos@pwr.wroc.pl

ABSTRACT

Wind power installations impact on power quality is crucial for power system operation. This paper presents modeling and simulation of an induction generator driven by wind turbine. Especially switching transients have been simulated and analyzed. Prony algorithm has been applied to determine signal parameters in different operation modes of wind generation unit. Detailed power quality studies on transients are helpful in better assessment of the phenomena.

INTRODUCION

The widespread implementation of wind energy conversion systems is a reality. Wind is seen as clean and renewable energy source, so the development of wind generation technologies is welcomed and supported by ecologists and governments. In the next years we will have even more generator units connected to the grid [1].

Wind turbines, despite of their advanced control systems and power electronic converters, influence in many different aspects the electrical system they are connected to [2, 3]. So fare, the electrical distribution networks were designed and operated under the assumption of centralized generation and energy flow from the substation to the consumer. It is no more the case [3, 4]. The connection of wind generators leads to many disturbances, such as: voltage fluctuation, flickers, harmonics, instability, blind power regulation problems, and transients [5]. Power quality issues connected with wind generation are not only important because of technical aspects, they are also crucial on the free energy market.

There are at least three main wind generators structures, which can be pointed out [4]. The simplest and most common one is the squirrel-cage induction generator connected directly to the grid. Second is the doubly-fed induction generator. The third structure of wind generation unit has a synchronous machine. That generators type requires a back-to-back converter for the grid connection, which can be operated in wide wind change range. Synchronous wind generators have significantly higher nominal power than asynchronous generators, but are also more cost intensive. Many of the wind energy converters installed today have a squirrel-cage induction machine connected directly to the grid [6, 7]. This type of the generator cannot perform voltage control and it absorbs reactive power from the grid. Compensating capacitors are often directly connected. That type of installation is cost saving, and therefore popular, but from the system analysis point of view it can be considered as the worst case [4].

During the switching of capacitors transients occur [7], which are devastating for sensitive equipment, protection relays and insulation. Also the impact on power quality indices can not be neglected [5]. Transient overvoltages can theoretically reach peak values up to 2.0 pu. High current transients can reach values up to ten times the nominal capacitor current with duration of several milliseconds [8].

The purpose of this paper is the assessment of transients in electrical system with asynchronous generator. A wind converter connected to distribution system was modeled in Matlab SimPowerSystemsTolbox [9].
The Prony method was considered an appropriate tool for parameters estimation of transients. The analysis was carried out for different operation conditions of the wind converter.

PRONY METHOD

Prony method is a technique for modeling sampled data as a linear combination of exponential [8]. Although it is not a spectral estimation technique, Prony method has a close relationship to the least squares linear prediction algorithms used for AR and ARMA parameter estimation. Prony method seeks to fit a deterministic exponential model to the data in contrast to AR and ARMA methods that seek to fit a random model to the second-order data statistics.
Assuming the N complex data samples the investigated function can be approximated by p exponential functions:

$$y[n]=\sum_{k=1}^{p} A_k e^{(\alpha_k + j\omega_k)(n-1)T_p + j\psi_k} \tag{1}$$

where
$n = 1,2,...,N$, T_p - sampling period, A_k - amplitude, α_k - damping factor, ω_k - angular velocity, ψ_k - initial phase.
The discrete-time function may be concisely expressed in the form

$$y[n]=\sum_{k=1}^{p}h_k z_k^{n-1} \tag{2}$$

where

$$h_k = A_k e^{j\psi_k}$$
$$z_k = e^{(\alpha_k + j\omega_k)T_p}$$

The estimation problem bases on the minimization of the squared error over the N data values

$$\delta=\sum_{n=1}^{N}\left|\varepsilon[n]\right|^2 \tag{3}$$

where

$$\varepsilon[n]=x[n]-y[n]=x[n]-\sum_{k=1}^{p}h_k z_k^{n-1} \tag{4}$$

This turns out to be a difficult nonlinear problem. It can be solved using the Prony method that utilizes linear equation solutions.

If as many data samples are used as there are exponential parameters, then an exact exponential fit to the data may be made.

Consider the p-exponent discrete-time function:

$$x[n]=\sum_{k=1}^{p}h_k z_k^{n-1} \tag{5}$$

The p equations of (5) may be expressed in matrix from as:

$$\begin{bmatrix} z_1^0 & z_2^0 & \cdots & z_p^0 \\ z_1^1 & z_2^1 & \cdots & z_p^1 \\ \vdots & \vdots & & \vdots \\ z_1^{p-1} & z_2^{p-1} & \cdots & z_p^{p-1} \end{bmatrix} \cdot \begin{bmatrix} h_1 \\ h_2 \\ \vdots \\ h_p \end{bmatrix} = \begin{bmatrix} x[1] \\ x[2] \\ \vdots \\ x[p] \end{bmatrix} \tag{6}$$

The matrix equation represents a set of linear equations that can be solved for the unknown vector of amplitudes.

