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Abstract—**two very important parameters especially in frequency stability analysis, are inertia constant and equivalent load damping constant of system. Equivalent inertia constant depends on inertia constant of synchronous machines in the grid and load damping factor depends on frequency sensitivity of load, especially induction motors. By appearing wide area monitoring systems (WAMS) based on phasor measurement units, equivalent system frequency response can be obtained with high accuracy. In this paper firstly, the equivalent frequency response is achieved by phasor measurements and then according to the transient and steady state characteristics of the frequency response, the inertia and load damping constants are estimated. The performance of proposed method in estimating the equivalent parameters of the system is investigated under different conditions. The developed method is implemented in IEEE 39-Bus dynamic test grid.**

Keywords-Estimation; Frequency response; Inertia constant; Load damping constant; Phasor measurement units

I. NOMENCLATURE

P_{mi}	Input mechanical power of generator *i*
P_{ei}	Electric power output of generator *i*
$\mathrm{H_i}$	Inertia constant of generator i
H	Equivalent inertia constant of the system
$\mathrm{f_i}$	Frequency of bus i
N_g	Number of generators
S_i	Apparent power of generator i
S	Equivalent apparent power of the system
d	Differential operator
t	Subscript of time instant
P_{m}	Total mechanical power of the system
P_e	Total electrical power of the system
P^{acc}	Accelerating power
P_g	Active generation by governor action
P_c	Generation deficiency caused by unit outage
D	Load damping constant
f_0	System nominal frequency
T	Governor time constant
R	Equivalent speed droop of governors
R_i	Speed droop of governor i
n	Counter of time step
Δt	Time step

II. INTRODUCTION

Stability of interconnected power systems is a major concern of network operators. Having a reliable and secure power system depends on stability of that system at all times. Stability of a power system refers to the ability of an electric network, for a given initial operating condition, to regain a state of equilibrium point in normal condition and after a physical disturbance, with most system variables bounded so that practically the entire system remains intact [1].

Power system stability usually includes rotor angle transient stability, rotor angle small signal stability, voltage stability and frequency stability.

In some kinds of stabilities knowing system parameters such as equivalent inertia constant and load damping factor is necessary.

Load frequency control as one of the power system common control method is done in three different layers including primary frequency control by power plants governor, secondary frequency control by means of automatic generation control(AGC) for minimizing the steady state error and the tertiary frequency control by means of replacement reserves. In normal condition that generated power is equal to consumed power (i.e. complete power balance), the frequency remains at its nominal value. Following an active power imbalance due to generation outage, the system frequency declines and in case of severe generation deficiency the resulted frequency decline may cause frequency instability and subsequent trips of power plants. Forecasting and estimating the changes of frequency following an event can be used for system studies such as frequency stability analysis and under frequency load shedding (UFLS) design.

The fundamentals of frequency stability and load frequency control are discussed in [1]. Appearing phasor measurement

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units (PMU) technologies have realized the dynamic monitoring of power system stability.

Wide area monitoring, protection and control (WAMPAC) systems can be designed and implemented by means of phasor measurement units. PMU placement has an important role in achieving WAMPAC purposes and functions. Locating PMUs usually is done to provide a reasonable degree of power system observability. By gathering phasor measurements throughout the system and transmitting this data for a phasor data concentrator (PDC) or an energy management system (EMS) the dynamic or steady state conditions of power system can be evaluated.

As an example monitoring of low frequency oscillations (LFO) is an important application of wide area measurement system [9]-[11].

The system frequency response can be determined (i.e. monitored) using frequency measurement by PMUs. Using the measured or recorded frequency responses some system parameters such as inertia and load damping constants can be estimated.

Few methods have been presented in previous studies, to estimate network parameters such as equivalent inertia and load damping constants. In [12] the inertia constant has been estimated using phasor measurements data without considering the activation of unit governors. In [13] the Kalman filter is used to estimate the frequency response of the system, and hence the estimation of the inertia constant parameter of the network. One of the common methods for estimating network parameters is to estimate the frequency response of a system using curvature fit methods based on phasor data as proposed in [14]. In previous studies, the simultaneous estimation of inertia and load damping constant has been ignored.

