Asynchronous Generator Behavior after a Sudden Load Rejection

Waldemar Rebizant, Member, IEEE, and Vladimir Terzija, Senior Member, IEEE

Abstract-- In the paper load rejection test, performed at a hydro power plant in Sweden, equipped with asynchronous generators, is described and analysed from the electromechanical transient processes and signal distortions points of view. During the test voltages and currents at shunt capacitor and generator terminals are digitised, recorded and thereafter off-line processed. Two adaptive methods are applied for signal processing: the Newton-Type Algorithm (NTA) and the Adaptive Fourier Filter (AFF) Scheme. The features of both methods during nominal frequency conditions and severe frequency changes and signal distortions are investigated. It is proved that the adaptive approach proposed is well suited for voltage and current measurements when the signal frequency changes in a wide range.

Index Terms-- asynchronous generator, transient analysis, load rejection, frequency, distortions, adaptive measurements.

I. INTRODUCTION

In the paper an asynchronous generator (ASG) is investigated during load rejection test. The measurements are performed at a small hydro power plant in Knisslinge, Sweden. The main goal was to analyze the transients and ASG behavior after a sudden load rejection, i.e. after its sudden disconnection from the external grid. The transients are analyzed through digital processing of recorded voltages. As expected, signals processed were distorted and frequency modulated. At the very beginning of the transient the generator mechanical driving power remains constant, thus the difference, the so-called power of inertia, accelerated the generator’s shaft speed. That means that the expected distortions of signals are determined during off-nominal frequency conditions and during the rapid frequency changes. The importance of described experiments has grown up since the use of ASGs in the production of wind energy [1, 2].

In modern power plants, microprocessors are commonly used in protection, monitoring, control and measurement devices. Each microprocessor is programmed with the suitable numerical algorithm (software) providing the desired function. The review of modern signal processing algorithms that are usually used can be found in [3]. Unfortunately, most of the traditional estimation algorithms are designed to operate at the nominal power system frequency (within a narrow margin around 50 or 60 Hz). This makes them inadequate for applications when the frequency may vary in a wider range. In this paper two efficient adaptive wide-frequency band algorithms are proposed for the processing of recorded data and for the simultaneous estimation of signal power spectrum and frequency. The Total Harmonics Distortion (THD) factor is further calculated from the harmonics measured in the first algorithm stage. In the paper the load rejection test is described (section II), followed by presentation of the adaptive estimation methods and discussion of the results obtained (section III).

II. LOAD REJECTION TEST DESCRIPTION

The experiment investigated in this paper is the load rejection test at an asynchronous (ASG) generator. In the test the generator was loaded to 10-20% (or more) of rated load, then the generator breaker was tripped. As the breaker opens, the electrical torque goes to zero and the turbine accelerates the generator. This causes an increase in frequency before the turbine governor controls the turbine output. This test is often done to determine the inertia constant of generator and turbine, which is an important parameter for multi-machine electrical power system dynamic models. In this paper the test results are used to analyze the frequency behavior and harmonic content of the ASG terminal signals.

A. Measuring System

As a measurement unit a multi-channel Daqbook 200, which allows up to 16 inputs with 16-bit A/D conversion, was used. The sampling frequency was set to \( f_s = 2.0 \text{ kHz} \) (\( N=40 \) samples per 50 Hz cycle). The Daqbook was connected to the parallel port of a portable PC. Two inputs were used for voltage and current measurement. The inputs had industrial “5B-modules” for signal conditioning and galvanic isolation. Data acquisition was initiated short time before the load was rejected from the generator. The recorded data were later on off-line processed.

B. Knisslinge Test

Knisslinge is a small hydro power plant in southern Sweden. Fig. 1 shows the test setup at Knisslinge. The station is equipped with two standard induction motors operating in the generator mode. This is a common practice in smaller power plants, typically with ratings of less than 1 MVA. The rated voltage is 400 V, the rated power 440 kVA, the power factor 0.84 and speed 760 rpm at rated data. The generator is
connected to the 10 kV bus via a step-up transformer with a circuit breaker at the low voltage side.

An induction generator, contrary to a synchronous machine, is not equipped with a separate excitation system. The magnetization current of the rotor (i.e. the reactive power) is taken from the power system to which the generator is connected [4]. In order to improve the power factor of the generator, it is often equipped with shunt capacitors (SC). Three delta-connected capacitors with total rating of 150 kVAr compensate for approximately half of the reactive power that the generator draws at the rated operating point. In the steady state the reactive power needed by the generator is taken both from the capacitors and the network. A strong external network helps to keep the voltage constant at the generator terminal.

