Estimation of rotor angle based on operating variables measured by PMU

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Abstract

The rotor angle of generators is an important element for estimating stability of synchronous generators and dynamic stability in power systems. Rotor angel has an electro mechanic nature; therefore it can not be measured via electric measurement units. A possible way for rotor angle estimation is the other electric parameters of generator. This paper investigates a possibility for estimation of rotor angle in the time frame of transient stability of electric power systems in real time. The proposed dynamic state estimation technique is based on using voltage and current phasors obtained from a phasor measurement unit supposed to be installed on the extra –high voltage side of the substation of a power system.

Introduction

Extending of the power system, consumers growth and the great need for economical operation in recent years, has caused the security of power systems to become very noteworthy. Transient stability is the ability of the power system to maintain synchronism, when subjected to sever transient disturbances such as a sudden loss of supply or outage of load. The response to this kind of disturbance involves sever oscillations of rotor angle, active power, bus voltage and some other variables. Therefore, it may cause large excursions of rotor angle and is influenced by non-linear power-angle relationship. Stability depends on the initial operating state of the system and the severity of the disturbance. The system usually alters after the disturbance, which may cause the system to operate in a different steady-state status from that prior the disturbance [1].

An introduced method for estimation of the rotor angle of a constant magnetic generator is referable in [2]. If we consider the non-linear variables of generator unknown, in [3] a method for estimation of rotor angle based on measurable variables like voltage, current, active and reactive power is introduced. In [4], the approach using artificial neural networks (ANN) to estimate and predict rotor angles based on phasor measurement unit (PMU) quantities, is enhanced and investigated in depth. The [5] has made an effort on rotor angle estimation based on fuzzy logics. In [6] although, the inner variables of generator such as load angle, have been estimated by a non linear estimator. The [7] aims to replace the center of inertia (COI) for on-line transient stability assessment and then proves that it is not an accurate method in a large scale power system. Also in [7], an estimation method using the derivative of active and reactive power, has been investigated; which has caused the estimation to be severely affected while changing of power value; such that a little measurement error may cause a large deviation in estimated rotor angle. The [8] has presented a new method which is designed to detect the rotor position at standstill and also low speeds in WPMBLDC motor. The [9] presented a technique to calculate the absolute position of the initial rotor angle of a non-salient pole PM motor. By applying voltage pulses that partially drive the stator iron into saturation the absolute position of the rotor can be measured for a given pole pair. A new method for rotor angle estimation of a synchronous generator with unknown dynamic parameters from commonly available signals in online measurements such as electrical power, reactive power, terminal voltage, field current and field voltage, following a small perturbation of the field voltage, is described in [10]. Simple and robust estimator based on the DDF has been proposed in [11] for estimating the rotor angle of synchronous generators in the power system. The proposed approach utilizes the measured field voltage available from the generator and the terminal measurements obtained from the PMU.

In this paper, we evaluate generator's rotor angle oscillations. Despite their strong effect on the electrical behavior of generators, generators' rotor angle has a mechanical nature which is not measurable directly by PMU. For this reason, rotor angle should be estimated from the electrical operating variables measured by PMU. For a given generator, at each time instant, based on the amplitude and phase angle of the generator terminal voltages ($V\angle\theta$) and generators output current ($I\angle\varphi$) measured by PMU, rotor angle can be estimated. The generators terminal voltage and current phasors can be measured by PMU in real time using the wide area measurement (WAM) techniques with respect to an arbitrary reference bus (slack bus).

Rotor angle estimation algorithm

The equivalent generator represents the aggregated effects of components in the multi-machine power system. Ignoring the subtransient variables of power system, we can illustrate electrical variables by the phasor diagram of Fig.1.