In this research, the system frequency response is determined using the discretized swing equation. The activation of governors and load damping are considered. Afterward using the transient and steady state characteristics of the developed system frequency response the system parameters are estimated.

It is noted that due to the lack of actual recorded system frequency response the swing equation is discretized and solved. Also, the system frequency response is expressed according to the center of inertia (COI) reference.

It should be noted that the estimation of these parameters is done in two different procedures including offline and online modes. In offline mode, it is assumed that the phasor measurement units store all the data related to the frequency response and the response is fully available. However, in the online estimation method, it is assumed that the complete frequency response is not available due to missing phasor data. In online estimation, the frequency response is firstly estimated using a given polynomial curve and secondly, the parameter estimation is done over the fitted polynomial curve.

The rest of this paper is organized as follows. In next section, the frequency response model is expressed based on the discrete time model on the COI reference. In section III, the proposed estimation model is presented.In section IV, the results of the simulations are presented and discussed. Finally, the paper is concluded in section V.

III. Frequency Response Modeling

Firstly, the swing equation model including the dynamics of governors and load damping is developed. This model is then linearized and discretized in time. The system frequency response is firstly presented for single machine model. Afterward, using the concept of center of inertia (COI), the model is generalized to the multi-machine system. In time discrete model, frequency is sampled in steps of Δt seconds and the resulted algebraic equations are solved in each time step.

The system frequency response based on the rotor swing equation is expressed as follows:

$$\frac{2H_i}{f_0}\frac{df_i(t)}{dt} = (P_{mi} - P_{ei}) \;, i = 1,2,\ldots,N_g \tag{1}$$

For a multi-machine system, the system frequency response can be calculated according to COI concept on a new power basis in terms of MVA as given in (2) and (3) [1].

$$S = \sum_{i=1}^{N_g} S_i \tag{2}$$

$$\frac{2H}{f_0}\frac{df(t)}{dt} = (P_m - P_e) \tag{3}$$

The equivalent COI frequency and inertia constant of the system are defined as follows:

$$f = \sum_{i=1}^{N_g} \frac{f_i H_i}{H} \tag{4}$$

$$H = \sum_{i=1}^{N_g} \frac{H_i S_i}{S} \tag{5}$$

Also to develop an equivalent system frequency response the equivalent mechanical and electrical powers of synchronous machines are introduced as given below:

$$P_e = \sum_{i=1}^{N_g} P_{ei}\frac{S_i}{S} \tag{6}$$

$$P_m = \sum_{i=1}^{N_g} P_{mi}\frac{S_i}{S} \tag{7}$$

For developing a discrete time model of system frequency response, the resulted swing equation including the generation deficiency caused by the unit outage, the governor dynamic and load damping is linearized as follows.

$$\frac{d\Delta f(t)}{dt} = \frac{f_0}{2H}\Delta P^{acc}(t) \tag{8}$$

According to the single bus model of swing equation, the accelerating power is expressed as follows:

$$\Delta P^{acc}(t) = \Delta P_g(t) - \Delta P_c - D\Delta f(t) \quad (9)$$

Also, the governor dynamic is formulated as given in (10).

$$\frac{\mathrm{d}\Delta \mathrm{P_g}}{\mathrm{dt}} = \frac{1}{\mathrm{T}}\left(-\Delta P_g(t) - \frac{\Delta f(t)}{R}\right) \quad (10)$$

Furthermore, equivalent droop of governor is obtained as follows:

$$\frac{1}{\mathrm{R}} = \sum_{i=1}^{N_g} \frac{S_i}{R_i S} \quad (11)$$

Let assume that the frequency and governor actions at the n^{th} time step (i.e. $n\Delta t$) are written as follows :

$$\Delta f(n\Delta t) = \Delta f_n \quad (12)$$

$$\Delta P^g(n\Delta t) = \Delta P_n^g \quad (13)$$

Euler's method is used to solve the discrete frequency response of the system. In this method, the mean gradient is considered in steps t_n and t_{n+1}.

