ISSN: 2251-9246
EISSN: 2345-6221
pp.73:78

Online Inertia Constant and Thévenin Equivalent Estimation Using PMU Data

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Abstract

In this paper a new algorithm based on phasor measurements for estimating the Thévenin Equivalent (TE) and system inertia constant is proposed. The method estimates the network TE seen from a generator terminal and equivalent system inertia constant by means of phasor data that is available at Phasor Data Concentrator (PDC) center. It is shown that the parameters of the TE could be estimated at any system condition, but the value of system inertia constant is available only after some disturbances. The algorithm is tested on a standard Nine-Bus test system in different conditions. Results show that this method can efficiently estimate the TE both in steady-state and transient conditions as well as system inertia constant.

Keywords Thevenin Equivalent, System Inertia Constant, Phasor Measurement Units; Wide Area Measurement;

1. Introduction

One of the main applications of Wide Area Measurement Systems (WAMS) is online monitoring of system parameters in order to estimate the system states or equivalent that is used for different studies such as estimating the generators power production capability, backup protection of transmission lines and power system stability margin. The main feature of WAMS is synchronized measurement in its infrastructure available from Phasor Measurement Units (PMUs) which normally installed in some power system buses.

Many applications in recent years are introduced for WAMS implementation in power system. In [1] authors propose a new method for modeling the distribution loads by means of PMU measurements. The online zero sequence impedance estimation of transmission-lines is stated in [2], which could be very useful for backup high impedance earth fault protection. In [3] a new algorithm based on phasor measurements and discrete wavelet transformation is developed to detect the unstable low frequency oscillations in power system. Some others use PMU measurements and state estimation for predicting the system stability [4]. The approach of state estimation by PMU data is also another applications proposed in some researches [5].

The network TE from a generator terminal in the power system helps the system operators to analyze the online system stability [6]. In addition, the increasing dynamic nature of the advanced power systems obliges the system operators to know the system inertia constant in order to predict the system frequency responses in case of large disturbances.

Some recent studies are proposed some novel methods to estimate the TE and system inertia constant. In [7], an improved recursive method that was tested on IEEE 14-Bus test system is stated. In addition, a model based on PMU local measurements is proposed in [8]. Three consecutive phasor measurements of voltages and currents, recorded at one location, are used in [9] which a new algorithm for online tracking of TE parameters based on PMU measurements is proposed. In [10], the accuracy of the proposed algorithm is examined on New-England 39Bus (NE39) test system. A new approach to estimate the system inertia constant through simulations is developed in [11] based on phasor and frequency measurements. Knowing the TE and system inertia constant is useful for reducing the total system into two machine model in order to voltage and transient stability studies [12].

In this paper, a new method based on analyzing the data received from PUMs in PDC center is proposed to estimate the TE parameters and system inertia constant. In this method, the TE is calculated from generator terminal based on active and reactive power measurement. The system inertia constant also is estimated after a disturbance based on Rate of Change of Frequency (ROCOF) value which is available at PMU output. In addition, the PMU module also is simulated with its low-pass filters and its real phasor calculation and reporting rate.

In the second part, the PMU structure is proposed. In section three, the concept of proposed algorithm and in section four the results from simulations are declared. The results show that the algorithm could be used for estimation the TE and system inertia constant of the power system for online applications.

1. PMU Simulation

PMU Structure

Fig. 1 shows a typical PMU module and its main components. The analogue signals measured by current and voltage transformers are input to an analogue anti-aliasing filter where are sampled with an adequate frequency ($48kHz$ in most industrial PMUs). IEEE C37.118 standard states a complete inspection about phasor measurement requirements. This standard defines two classes of performances, named as class P and class M. For application with fast responses requirements, class P is suitable while class M is used for measurement purposes in which greater precision is needed [13].

B) phasor calculation

The phasor value $X(i)$ of a given set of samples of a power signal $x(i)$ can be calculated at the i^{th} sample as:

$$X_{(i)}^{k} = \frac{1}{N}\sum_{n=-N}^{N} x_{(i+n)} exp\,(-j\frac{k\pi(i+n)}{N}) \qquad (1)$$

Where:

k: Harmonic order ($k=1$ for principle harmonic)

N: Filter half order (number of filter taps is equal to $2\times N$)

$x(i)$: Signal value at sample i

The $exp\,(-j\frac{k\pi(i+n)}{N})$term in (1) is Euler's equation and indicates the multiplication of input signal, $x(i)$ by quadrature oscillator (sine and cosine) wave.