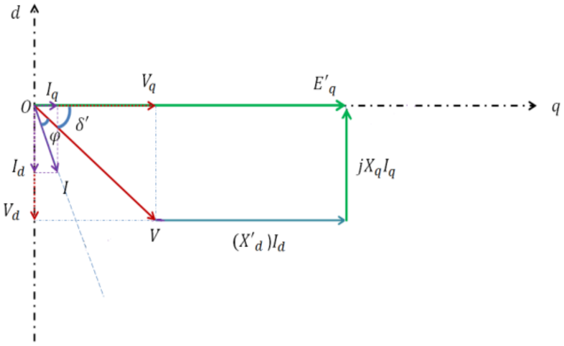

Fig. 1. Equivalent system's voltage-current phasor diagram

where:

δ': rotor angle of the generator with respect to its local terminal voltage
V_t: magnitude of the generator terminal voltage measured by PMU
I_a: magnitude of the generator current measured by PMU
φ: phase angle of the generator current with respect to its terminal voltage measured by PMU

$V_d = X_q \;\, I_q$

$$V_t\, sin(\delta') = X_q\ I_a\ cos(\delta' + \varphi)$$

$$V_t\, sin(\delta') = X_q\ I_a\ \times [\, cos(\delta').cos(\varphi) - \ sin(\delta').sin(\varphi)]$$

$$[V_t +\ X_q\ I_a\ sin(\varphi)] \times sin(\delta') = \left[X_q\ I_a\, .cos(\varphi)\right] \times cos(\delta') \qquad (1)$$

By dividing both sides of Eq. (1) to $cos(\delta^{'})$ it yields Eq. (2) from which generator rotor angle with respect to its terminal bus can be estimated.

$$Tan(\delta') = \frac{X_q\ I_a\, .cos(\varphi)}{V_t + X_q\ I_a\ sin(\varphi)} \qquad (2)$$

Where:
$\delta^{'}$: rotor angle of the generator with respect to its local terminal voltage
V_t: magnitude of the generator terminal voltage measured by PMU
I_a: magnitude of the generator current measured by PMU
φ: phase angle of the generator current with respect to its terminal voltage measured by PMU
Having estimated rotor angle of each generator (i) with respect to its terminal voltage, the rotor angle with respect to the network reference bus (slack) and reference machine (connected to the slack bus) are evaluated by Equation 4 and Equation 5 respectively.

$$\delta_{iS} = \theta_i + \delta_i' \qquad (3)$$

$$\delta_{iR} = \delta_R' - \delta_{iS} \qquad (4)$$

Where:
$\delta_i^{'}$: rotor angle of generator i with respect to its terminal bus (#i) estimated by Eq. 3
$\delta_R^{'}$: rotor angle of reference machine with respect to its terminal bus (slack) estimated by Eq. 3
θ_i : the phase angle of the generator terminal voltage with respect to the network reference bus (slack) measured by PMU.
δ_{iS} : rotor angle of generator i with respect to network reference bus (slack).
δ_{iR} : rotor angle of generator i with respect to system reference machine

Simulation

To validate the accuracy of the proposed algorithm, it is performed on the generators of IEEE-39 bus system, in which bus 40 and generator 39 are the reference bus and reference machine. In section 3.1 the outage of line 17-27 and in section 3.2 the three phase to ground fault on line 8-9 on third second are applied as disturbances on the system. At the end of each section the estimated rotor angle is compared to the actual values calculated by time domain simulation carried out by Power Factory@ software which are regarded as measured values by PMU.

Simulation results of outage event of line 17-27 in IEEE – 39 bus system

In this section, the outage of line 17-27 is applied to the system as disturbance on third second. The exited line will not be brought back to the system. Following this fault, the variation of rotor angle of generator 35 with respect to its local bus(bus#35), network's slack bus(bus#40) and reference machine (G39) are estimated by proposed technique and compared with the actual values. The result of comparison is illustrated in table 1. Fig. (2) shows rotor angle of generator G35($\delta_{35}^{'}$) with respect to its terminal voltage (Bus35) estimated by Eq. (2), in comparison with the actual value which is calculated by time domain simulation using Power Factory$^{@}$ software.