In this test only generator G1 from Fig. 1 was disconnected from the external grid. The test started at \( t = 1.79 \) s. The recorded ASG voltage is presented in Fig. 2. After load rejection the voltage magnitude is slowly decreasing. At the same time the frequency is going up. The harmonic content is changing as well. A short (enlarged) segment of the recorded ASG and SC voltages and currents is presented in Figs. 3 and 4, respectively. Severe distortions of the signals recorded can be noticed. During the transient the harmonic content was changing, in particular after the instant of load rejection. The detailed spectral estimation and analysis of voltages from Figs. 3 and 4 are presented in the next sections of the paper. Due to the limited space the results of current processing are omitted from the paper.

III. Algorithm Description and Tests

The global block diagram of data processing is depicted in Fig. 5. Two-stage measurement process is performed. First, the fundamental frequency components and harmonic content of input signals (recorded voltages) are determined. In the second step the total harmonic distortion factor \( THD \) is calculated.

By even rough analysis of recorded signals presented in Figs. 3 and 4, one concludes that generator frequency has to be estimated from distorted signals. Additionally, the frequency of input signals varies in a wide range, therefore making estimation of signal amplitude and spectrum a challenging task. Below two approaches for the adaptive measurement are presented, followed by the selected results obtained.

A. NTA Method

For the purpose of voltage and current spectra estimation, the Newton Type Algorithm (NTA) was developed and presented in [5]. The NTA algorithm considers the system frequency as an unknown signal-model parameter to be estimated. This solves the problem of the algorithm sensitivity to frequency changes. With the introduction of the power frequency into the vector of the unknown model parameters, the signal-model becomes non-linear and the strategies of non-linear estimation are used.

The developed NTA algorithm is an efficient nonlinear estimator. It is based on an advanced mathematical model of the input signal. Let us assume the following observation model of the measured signal \( s(t) \) (arbitrary voltage, or current), digitized and recorded at the measurement location:

\[
s(t) = h(x,t) + \xi(t)
\]

where \( \xi(t) \) is a zero mean random noise, \( x \) – a suitable time varying parameter vector to be estimated and \( h(x,t) \) – nonlinear function of time and unknown model parameters, expressed as follows:
\[ h(x,i) = \sum_{k=1}^{M} C_k \sin(k\omega r + \theta_k) \] (2)

The vector of unknown parameters is \( x = [\omega, C_1, \ldots, C_M, \theta_1, \ldots, \theta_M] \). Its dimension, i.e. the model order, is \( n \cdot 1 \), where \( n = 2M + 1 \). For example, if \( M = 5 \), then \( n = 11 \). The model order depends on the application and the nature of the signal to be processed. \( C_k \) and \( \theta_k \) are the amplitude and phase angle of the \( k \)-th harmonic, respectively, whereas \( \omega \) is frequency. One of the key assumptions here is that the unknown parameters (i.e. the unknown vector \( x \)) are constant in the measurement data window. The estimates are derived from the measurement vector \( s \), containing \( m (m > 2M + 1) \) uniformly sampled signal values, recorded with the sampling frequency \( f_s \), during a finite period of time \( T_{dw} \). The calculations are based on the following vector equation:

\[ \hat{x}_{n+1} = \hat{x}_n + J_n^s (s - \hat{h}(\hat{x}_n)) \] (3)

where: \( \hat{x} \) is the vector of estimated unknown model parameters, \( \hat{h}(\cdot) \) is the nonlinear signal model, \( J^s \) is the pseudoinverse matrix of the Jacobi matrix (its elements are the first derivatives of the signal model through the unknowns) and \( n \) is the iteration (time) index. The parameter vector estimated at the step \( n \) is updated at each next iteration, i.e. within each new data window (step \( n+1 \)). As shown in [5], the algorithm has excellent convergence properties. The order of convergence is \( 2 \) and the duration of convergence is no longer than the length of the data window \( T_{dw} \). The algorithm must be initialized with an initial guess for \( x_0 \). It is reasonable to select the initial frequency value equal nominal 50 (or 60) Hz, whereas the initial spectrum may be calculated with FFT algorithm. Once initialized, NTA algorithm is robust enough to estimate the unknown parameters during fast and slow transients in power systems.