The frequency response of the discrete system is described by using the modified Euler method as follow [17]:

$$RHS(t) \triangleq \frac{f_0}{2H}\Delta P^{acc}(t) \quad (14)$$

$$\Delta f_{n+1} = \Delta f_n + \int_{t_n}^{t_{n+1}} RHS(t_n, \Delta f_n) \quad (15)$$

Using the trapezoidal rule, the integral term given in (15) is approximated as follows:

$$\Delta f_{n+1} \simeq \Delta f_n + \frac{\Delta t}{2}[RHS(t_n, \Delta f_n) + RHS(t_{n+1}, \Delta f_{n+1})] \quad (16)$$

$$RHS(t_n, \Delta f_n) = \frac{1}{2H}\left(\Delta P_n^g - \Delta P^c - D\Delta f_n\right) \quad (17)$$

$$\Delta P_{n+1}^g = \Delta P_n^g + \frac{\Delta t}{T}\left(\frac{-\Delta f_{n+1}}{R} - \Delta P_n^g\right) \quad (18)$$

Before any outage (i.e. generation deficiency), the frequency of the system lies in its nominal value and there is no change in frequency. So the initial value of the frequency change is zero ($\Delta f_0 = 0$). By solving the above equations, the frequency Response of the network is obtained.

The purpose of the developed discrete model is to generate a reliable frequency response without utilizing any commercial transient stability software. Also due to lack of a recorded practical system frequency response, it is required to verify the efficacy of the estimation method over a full known test system.

A. The proposed estimation method

The overall structure of the proposed estimation algorithm has been illustrated in Fig. 1. According to Fig. 1, the estimation of system parameters including the system inertia and load damping constants is carried out in two different modes.

In the first mode, it is assumed that the frequency response of the network is completely available by accurate PMU devices. Therefore the system parameters can be estimated in an offline mode. In this condition, it is assumed that the PMU devices have been located throughout the network considering observability constraints.

In the second mode, it is assumed that the frequency response is not completely known. In other words some phasor measurements are missing. Therefore in this condition it is required to estimate the frequency response using limited number of frequency samples. To this end, the polynomial extrapolation curve with suitable order is utilized. After estimating the frequency response, system parameters can be estimated as done in the first mode. This method is used when the operator wants to study the network in an online mode. After choosing the offline or online procedures the second question is that the amount of generation deficiency is known or not? If the answer is yes, then the inertia and load damping constants can be estimated directly using (19)-(21). If the answer is No, first the amount of generation deficiency should be estimated using a suitable method. Assuming a wide area network of sensors or a state estimation program the amount of generation deficiency could be determined. In this paper it is assumed that the amount of generation deficiency is known.

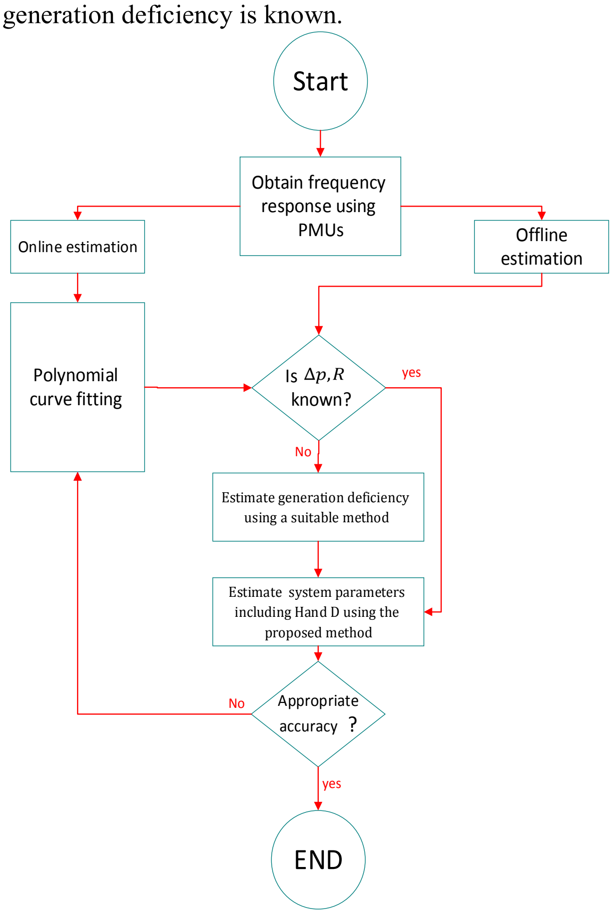

Figure 1. The overall structure of the proposed estimation algorithm

The rate of change of frequency (RoCoF), refers to the variation of frequency due to an imbalance between generation and load. The RoCoF value depends on the amount of inertia constant and the amount of generation deficiency.