Prony proposed to define the polynomial that has the exponents as its roots:

$$\begin{aligned} F(z)&=\prod_{k=1}^{p}(z-z_k)= \\ &=(z-z_1)(z-z_2)\ldots(z-z_p) \end{aligned} \tag{7}$$

The polynomial may be represented as the sum:

$$\begin{aligned} F(z)&=\sum_{m=0}^{p}a[m]z^{p-m}= \\ &=a[0]z^p+a[1]z^{p-1}+\ldots+a[p-1]z+a[p] \end{aligned} \tag{8}$$

Shifting the index on (5) from n to n-m and multiplying by the parameter $a[m]$ yield:

$$a[m]x[n-m]=a[m]\sum_{k=1}^{p}h_k z_k^{n-m-1} \tag{9}$$

The equation (9) can be modified into:

$$\begin{aligned} &\sum_{m=0}^{p}a[m]x[n-m]= \\ &=\sum_{k=1}^{p}h_k z_k^{n-p}\left\{\sum_{m=0}^{p}a[m]z_k^{p-m-1}\right\} \end{aligned} \tag{10}$$

The right-hand summation in (10) may be recognize as polynomial defined by (8), evaluated at each of its roots yielding the zero result:

$$\sum_{m=0}^{p}a[m]x[n-m]=0 \tag{11}$$

The equation can be solved for the polynomial coefficients. In the second step the roots of the polynomial defined by equation (8) can be calculated. The damping factors and sinusoidal frequencies may be determined from the roots z_k.

For practical situations, the number of data points N usually exceeds the minimum number needed to fit a model of exponentials, i.e. $N>2p$. In the overdetermined data case, the linear equation (11) should be modified to:

$$\sum_{m=0}^{p}a[m]x[n-m]=e[n] \tag{12}$$

The estimation problem bases on the minimization of the total squared error:

$$E=\sum_{n=p+1}^{r}\left|e[n]\right|^2 \tag{13}$$

STUDY SYSTEM SIMULATION

A single line diagram of the wind generator connected to distribution grid is shown in Fig. 1. It was simulated in Matlab using SimPowerSystem Toolbox [9].

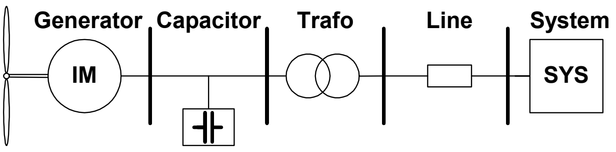

Fig. 1. Wind generator connected to distribution grid

Wind turbine generates mechanical torque on rotating shaft, while electrical machine produce an opposing electromagnetic torque [4]. In steady state operation, the mechanical torque is converted to real electrical power and delivered to the grid. The power generated by the wind turbine is [4, 6]

$$P=\frac{1}{2}\rho A C_p V^3 \tag{14}$$

and the torque

$$T=\frac{P}{\omega_s} \tag{15}$$

where ρ - density of air, A - swept area of the blade, C_p -

performance coefficient, V - wind speed, T mechanical torque, P - output power of the turbine, ω_s rotor speed of the turbine. By constant wind speed, the C_p coefficient depends on the rotor speed ω_s and pitch angle and is often presented in a table form [10]. The turbine characteristic used in simulation is shown in Fig. 2.

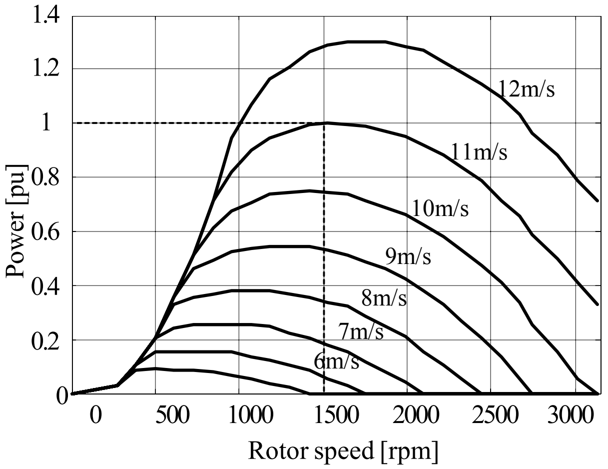

Fig. 2. Wind Turbine characteristic for different wind speeds (output power vs. angular velocity)

The pitch control dynamic can be neglected in power system transient analysis [6]. The generator is a 150 kW, 400 V, 1487 rpm, induction machine. It is connected to the grid through a Dyg 25/0.4 kV distribution transformer which nominal power was varied between 0.5 and 2 MW during the research process and other parameters were set with accordance to [11]. A typical 5 km overhead line [11] connected the generator to a system. The system was represented by equivalent source with short circuit capacity of 100 MVA and X/R ratio of 7. The induction generator reactive power demand varies with produced real power [10]. During the research different compensation levels were simulated. Simulation results correlated with measured values [7].