The NTA algorithm was simultaneously applied to three-phase signals (voltages and currents). The data window length was selected to be \( T_{dw} = 80 \text{ms} \).

**B. The \( \Delta \theta \) (\( \Delta N \)) – Based Adaptive Fourier Filter Scheme**

The procedure of measurement with Adaptive Fourier Filters (AFF) can be represented by the block diagram shown in Fig. 6. Signal amplitude and spectra are calculated with use of orthogonal components of fundamental and harmonic components obtained at the output of a number of filters tuned up to selected base frequencies.

In order to remove or minimize estimation errors in case of application of the scheme for wide frequency band measurements (e.g. for generator protection), it is necessary to adapt the orthogonal filters to the actual frequency (ies) of the signals. It is realized by the following procedure:

- determine the number of samples in one period of input signals \( N \) (directly or by signal coarse frequency estimation),

- set the filter data window length to \( N \) and modify filter coefficients (i.e. the filter impulse responses).

Such a type of adaptation has already been suggested by the authors in [6]. The new approach presented here uses similar principles to the method presented before. The difference lies in the manner of adapting the filter window lengths and in frequency calculation algorithm. Instead of determining the deviation from power frequency, here the signal frequency itself is coarsely estimated according to the formulae:

\[ f = \frac{1}{2\pi T_s} \arccos \left( \frac{1}{2} \frac{u(n-2p)u(n-p)-u(n)u(n-3p)}{u(n-p)u(n-p)-u(n)u(n-2p)} \right) \] (4)

With the input signal \( u \) unfiltered the eq. (4) remains somewhat sensitive to possible signal distortions, however, which is of great importance, assures very fast response to signal frequency changes. With the value of \( f \) from (4) the actual length of fundamental frequency period can be found:

\[ N_n = \frac{T_n}{f_s} \] (5)

Determined number \( N_n \) is usually not a discrete value and thus can not be directly used for updating the filters’ DW length \( N \). The direction of frequency changes can be known by calculating the difference between previously set discrete value \( N \) and obtained number of \( N_n \):

\[ \Delta N = N - N_n \] (6)

The procedure of upgrading DW length is then as follows:

\[ \begin{cases} \Delta N < -1 \rightarrow \text{increment } N \text{ by } 1 \\ \Delta N > 1 \rightarrow \text{decrement } N \text{ by } 1 \\ \Delta N = -1 \rightarrow \text{no change of } N \end{cases} \] (7)

According to the results of (7) the data window length of the filters used is always extended (or compressed) to the

![Fig. 6. Block scheme of the \( \Delta \theta \) – based adaptive estimator.](image-url)
actual value of $N$ (for full cycle filters). Provided the algorithm (9) is further used for amplitude calculation, the actual value of delay $k$ has to be newly set as well. Keeping in mind that $p$ should be an integer number, its updating is only possible after four consecutive changes of $N$ in one direction (up or down), i.e. only when $N/4$ becomes integer.

C. Amplitude and Spectrum Measurement Equations

For measurement of signal amplitudes (e.g. voltage $U$) the following digital algorithms are usually used:

$$U^2(n) = u_c^2(n) + u_s^2(n)$$

$$U^2(n) = \frac{1}{\sin(p\omega_1 T_s)} \left( u_c(n-p)u_c(n) - u_s(n-p)u_s(n) \right)$$

where $u_c, u_s$ are voltage phasors (of fundamental or any other frequency component to be measured) at the orthogonal filter outputs (for instance full-wave Fourier cosine and sine ones), $\omega_1$ is the angular fundamental frequency (to be substituted for $k\omega_1$ if $k$-th harmonic amplitude is estimated), $T_s$ is the sampling period and $p$ is a number of delay samples (chosen from the range $1 \ldots N/4$).

The features of algorithms (8) and (9), including their frequency responses, are thoroughly discussed in [7]. It is obvious that the estimators in both versions deliver correct values of measured quantities only when the signal frequency is equal to its nominal value for which the estimators were designed. When the frequency changes, certain measurement errors appear, either constant or oscillatory, depending on the estimator type. This is a result of inadequate filter gains that had been set for other signal frequency. The adaptation procedure proposed is applied here to make the measurement insensitive to signal frequency changes and thus more accurate in off-nominal frequency conditions.