The linearized swing equation is utilized for estimating the inertia and load damping constants as given below:

$$\frac{df}{dt} = \frac{\Delta P}{2H} \times f_0 + \frac{D}{2H} \times \Delta f \tag{19}$$

If the load damping constant (D) is assumed to be negligible, (19) is expressed as given in (20).

$$\frac{df}{dt} = \frac{\Delta P}{2H} \times f_0 \tag{20}$$

The transient regime of the frequency response is dominated by the inertia response. The steady state change of frequency could be obtained as given in (21). According to Fig. 2, the transient and steady state change of frequency are utilized to estimate the system parameters including inertia and load damping constants.

$$\Delta f_{ss} = \frac{\Delta P}{D + \frac{1}{R}} \times f_0 \tag{21}$$

The RoCoF value can be computed during the system frequency variations. However the first part of frequency response or transient regime is a good representative of the inertia response. The RoCoF value is calculated using the following equation:

$$\frac{df}{dt} = \frac{1}{N_s} \sum_{i=1}^{N_s} \frac{\Delta f_i}{\Delta t} \tag{22}$$

The number of cycles as the RoCoF window (i.e. N_s) may be selected from 5 to 10 cycles. In this paper the number of cycles has been assumed equal to 5.

IV. SIMULATION MODES

The performance of the estimation algorithm highly depends on the accuracy of the input data. In this paper the frequency response is generated by direct solution of swing equation. Afterward, the efficacy of the estimation algorithm is verified by comparing the actual and estimated values of system parameters. In this paper the proposed method is simulated over the IEEE 39-bus test system. The input data are as given in Table I.

The single line diagram of IEEE 39-bus test system has been illustrated in Fig. 3. This test system has 10 generators and 29 load points. The total load of the network at normal operating conditions is 3500 megawatts and the apparent power of each generator is equal to 500 MVA. Also, the power factor of each generator is assumed to be 0.85. The simulation results are presented in two different parts including offline and online modes.