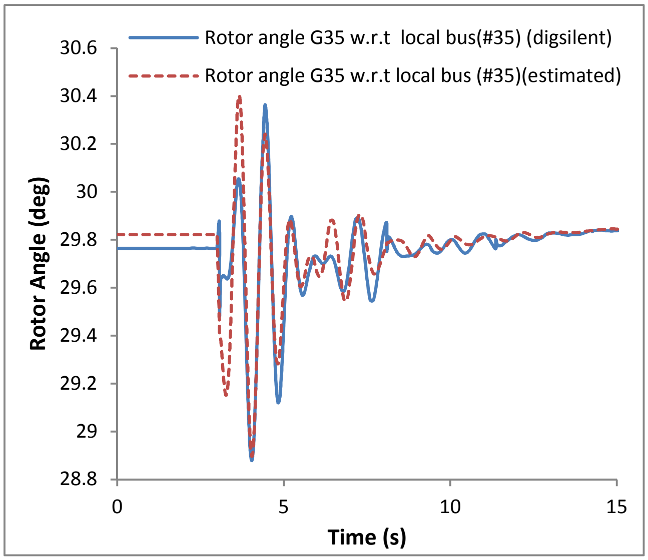

Fig.2. Estimated rotor angle variation of G35 with respect to its local bus compared to the actual value

The rotor angle of generator G35 with respect to slack bus (#39) and reference machine (G39), are estimated as follows:

$$\delta_{35S} = \theta_{35} + \delta'_{35} \tag{5}$$

$$\delta_{35R} = \delta'_{39} - \delta_{35S} \tag{6}$$

Where:
δ'_{35}: Rotor angle of generator G35 with respect to its terminal bus (#35) estimated by Eq. (2)
δ'_{39}: Rotor angle of reference machine with respect to its terminal bus (slack) estimated by Eq. (2)
θ_{35}: Phase angle of terminal voltage of unit G37 with respect to the network's slack bus (#39) measured by PMU.

δ_{35S}: Rotor angle of generator G35 with respect to network's slack bus (#39).
δ_{35R}: Rotor angle of generator G35 with respect to system's reference machine (G39).
Fig. (3) and Fig. (4) show estimated rotor angle of generator G35 with respect to the network's slack bus and reference machine compared to the actual values calculated by the Power Factory@ software.

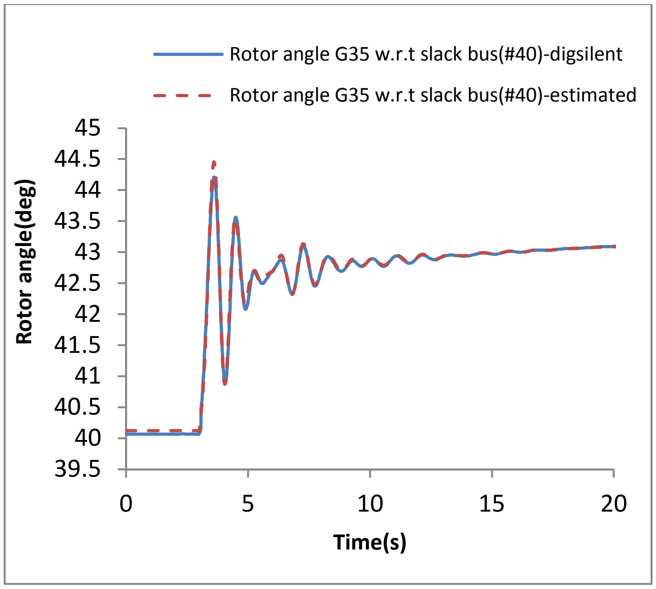

Fig.3. Estimated rotor angle variation of G35 with respect to slack bus #40 compared to the actual value