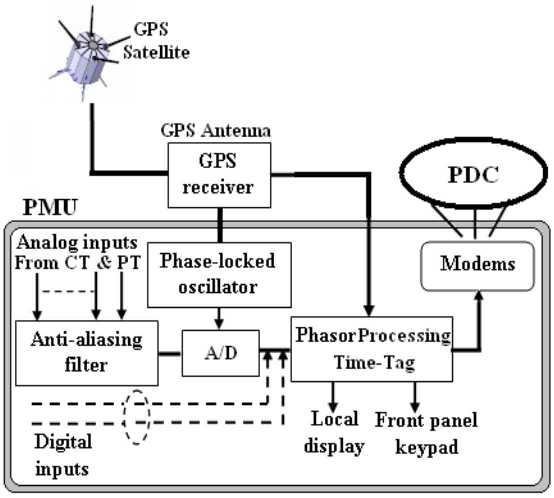

Fig. 1. PMU phasor signal processing structure

C) Time and synchronization communication

PMU calculates the instantaneous phase angle of power signal by calculating its phase relative to a cosine function synchronized with Coordinated Universal Time (UTC). Therefore, a time source input is required. It may be supplied from a time broadcast system such as GPS and it can follow from various protocols such as 1PPS or IRIG-B time coding standard.

All measurements are reported at a constant rate F_S, which is an integer number of times per seconds. Table I is listed standard reporting rate for a $50Hz$ system. However, greater reporting rateis allowed, but it is not recommended because it may lead to excessive data accumulation in PDC center.

Table.1.
Standard PMU reporting rate for 50Hz power system

Frequency*(fps)*	50Hz power system		
F_S	10	25	50

In this paper, for protection purposes, a value of F_S equal to $50fps$ is selected for reporting rate.

2. Concepts of the proposed algorithm

TE estimation

Suppose a generator which is connected to a power system as shown in Fig. 2 for generator $G1$.

The purpose of network TE estimation is to reduce the total system to a single machine connected to a voltage source with V_{th} voltage and X_{th} impedance as one depicted in Fig. 3 for the TE seen from generator $G1$ terminal.

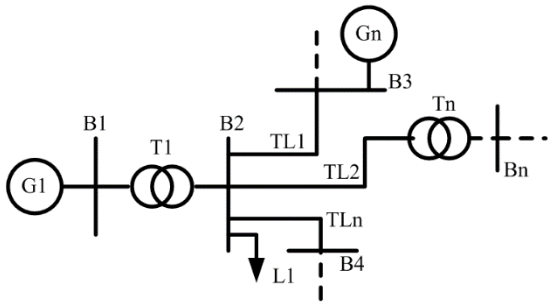

Fig. 2. Power system model

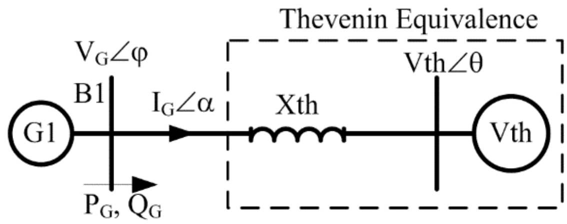

Fig. 3. TE seen from generator G1 terminal

The aim of TE is to find X_{th} and V_{th} in Fig. 3, while in this paper, the real part of Thévenin impedance is considered as negligible. According to quadrature axis theory, following phasor diagram can be obtained as:

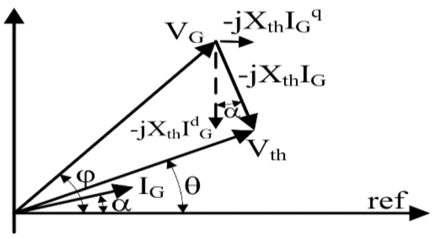

Fig. 4. Phasor representation of TE

Where I_G^q and I_G^d are generator quadrature and direct currents. According to Fig. 4 and by separating the real and imaginary parts, it can be said that:

$$V_G sin\varphi - V_{th} sin\theta = X_{th} I_G cos\alpha \quad (2)$$

$$V_G cos\varphi - V_{th} cos\theta = -X_{th} I_G sin\alpha \quad (3)$$

In TE shown in Fig. 3, the total active and reactive power delivered to the network from generator $G1$ terminal can be calculated from (2) and (3) as:

$$P_G = \frac{V_G V_{th}}{X_{th}} \sin(\varphi - \theta) \quad (4)$$

$$Q_G = \frac{V_G}{X_{th}} (V_G - V_{th} \cos(\varphi - \theta)) \quad (5)$$

From (4) and (5) and by taking the Thévenin voltage as reference vector, the value of V_{th} could be calculated as:

$$V_{th} = \frac{P_G V_G}{Q_G sin\varphi + P_G cos\varphi} \quad (6)$$

and X_{th} could be obtained from:

$$X_{th} = \frac{V_G^2 sin\varphi}{Q_G sin\varphi + P_G cos\varphi} \quad (7)$$

For estimating the V_{th} and X_{th} both single-phase P_G and Q_G should be available which can be calculated from phasor values of PMU measurements as:

$$P_G = V_G I_G \cos(\varphi - \alpha) \quad (8)$$

$$Q_G = V_G I_G \sin(\varphi - \alpha) \quad (9)$$

This algorithm is used for estimation of TE of generator terminal in power system. In the first step and at each time step, the P_G and Q_G are calculated from (8) and (9) then, the V_{th} and X_{th} are computed from (6) and (7).

B) System inertia constant estimation

The swing equation of a single generator i is defined as:

$$\frac{2H_i}{f_n}\frac{df_i}{dt} = (P_m^i - P_e^i)^{pu} = \Delta P_i^{pu} \quad (10)$$

Where H_i is the i^{th} generator inertia constant in seconds, f_i is the frequency of the i^{th} generator at its terminal, f_n is the system nominal frequency, P_m^i and P_e^i are mechanical input and output power respectively. The system equivalent inertia constant H_{sys} is defined as:

$$H_{sys} = \frac{\sum_{i=1}^{n}(\frac{1}{2}J_i\omega_s^2)}{\sum_{i=1}^{n} S_n^i} = \frac{\sum_{i=1}^{n}(S_n^i H_i)}{\sum_{i=1}^{n} S_n^i} \quad (11)$$

Where, S_n^i and J_i are i^{th} generator apparent power and inertia respectively. It should be noted that ω_S is nominal angular frequency which is constant for all generators in the system and $H_i = (\frac{1}{2}j_i\omega_s^2/S_n^i)$. Substituting H_i from (10) in (11) resulted in:

$$H_{sys} = \frac{\sum_{i=1}^{n} S_n^i \left(\frac{f_n \Delta P_i^{pu}}{2\frac{df_i}{dt}}\right)}{\sum_{i=1}^{n} S_n^i} \quad (12)$$

In (12), the value of $\frac{df_i}{dt}$ is the Rate of Change of Frequency (ROCOF) value for i^{th} generator which is available at PMU output. Therefore, the H_{sys} can be evaluated from:

$$H_{sys} = \frac{1}{2} f_n \frac{\sum_{i=1}^{n}\left(\frac{\Delta P_i}{ROCOF_i}\right)}{\sum_{i=1}^{n} S_n^i} \quad (13)$$

The value of H_{sys} from (13) should be calculated immediately after disturbance before generator control systems such as AVRs or governors will be operated. During this condition, the value of P_m^i will be equal to its previous values before disturbance. The disturbance can be either load switching or fault depending on the system type.

3. Simulation and Results

The standard Nine-Bus test system shown in Fig. 5 is used to simulate the algorithm functionality. The power network are simulated in DigSILENT software in time domain and it is supposed that there is a PMU installed at every generator terminal to report required phasors and ROCOF value .All measurements are reported with a rate of $20ms$ to the control center.

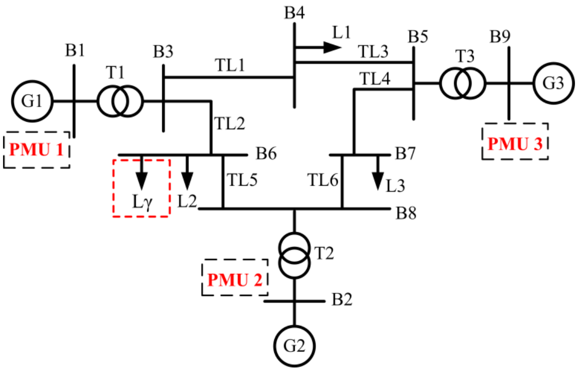

Fig. 5. The standard Nine-Bus test system

All transmission lines have a resistance equal to $4.5\Omega/km$ and an inductance equal to $121.2mH/km$ with a length of $1km$. All transformers voltage ratio is $20kV/400kV$ with a short circuit reactance equal to12.5% based on $400MVA$. The active and reactive powers of transmission loads L1, L2 and L3 are $(100MW, 35MVAR)$, $(125MW, 50MVAR)$ and $(90MW, 30MVAR)$ respectively. A virtual load named L_γ equal to $1.25MW$ and $0.05MVAR$is added to Bus-B6 for disturbance modelling.Simulations are performed in two scenarios as steady-state and load disturbance. In all scenarios, the system pre-disturbance conditions are the same and system is in steady-state operation with all components in service.