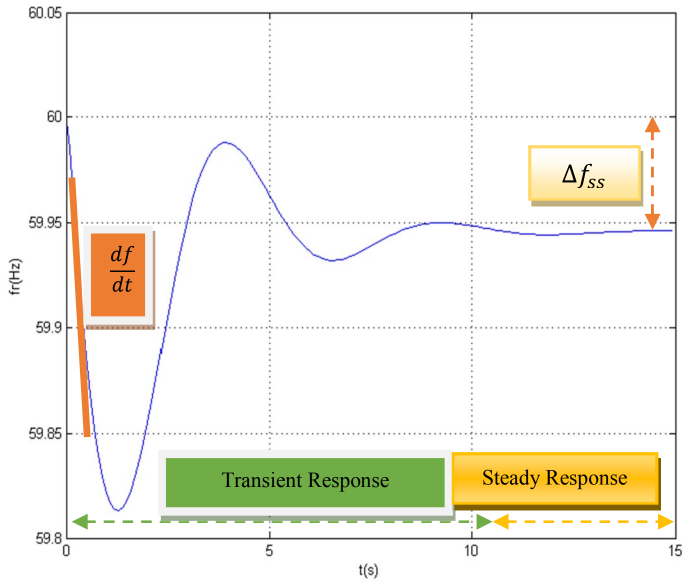

Figure 2. Transient and steady-state regimes of frequency response

Table I. Input parameters of the IEEE 39-bus test system

Parameters	Value
S	*5000MVA*
R	*0.02pu*
H	*5s*
T	*3.5s*

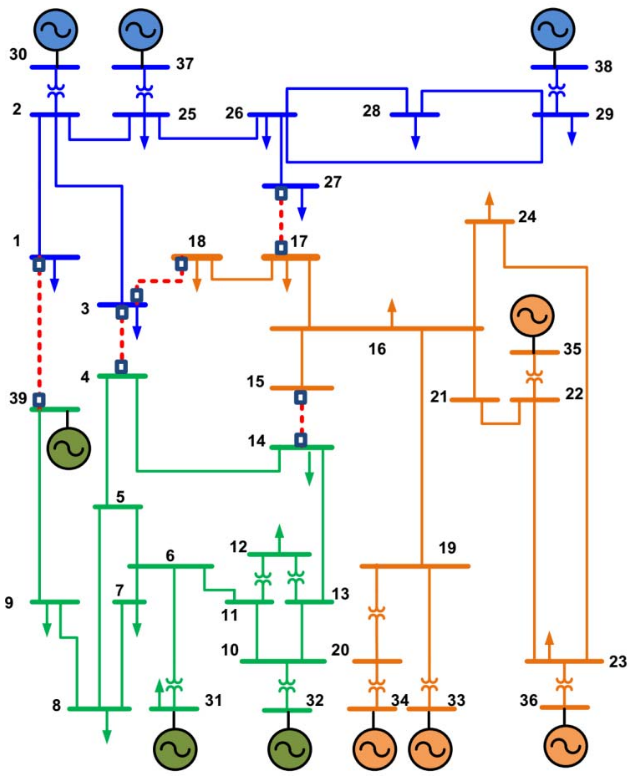

Figure 3. Single line diagram of the IEEE 39-Bus system

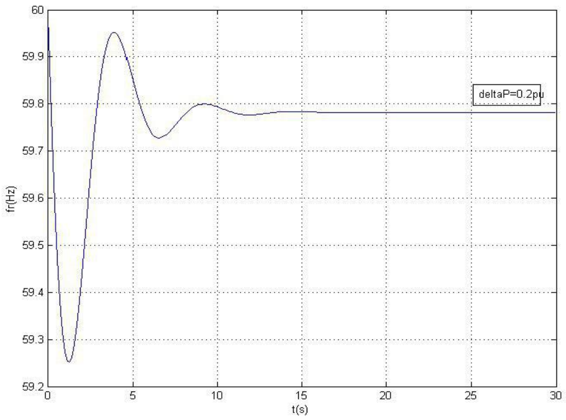

Figure 4. Frequency response curve assuming 0.2 Disturbance

A. Offline estimation of system parameters

In this simulation, the inertia constant of the system is assumed to be equal to 5 seconds, and the load damping constant is also assumed equal to 5. According to the proposed estimation algorithm, the frequency response under the disturbance ΔP = 0.2pu is obtained using the developed system frequency model as illustrated in Fig. 4.

Practically this response is obtained using PMU devices. At two points as t=0.1s and t=0.2s, the RoCoF value (i.e. the slope of the frequency variation) is calculated and then the inertia time constant, H, is obtained using (18).

The same procedure is carried out under the disturbance ΔP = 0.15pu. The simulation results are presented in Table II. In this part it is assumed that the value of load damping is known in prior.

B. Simultaneous estimation of inertia and load damping constants

In this part, first, using the steady state change of frequency the load damping constant is estimated. The value of H is then estimated using the transient regime of the frequency response.

In this step, the value of the load damping constant is assumed to be 3, as well as the value of H, as in the previous steps, is considered to be 5. Now, using the proposed method, the value of D is estimated, and then, by means of (18), the value of H is obtained. The frequency response using the input parameters is illustrated in Fig. 5.