For signal frequency measurement the following digital algorithm was used [7]:

$$f = \frac{1}{2\pi p T_s} \cos^{-1} \left\{ \frac{1}{2} \left( 1 - u_c(n-2p)u_s(n) - u_s(n-2p)u_c(n) \right) \right\}$$

Having the amplitudes of particular frequency components determined with (8) or (9), the total harmonic distortion factor is then calculated according to:

$$THD = \sqrt{\frac{\sum_{k=2}^{n} U_k^2}{\sum_{k=1}^{n} U_k^2}}$$

Only the odd harmonic components from 3$^{rd}$ to 13$^{th}$ (150 – 650 Hz) have been taken into account by calculation of THD.

D. Measurement Results with NTA Method

In Fig. 7 the ASG fundamental voltage amplitude, harmonics, THD and frequency estimated from the voltage signal are presented. The results obtained for the NTA algorithm are further compared with that for the second measurement scheme (AFF).

As depicted in Fig. 7, at the instance of load rejection, a step change of the reactive power flow through generator causes a step change in the fundamental voltage amplitude. Later on damped amplitude decrease is determined by the slowly disappearing of ASG reactive energy. Due to a huge load-generation imbalance, the generator accelerates. The acceleration is proportional to the magnitude of power imbalance and inversely proportional to the generator size, defined by the generator inertia constant $M = 2H$ (s).

Within short period of time the ASG frequency (angular speed) rises up to over 70 Hz, which would cause significant difficulties for the standard algorithms to measure the signal parameters in such a non-stationary off-nominal frequency conditions (see Fig. 10 in section E). Contrary, the proposed
non-linear estimation method based on NTA algorithm is able
to calculate the signal spectrum (harmonic amplitudes and
THD factor) with reasonable accuracy. The oscillations on the
curves in Fig. 7b,c are an effect of rapid changes in the signal
spectrum, including quickly decaying fundamental
component, increase of signal frequency as well as transients
of the estimation process itself.

The estimated amplitudes, THD factor and frequency of the
SC voltage signal are shown in Fig. 8. It is seen that in this
case the signal frequency remains almost constant, changing a
little only at the moment of load rejection. Signal variations
are small (capacitor voltage increases step-wise), the harmonic
content rises by 50%, mainly because of changing level of the
7th harmonic component.

E. Application of the ∆N-adaptive Scheme (AFF)

The results of estimation of fundamental frequency as well
as harmonic components of the ASG voltage signal with the
AFF scheme are presented in Fig. 9. The amplitude
calculations were done with algorithm (9). The signals \( u_c, u_s \)
in (9) are orthogonal components of given phasors (fundamental frequency, harmonics) for which the amplitude
is to be estimated. Signal frequency measured with (10) refers
to the signal fundamental frequency component. The
orthogonal quantities for considered frequency components
(1st, odd harmonics from 3rd to 13th) were obtained with
frequency-adapted full-cycle sine and cosine filters. The data
window of the filters were appropriately extended or
compressed on-line according to the coarsely estimated signal
frequency. Amplitude averaging (over 60ms) is additionally
applied to smooth out the measurement results. With the filter

![Fig. 8. Capacitor bank (SC) voltage parameters estimated with the NTA
algorithm: a) fundamental frequency component, b) amplitudes of harmonics,
c) THD factor, d) signal frequency.](image_url)

![Fig. 9. ASG voltage parameters estimated with the AFF algorithm:
a) fundamental frequency component, b) amplitudes of harmonics, c) THD
factor, d) signal frequency (ASG terminal voltage as input signal).](image_url)
From Fig. 9 it can be noticed (frequency measurement) that for the voltage signal at the ASG terminals the adaptation is really necessary. According to the coarse estimate of signal frequency (step-wise changing curve in Fig. 9d) the filter parameters are being changed. Significant improvement (reduce of oscillations and steady-state errors) is obtained for all measured values when the adaptation is on (compare Fig. 10 for adaptation switched-off). The procedure described provides frequency resolution equal 1/N, which is four times better than presented in [6]. Thus the filter windows become better tuned and the measurement errors are much lower.