C) Steady-state condition

As mentioned before, in steady-state condition, the TE parameters can be calculated online from (6) and (7), but the value of system inertia constant cannot be evaluated. For more realistic results a white Gaussian noise is also embedded to the measured signal with a high signal to noise ratio. Results are depicted in Figs. 6 and 7 for V_{th} and X_{th} respectively.

TE parameters seen from $G2$ and $G3$ terminals are shown. As seen, the value of $V_{th}$is near to 1pu in steady-state condition which is acceptable as in the steady-state condition the system voltages and states are near to the nominal value. In addition, a value equal to 0.46Ω is obtained for X_{th} from $G3$ terminal and 0.65Ω from $G2$ terminal. The exact values for X_{th} which are obtained from offline multiple load flow approach in DigSILENT software are equal to 0.459Ω and 0.818Ω for $G3$ and $G2$ respectively.

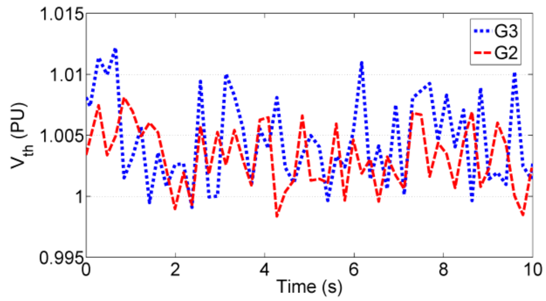

Fig. 6. Thévenin voltage in case of steady-state condition

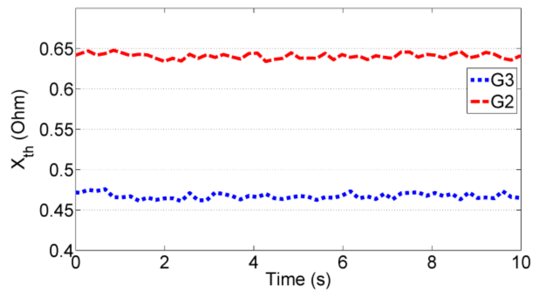

Fig. 7. Thévenin impedance in case of steady-state condition

D) Load Disturbance (load entrance)

The load L_γ at Bus-$B6$ is switched-on at $t = 1s$ by closing its circuit breaker. The generators meet a change in their output active and reactive powers and system frequency to reach a new stable operating condition. The network TE parameters seen from$G2$ and $G3$terminals (Buses $B2$ and$B9$) before and after disturbance are shown in Figs. 8 and 9 for Thévenin voltage and impedance respectively.

As seen, the value of V_{th} is facing with some disturbances which is due to system dynamic responses. The value of X_{th} also is decreased after load entrance which is due to decreasing in the system equivalent impedance. System equivalent inertia constant which is estimated from (13) is shown in Fig. 10 for this case.

As stated before, the value of H_{sys} that is obtained at some times after disturbance should be accounted for the equivalent system inertia. In this scenario, a value near to 17s is obtained as seen from Fig. 10. It then decreased to the 15s after some oscillations. The reduction in the value of H_{sys} in this time is because of plant control systems such as AVRs and governors which affect the system frequency. However, this value is not the exact value and the corrected value is about 17s.

E) Load Disturbance (load rejection)

In this scenario, the load L_γ at Bus-$B6$ is disconnected at $t = 1s$ by opening its circuit breaker.

Some transient states will be imposed to the system states and frequency. Figs. 11 and 12 show the TE parameters estimated at $G2$ and $G3$ terminals. The estimate value of system inertia constant is also shown in Fig. 13.