Table II. Results of estimation for inertia constant under two different contingencies

The input disturbance (p.u.) (ΔP)	The actual inertia constant(s)	The estimated inertia constant (s)	The actual load damping constant
$\Delta P = 0.2pu$	5	5.0952	5
$\Delta P = 0.15pu$	5	5.095	5

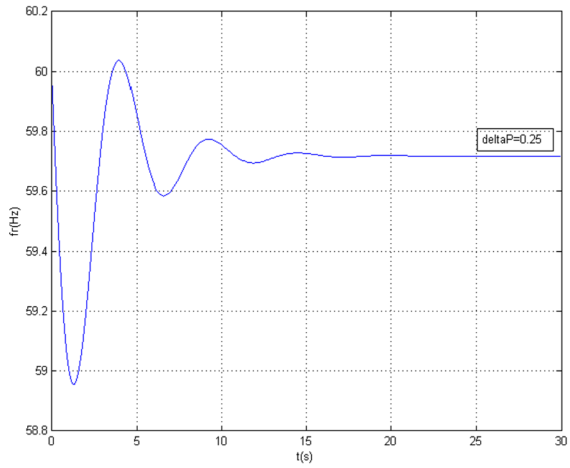

Figure 5. System frequency response under the contingency as
$$\Delta P = 0.25pu$$

Table III. Results of estimating system parameters under two different contingencies

The input contingency (p.u.)(ΔP)	The actual D	The estimated D	The actual H (s)	The estimated H (s)
$0.25pu$	3	3.003	5	5
$0.4pu$	5	4.919	5.092	5.099

In another scenario, the input contingency (i.e. generation deficiency) is assumed to be equal to 0.4pu and D is equal to 5. Also the value of inertia constant is assumed to be equal to 5.

The results of estimation have been reported in Table III. It can be seen that the accuracy of the estimation for both system parameters is under 1 percent.

C. Online estimation of inertia and load damping constants

In this section, it is assumed that only limited number of frequency samples are available by measuring devices and all the frequency response is unknown. Indeed, phasor measuring devices can provide approximately 12 to 15 phasors of each electric quantity per second. Therefore to have a better estimation it is required to generate a complete system frequency response. Frequency response can be determined using polynomial curves based on the least square error method (LSE). In this regard, it is assumed that an input contingency as ΔP = 0.25pu.

Also the equivalent inertia time constant is assumed to be equal to 5 seconds and load damping constant is equal to 3. Also it is assumed that frequency measurement are sampled from the system in steps of 0.1 second and the equivalent droop characteristic of governors is assumed as R= 0.02 p.u.

To generate such system frequency response, the complete system frequency response is obtained using the developed system frequency model and some frequency samples are then dropped from the response to generate an incomplete system frequency response. In other words, it is assumed that all samples of the frequency response are not available.

In this regard, using these samples, a suitable curve is fitted and then, according to the transient and steady state characteristics of the extrapolated frequency response, the inertia and load damping constants are estimated using polynomials of order 5, 13, 21 and 29. The obtained system frequency responses using different polynomial curves have been illustrated in Fig. 6 to Fig. 9. The results of estimations have been reported in Table IV. It can be seen that the proposed estimation algorithm gives accurate results in case of incomplete frequency response.

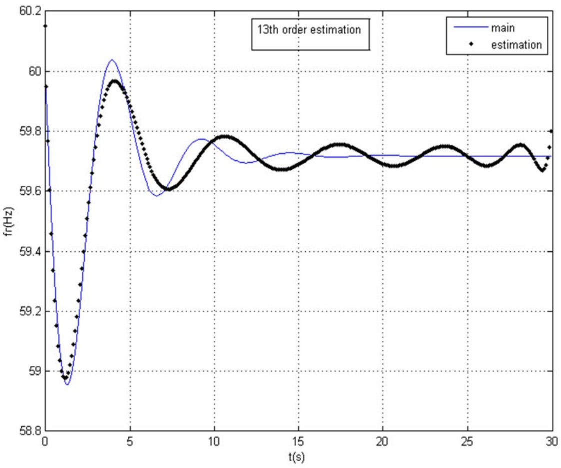

Figure 6. System frequency response estimated with a polynomial of order 13 under the contingency as $\Delta P = 0.25pu$.