TRANSIENS ASSESSMENT WITH PRONY ALGORITHM

For variable wend speeds the exact compensation of reactive power with capacitor bank is difficult [10]. Reactive power variation should be taken into account even if additional capacitors are switched on and off during the operation [7]. Fig. 3 shows the active and reactive power at different wind speeds. At the beginning, the generator operated with nominal power, and the reactive power was fully compensated by capacitor bank. In the case of wind decrease (Fig. 3) over compensation was observed and by wind increase - under compensation.

Table 1 shows the estimated parameters of *signal components* of fourth order Prony model. Two signal frequencies in the current (Fig. 5) were assumed and computed. The main 50 Hz frequency [No. 2] and additional capacitor bank switching transient [No. 1]. Application of Prony method enabled accurate computation of current amplitude I, transients' time constant, frequency f and phase (Table 1).

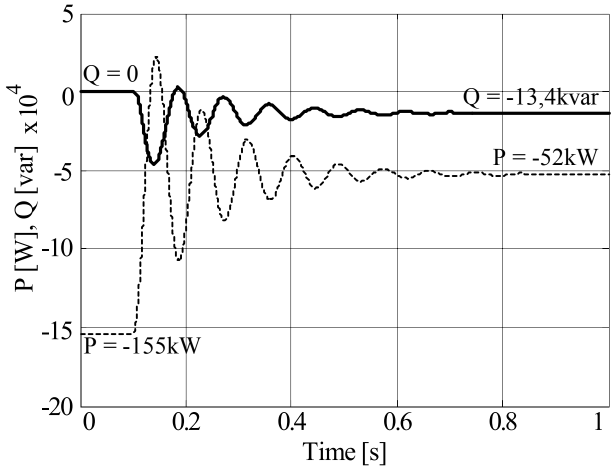

Fig. 3. Wind speed decrease from 11 m/s to 8 m/s at t=0.1 s

Table 1. Transients' parameters for Q_c=80.4 kvar and wind speeds of 14 m/s and 8 m/s

Signal com. [No.]	**I [A]**	**τ [s]**	**f [Hz]**	**ψ [rd]**
14m/s, Q_1=121kvar, Q_2=35.7kvar, P_1=P_2= -285kW				
1.	1248	0.0094	481	1.59
2.	577		49.9	0.238
8m/s, Q_1=66.7kvar, Q_2=-13.4kvar, P_1=P_2= -52kW				
1.	1226	0.0094	481	1.58
2.	106		49.8	0.027

In the case of constant capacitor reactive power Q_c and variable wind, transients' time constant and frequency were unchanged. Current amplitude and reactive power before (Q_1) and after (Q_2) wind speed change varied (Table 1). Switching on additional capacitors for more accurate reactive power compensation would strongly influence the transients parameters.

Table 2. Transients' parameters for different trafo P_n

Signal com. [No.]	**I [A]**	**τ [s]**	**f [Hz]**	**ψ [rd]**
P_n = 0.5 MW				
1.	805	0.0178	381	1.58
2.	312		49.8	0.208
P_n =1 MW				
1.	1238	0.0095	481	1.58
2.	311		49.8	0.128
P_n =2 MW				
1.	1789	0.0049	588	1.576
2.	310		49.9	0.063

For constant wind speeds transients' parameters are strongly influenced by system and generator parameters.

Table 2 shows estimated parameters of *signal components* using the same Prony model and symbols as previously (Table 1). Similarly, the Fourier transform of current shows two components (Fig. 6). However, the results are less accurate, then Prony estimation. Especially the amplitude and time constant of decaying transient can not be properly indicated by Fourier transform (Fig. 6).