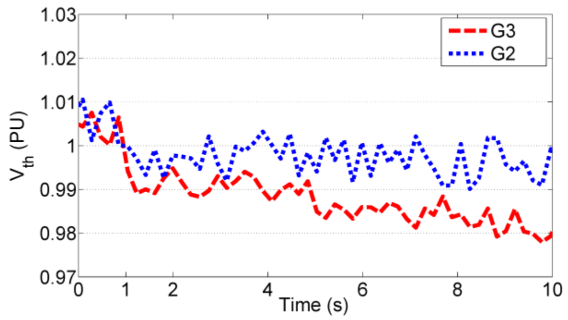

Fig. 8. Thévenin voltage in case of load entrance

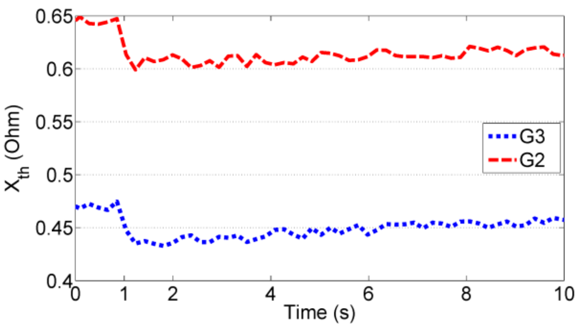

Fig. 9. Thévenin impedance in case of load entrance

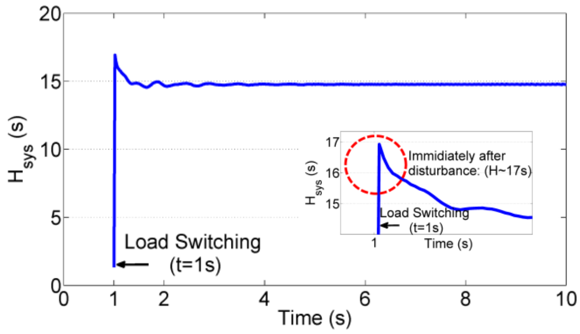

Fig. 10. System inertia constant estimation in load disturbance (entrance)

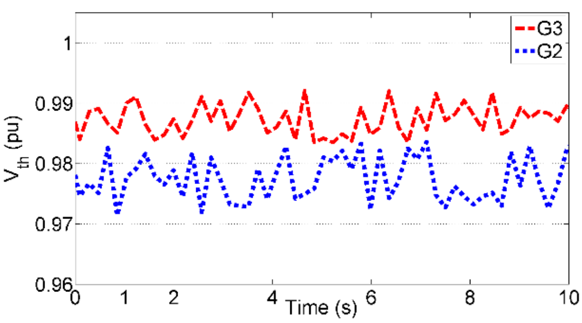

Fig. 11. Thévenin voltage in case of load rejection

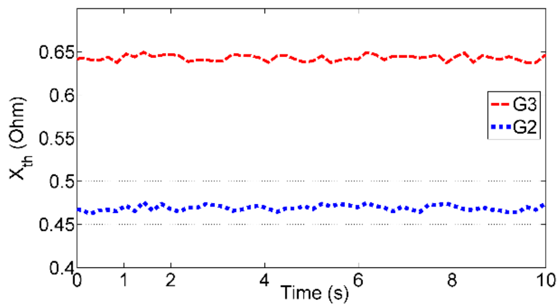

Fig. 12. Thévenin impedance in case of load rejection

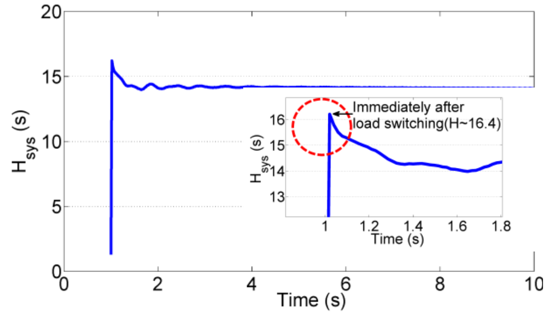

Fig. 13. System inertia constant estimation in load disturbance (rejection)

As seen from Figs. 11, 12 and 13, the obtained results are same as previous scenario. This means that while the system states do not have significant changes, the proposed method is independent of disturbance type or location of the system and is able to find the TE parameters and equivalent inertia with an acceptable precision.

4. Conclusion

A new algorithm based on PMU measurement of generator terminal voltage and current phasors for calculating the TE parameters and system equivalent inertia in the control center was presented. The algorithm was tested on a standard Nine-Bus test system for different scenarios. However, the results of the algorithm are acceptable and can be used in power system studies when the system frequency does not change abnormally. It is recommended that for a better performance, the algorithm will be tested on a real network and real PMU data.

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