Apart from somewhat greater transient peaks in harmonics and THD curves at the moment of load rejection (sudden signal changes) the results obtained for both estimation methods are comparable. Some additional ripples on the estimation curves (e.g. for 7th harmonic and THD) are a result of adaptation and dynamic switching between consecutive window lengths of the filters applied. The main difference between NTA and AFF results lies in the resolution of signal spectrum (THD) estimation for higher frequency deviations. The calculated value of THD decreases after load rejection, however, it starts to increase after 3.5 sec, since the amplitude of fundamental frequency component is lower and lower by almost constant harmonic content.

To illustrate the influence of adaptation on the measurement accuracy, in Fig. 10 the results of ASG voltage, for the case when the adaptation of filters and algorithm equations is off, is presented. The estimation errors (increasing with frequency deviation) are especially large for harmonics and THD measurement. Amplitude of the fundamental frequency component is also calculated with increasing error, approaching 40–50% for higher frequencies. Signal frequency calculations are relatively less distorted, however, significant oscillations appear when the frequency deviation exceeds 10 Hz.

In Fig. 11 the comparative analysis of the AFF and standard (non-adaptive) measurement results are presented in quantitative form, considering the AFF outcomes as accurate ones. The relative estimation error for the fundamental frequency component amplitude of ASG terminal voltage is given in Fig. 11a, while the relative error of THD factor measurement is shown in Fig. 11b. Though the results shown in Figs. 7a and 9a look quite similar, the relative measurement error of voltage amplitude after load rejection reaches considerable values, increasing up to 40% with changing signal frequency. Same applies to the results of THD measurement, however in this case the relative error is as high as 3000–4300%, which means that the values measured with non-adaptive algorithm are a few dozen times higher than they are in reality. This confirms that in off-nominal frequency conditions the adaptation of filters and measurement equations...
is really indispensable, especially when signal spectrum (harmonics, THD factor) is to be estimated.

IV. CONCLUSIONS

A sudden disconnection of asynchronous generator from the external grid is followed with the severe frequency acceleration, generator output voltage magnitude changes and signal distortion effects. Non-linear effects and interaction between shunt capacitor and generator introduce distortions in generator voltages and currents which is shown and discussed in the paper. The challenging problem of simultaneous estimation of the signal frequency and spectrum is with success solved by application of both NTA and AFF techniques. The main advantage of the two methods of adaptive measurement over the standard algorithms is the possibility of accurate estimation of signal parameters under non-stationary and off-nominal frequency conditions. Both the NTA and AFF schemes assure good accuracy of measurement and possibility of simultaneous tracking of signal amplitude and frequency for the cases when the signal parameters (amplitude, spectrum, and frequency) are changing rapidly. Thus the methods proposed might be successfully applied in fast digital protection and control equipment dedicated to synchronous and asynchronous generation units.

Further research on the adaptive measurement schemes proposed will concentrate on checking the possibility of their real-time hardware implementation. The results of the studies will be presented in next papers.

V. REFERENCES


VI. BIOGRAPHIES

Waldemar Rebizant (M’2000) was born in Wroclaw, Poland, in 1966. He received his M.Sc. and Ph.D. degrees (both with honors) from Wroclaw University of Technology, Poland in 1991 and 1995, respectively. Since 1991 he has been a faculty member of Electrical Engineering Faculty at the WUT. In June 1996 he was awarded Siemens Promotion Prize for the best dissertation in electrical engineering in Poland in 1995. In 1999 he was granted a prestigious Humboldt research scholarship for the academic year 1999/2000 (spent at the University of Stuttgart, Germany). In the scope of his research interests are: digital signal processing and artificial intelligence for power system protection purposes.

Vladimir V. Terzija (M’95, SM’2000) was born in Donji Baraći (ex-Yugoslavia) in 1962. He received his B.Sc., M.Sc. and Ph.D. degrees in Electrical Power Engineering from Department of Electrical Engineering, University of Belgrade, Yugoslavia, in 1988, 1993 and 1997, respectively. In 1988 he joined University of Belgrade, where he was an assistant professor teaching courses in Electric Power Quality, Power System Control, Electromechanic Transient Processes In Power Systems and Estimation Techniques in Power Engineering. In 2000 he was a Research Fellow at the Institute of Power Engineering, Saarland University, Saarbruecken, Germany, granted by Alexander von Humboldt Foundation. Since 2001 he has been employed with ABB Calor Enag Mittelspannung, Ratingen, Germany as an expert for protection, control and monitoring of medium voltage switchgear. His areas of scientific interest are power system protection, control, planning, electric power quality and DSP applications in power systems.