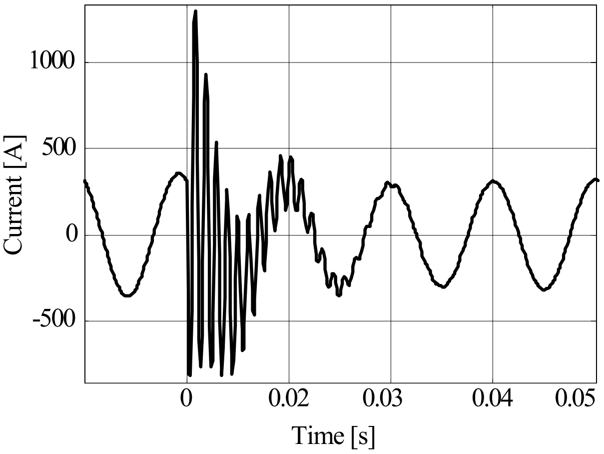

Fig. 5. Current waveform by capacitor switching

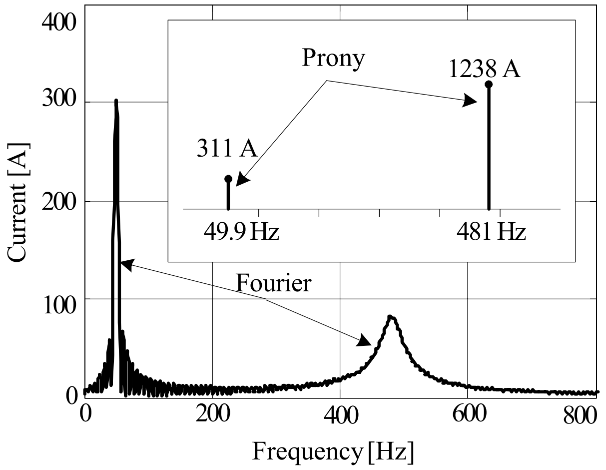

Fig. 6. Fourier vs. Prony spectrum estimation

For low transformer rated power (P_n=0.5 MW) the time constant was more then three times higher then for P_n=2 MW, so the transient duration was longer. On the contrary, the amplitude of transients for P_n=0.5 MW was 805 A and for P_n=0.5 MW 1789 A – more then twice as high. Additionally, the transient phase was computed. In similar way the change of other system parameters influence the transients.

Accurate transients' parameters estimation using Prony method is helpful in assessment of power quality and pointing out possible resonances.

CONCLUSION

This paper presents simulation of a power system with wind generator with capacitor bank. Switching on capacitors causes transients, which are dangerous for insulation, measurement transformers and other power system elements. Transients can also lead to resonance. Additionally, power quality indices are affected. Assessment of transients' parameters enables introducing of appropriate countermeasures and error free operation of power system. Prony method enables accurate estimation of amplitude, time constant and frequency of transient. The influence of wind speed changes and system parameters on switching transients was analyzed. Application of Prony method for transient assessment is more accurate than using Fourier transform.

REFERENCES

[1] T. Hammons, 2005, "Status of Integrating renewable electricity production in Europe into the grids", *Proceedings Universities Power Engineering Conference*, Cork, Ireland, p.73

[2] Z. Hanzelka, M. Mroz, R. Pawelek, K. Pitek, 2006, "Quality Parameters of 15kV supply voltage after connection of wind farms-case study", *Proceedings Conference on Harmonics and Quality of Power*, Cascais, Portugal, on CD, paper ID 124

[3] G. Quinonez-Varela, A. Cruden, A. D. Grant, A. Castaneda, 2001, "Electrical Integration Assessment of Wind Turbines into Industrial Power System: The Case of a Mining Unit", *Proceedings IEEE Power Tech Conference*, Porto, Portugal, paper ID DRS3-292

[4] Ch. Chompoo-inwai, L. Wei-Jen, P. Fuangfoo, M. Williams, J. R. Liao, 2005, "System Impact Study for the Interconection of Wind Generation and Utility System", *IEEE Trnas. on Industry Applications,* vol. 41, 163-168

[5] IEC 61400-21 Wind turbine generator systems. Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines.

[6] A. Tabesh, R. Iravani, 2005, "Transient Behavior of Fixed-Speed Grid-Connected Wind Farm", *Transactions International Conference on Power Systems Transients*, Paper No. IPST05-068

[7] T. Thiringer, 1996, "Power Quality Measurments Performed on a Low-Voltage Grid Equipped with Two Wind Turbines", *IEEE Trans. on Energy Conversion*, vol. 11, 601-606

[8] T Lobos, J. Rezmer, H.-J. Kolin, 2001, "Analysis of Power System Transients using Wavelets and Prony Method", *Proceedings IEEE Power Tech Conference*, Porto, Portugal, paper ID EMT-103

[9] The Matworks, 2006, *SimPowerSystems User's Guide*, The Math Works Inc.

[10] Z. Lubosny, 2003, *Wind Turbine Operation in Electric Power Systems*, Springer Verlag, Berlin Heidelberg

[11] SIEMENS, 1987, *Electrical Engineering Handbook*