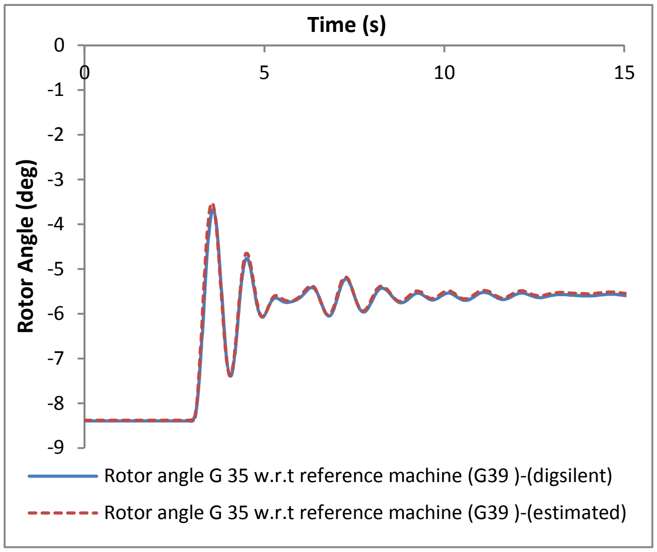

Fig.4. Estimated rotor angle variation of G35 with respect to reference machine G39 compared to the actual value

Equation 13 provides the possibility to calculate the percentage of difference between estimated rotor angle value and its actual value.

$$ERROR\% = \left|\frac{real\ \delta - estimated\ \delta}{estimated\ \delta}\right| \quad (7)$$

The result of error percentage in this type of fault can be seen as below:

TABLE1. PERCENTAGE OF DIFFERENCE BETWEEN ESTIMATED ROTOR ANGLE VALUE AND ITS ACTUAL VALUE

Rotor angle w.r.t to reference machine	**Rotor angle w.r.t to reference bus**	**Rotor angle w.r.t to local bus**	**Number of generator**	**Type of fault**
AVERAGE ERROR%	***AVERAGE ERROR%***	***AVERAGE ERROR%***		***Outage of line 17-27 Occurrence of fault on third second***
1.67	0.524	0.585	30	
1.646	0.165	0.174	31	
1.772	0.2108	0.245	32	
0.582	0.132	0.181	33	
0.404	0.219	0.253	34	
1.174	0.055	0.115	35	
0.705	0.085	0.127	36	
0.0643	0.0533	0.1091	37	
5.027	0.298	17.006	38	
-	0.418	0.139	39	

Simulation results of three phase short circuit event on line 8-9 in IEEE – 39 bus system

In this section, similar to section 3.1, bus 40 and generator 39 are reference bus and reference generator respectively. The fault here is a three phase short circuit on line 8-9, which occurs on third second and is cleared after 0.1 second by removal of the line due to the action of the protective relays. Following this fault, the variation of rotor angle of generator G35 with respect to its local bus (bus #35), network's slack bus (bus #40) and reference machine (G39) are estimated using Eq.(2)-Eq.(6) and compared with the actual values calculated by time domain simulation carried out by Power Factory@ software which are regarded as measured values by PMU.

Fig. (5) shows the rotor angle of generator G35 with respect to its terminal voltage (Bus35) estimated by Eq. (2), in comparison with the actual value which is calculated by time domain simulation using Power Factory@ software.

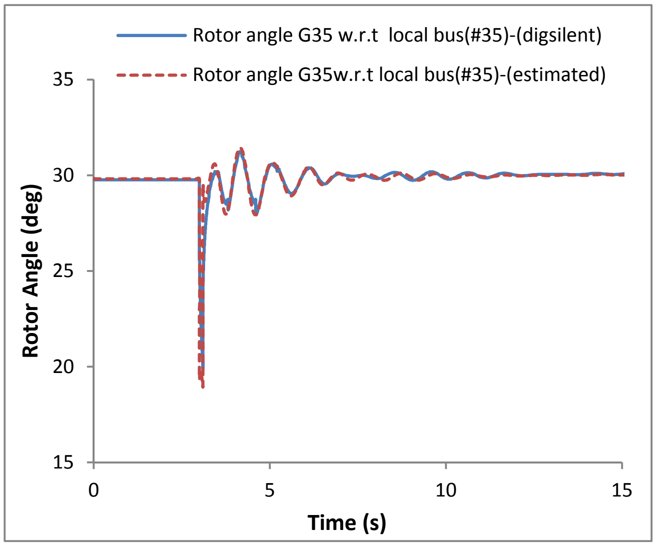

Fig.5. Estimated rotor angle variation of G35 with respect to its local bus compared to the actual value