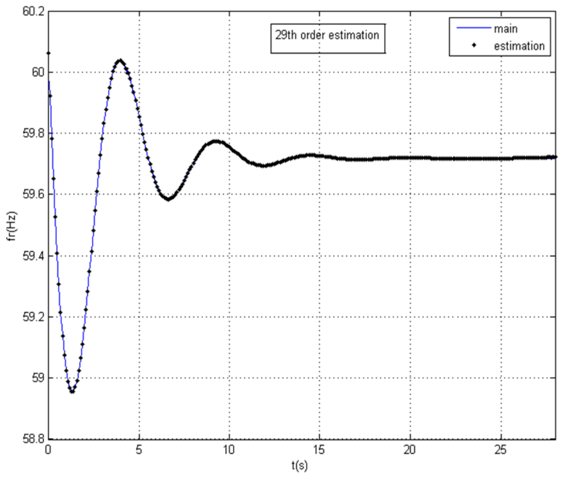

Figure 7. System frequency response estimated with a polynomial of ord In er 29 under the contingency as $\Delta P = 0.25pu$.

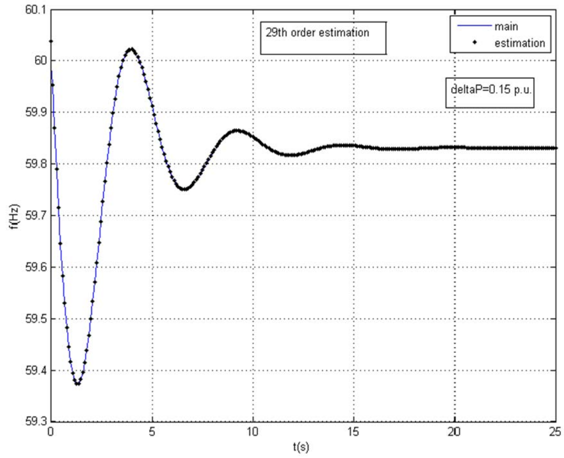

Figure 8. System frequency response estimated with a polynomial of order 29 under the contingency as $\Delta P = 0.15p.u.$

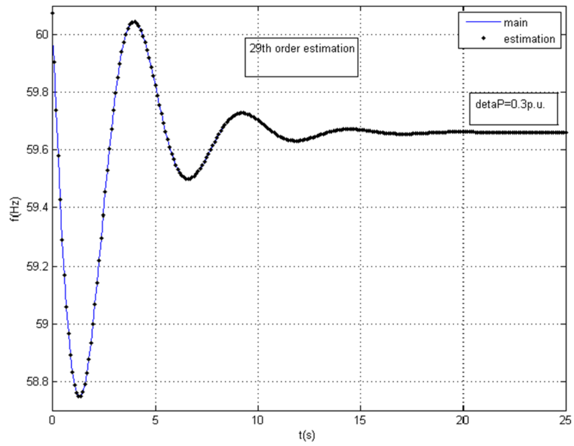

Figure 9. System frequency response estimated with a polynomial of order 29 under the contingency as $\Delta P = 0.3p.u.$

V. Discussion and Conclusion

In this paper, the estimation of system parameters including the inertia and the load damping constants were investigated in different conditions. It was shown that by measuring the transient and steady state characteristics of system frequency responses the system parameters can be estimated accurately. If all frequency samples are not available, the complete system frequency response can be determined by fitting a specific polynomial curve. The accuracy of the estimation in all simulated test cases were lower than 1 percent. To have a clear and fair verification of the performance of the proposed method, the swing equation were discretized and solved to generate a suitable system frequency response. Also, it was shown that to have an accurate estimation of system inertia it is required to utilize the RoCoF value measured at the transient

Table IV. Comparison of inertia and damping constant estimated with different polynomials

Polynomial degree	The inputted disturbance(p.u.) (ΔP)	The actual inertia constant(s)	The estimated inertia constant(s)	The actual load damping constant	The estimated load damping constant
5	0.25	5	38.874	3	3.763
13	0.25	5	6.19	3	1.194
21	0.25	5	5.96	3	2.817
29	0.15	5	4.951	3	2.941
	0.25	5	5.242	3	3.003
	0.3	5	4.9508	3	2.94

regime of the frequency response. The activations of governors and load damping were included in the developed system frequency response. It is noted that the activation of automatic generation control (AGC) as the secondary layer of frequency control will not affect the proposed method. Indeed the AGC action is decomposed from the primary response due to its slower time constant. Also the AGC is activated only for frequency changes caused by load perturbations (e.g. within $\pm 0.5\ Hz$ range). However some challenges still remain open for further researches. One of the challenges for the proposed method is the need to determine the amount of generation deficiency as the input contingency. In this paper it was assumed that the amount of generation outage or deficiency is known in prior.