Figs. (6) and (7) show the estimated rotor angle of generator G35 with respect to the network's slack bus and reference machine compared to the actual values calculated by the Power Factory@ software.

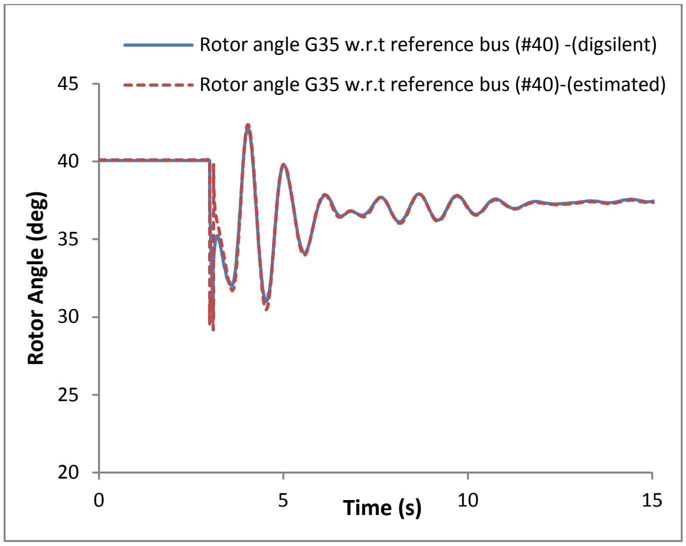

Fig.6. Estimated rotor angle variation of G35 with respect to slack bus #40 compared to the actual value

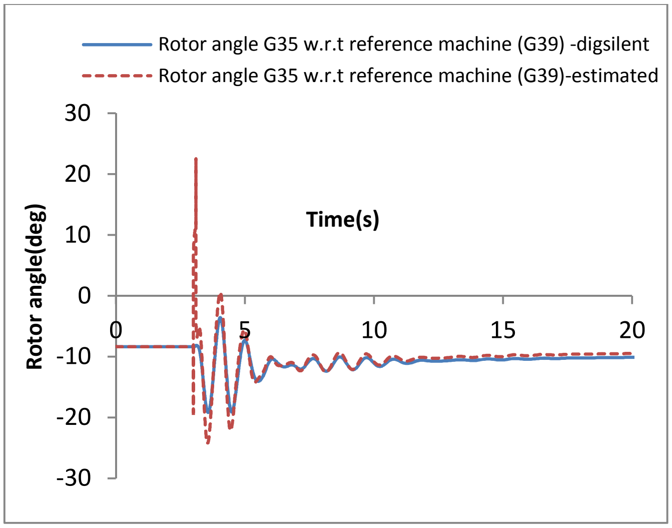

Fig.7. Estimated rotor angle variation of G35 with respect to reference machine G39 compared to the actual value

The result of error percentage in this type of fault can be seen as below:

TABLE2. PERCENTAGE OF DIFFERENCE BETWEEN ESTIMATED ROTOR ANGLE VALUE AND ITS ACTUAL VALUE

Rotor angle w.r.t to reference machine	**Rotor angle w.r.t to reference bus**	**Rotor angle w.r.t to local bus**	**Number of generator**	**Type of fault**
AVERAGE ERROR%	***AVERAGE ERROR%***	***AVERAGE ERROR%***		
417.36	42.67	36.586	30	***3 phase short circuit on line 8-9*** ***Occurrence of fault on third second*** ***Fault clearance on second 3.1***
42.703	4.86	4.914	31	
640.282	3.651	3.968	32	
58.202	1.943	2.028	33	
10.838	2.368	1.822	34	
17.977	2.1306	2.936	35	
93.068	6.258	3.736	36	
7.125	2.9409	3.557	37	
96.365	2.702	3.171	38	
	3.648	3.648	39	

Conclusion and future work

In this paper the use of TAN (δ) method on the analysis of the transient stability in the multi-machine power system has been investigated. The results of table 1 show that the accuracy of estimation for generators closer to the fault occurrence location, are less than others, meaning that the distance between generators and location of fault affects the accuracy of estimation. Using the local generator's data, such as current and voltage values, makes this method very easy and inexpensive.

In addition, the proposed technique potentially provides a new way to evaluate the impact of renewable energy sources on the power system transient stability. Because the common renewable energy sources do not have a rotor or direct electro-magnetic linkage between the rotor and the grid, it is difficult to quantitatively identify the severity of their impact. The proposed technique can be used to obtain a virtual rotor angle difference for renewable energy sources. This could enable new possibilities in power system transient stability related studies.

References

[1] Al Marhoon, H. H. (2011). A Practical Method for Power Systems Transient Stability and Security.

[2] Corley, M. J., & Lorenz, R. D. (1998). Rotor position and velocity estimation for a salient-pole permanent magnet synchronous machine at standstill and high speeds. Industry Applications, *IEEE Transactions on*, 34(4), 784-789.

[3] Sumina, D., Šala, A., & Malarić, R. (2010). Determination of Load Angle for Salient-pole Synchronous Machine. *Measurement Science Review*, 10(3), 89-96.

[4] Del Angel, A., Geurts, P., Ernst, D., Glavic, M., & Wehenkel, L. (2007). Estimation of rotor angles of synchronous machines using artificial neural networks and local PMU-based quantities. *Neurocomputing*, 70(16), 2668-2678.

[5] Darie, E., Cepisca, C., & Darie, E. (2009, June). Artificial neural networks applied to measurements rotor angle in a synchronous generator. *In 3rd Int. Conf. Eur. Computing Conf.*, Tbilisi, GA.

[6] Jiaomin, H. X. C. Y. L. (2003). Rotor Position Angle Estimation and Speed Control in SRD Using Fuzzy Logic Based Motor Model. *Electric Drive*, 5, 004.

[7] Wang, Z., Makram, E. B., Venayagamoorthy, G. K., & Ji, C. (2013). Dynamic estimation of rotor angle deviation of a generator in multi-machine power systems. *Electric Power Systems Research*, 97, 1-9.

[8] Moradi, H., Afjei, E., & Yazdi, M. S. (2010, June). Indirect rotor angle estimation in without permanent magnet brushless dc motor with employment of the Maxwell-Wien Bridge. *In Power Electronics Electrical Drives Automation and Motion (SPEEDAM), 2010 International Symposium on* (pp. 987-990). IEEE.

[9] Schmidt, P. B., Gasperi, M. L., Ray, C., & Wijenayake, A. H. (1997, October). Initial rotor angle detection of a nonsalient pole permanent magnet synchronous machine. *In*

Industry Applications Conference, 1997. Thirty-Second IAS Annual Meeting, IAS'97., Conference Record of the 1997 IEEE (Vol. 1, pp. 459-463). IEEE.

[10] Ghahremani, E., Karrari, M., Menhaj, M.B., & Malik, O.P. (2008). Rotor Angle Estimation of Synchronous Generator from Online Measurement. *In 43rd Int. UPEC Conference,* 2008.

[11] Tripathy, P., Srivastava, S. C., & Singh, S. N. (2010). A Divide-by-Difference-Filter Based Algorithm for Estimation of Generator Rotor Angle Utilizing Synchrophasor Measurements. Instrumentation and Measurement, *IEEE Transactions on*, 59(6), 1562-1570.

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