REFERENCES

[1] Kundur, Prabha, John Paserba, Venkat Ajjarapu, Göran Andersson, Anjan Bose, Claudio Canizares, Nikos Hatziargyriou et al. "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions." *IEEE transactions on Power Systems* 19, no. 3 (2004): 1387-1401.J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Yan, Jie, Chen-Ching Liu, and Umesh Vaidya. "PMU-based monitoring of rotor angle dynamics." *IEEE Transactions on Power Systems* 26, no. 4 (2011): 2125-2133.

[3] Terzija, Vladimir, Gustavo Valverde, Deyu Cai, Pawel Regulski, Vahid Madani, John Fitch, Srdjan Skok, Miroslav M. Begovic, and Arun Phadke ."Wide-area monitoring, protection, and control of future electric power networks." *Proceedings of the IEEE* 99, no. 1 (2011): 80-93.

[4] Begovic, Miroslav, and Arturo Messina. "Wide area monitoring, protection and control." *IET Generation, Transmission & Distribution* 4, no. 10 (2010): 1083-1085.

[5] Karlsson, Daniel, Morten Hemmingsson, and Sture Lindahl. "Wide area system monitoring and control-terminology, phenomena, and solution implementation strategies." *IEEE power and energy magazine* 2, no. 5 (2004): 68-76

[6] Manousakis, Nikolaos M., George N. Korres, and Pavlos S. Georgilakis. "Taxonomy of PMU placement methodologies." *IEEE Transactions on Power Systems* 27, no. 2 (2012): 1070-1077.

[7] Hajian, Mahdi, Ali Mohammad Ranjbar, Turaj Amraee, and Babak Mozafari. "Optimal placement of PMUs to maintain network

[8] observability using a modified BPSO algorithm." *International Journal of Electrical Power & Energy Systems* 33, no. 1 (2011): 28-34.

[9] Roy, BK Saha, A. K. Sinha, and A. K. Pradhan. "An optimal PMU placement technique for power system observability." *International Journal of Electrical Power & Energy Systems* 42, no. 1 (2012): 71-77.

[10] Zhang, Shuqing, Xiaorong Xie, and Jingtao Wu. "WAMS-based detection and early-warning of low-frequency oscillations in large-scale power systems." *Electric Power Systems Research* 78, no. 5 (2008): 897-906.

[11] Xiao, Jinyu, Xiaorong Xie, Yingduo Han, and Jingtao Wu. "Dynamic tracking of low-frequency oscillations with improved Prony method in wide-area measurement system." In *Power Engineering Society General Meeting, 2004. IEEE*, pp. 1104-1109. IEEE, 2004.

[12] Ceja-Gomez, Frida, Syed Saadat Qadri, and Francisco D. Galiana. "Under-frequency load shedding via integer programming." *IEEE Transactions on Power Systems* 27, no. 3 (2012): 1387-1394.

[13] Inoue, Toshio, Haruhito Taniguchi, Yasuyuki Ikeguchi, and Kiyoshi Yoshida. "Estimation of power system inertia constantand capacity of spinning-reserve support generatorsusing measuredfrequencytransients." *IEEE Transactions on Power Systems* 12, no. 1 (1997): 136-143.

[14] Chassin, David P., Zhenyu Huang, Matthew K. Donnelly, Candee Hassler, Enrique Ramirez, and Cody Ray. "Estimation of WECC system inertia using observed frequency transients." *IEEE Transactions on Power Systems* 20, no. 2 (2005): 1190-1192.

[15] Saadat, Hadi. *Power system analysis*. McGraw-Hill, 1999.

[16] Kundur, Prabha, Neal J. Balu, and Mark G. Lauby. *Power system stability and control*. Vol. 7. New York: McGraw-hill, 1994

[17] Darebaghi, Mohammad Ghaderi, and Turaj Amraee. "Dynamic Multi-Stage Under Frequency LoadShedding Considering Uncertainty of GenerationLoss." *IET Generation, Transmission & Distribution* (2016)