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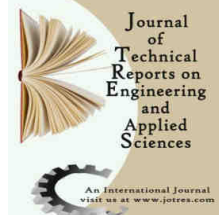
Load modeling in power systems using WAMS measurement system

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ARTICLE INFO	ABSTRACT	ORIGINAL RESEARCH ARTICLE

Clearly, modern power system is a complicated nonlinear and dynamic system. Analysis of power system is heavily dependent on computer techniques. Reliability and precision of power system simulation results depend on component models used in simulations. It is also obvious that load model has prominent effect on power system simulations especially for dynamic simulations. Inappropriate or imprecise load models may lead to unreliable results in power flow, short circuit and stability studies. Therefore, in this study load modeling using Wide Area Measurement System (WAMS) is investigated. In this research system-wide load modeling strategy is proposed and output variables of power system are chosen. Goal function is generated utilizing WAMS data. Parameters are effectively estimated employing a smart parameter estimation technique. This method is implemented on IEEE 14 bus system to evaluate its efficiency in comparison with conventional load modeling methods.

Problem Formulation

In power system engineering, load represents different concepts including [1]:

- A device which is connected to power system and consumes power
- Total active or reactive power consumed by all devices which are connected to power system
- Output power of a generator or power plant
- A part of system which is not shown in system model but is treated like a power consuming device.

Load model refers to a mathematical representation of relation between voltage (amplitude and frequency) and power (active or reactive) or load current. In a generic classification load models are divided into two groups; static and dynamic. The most of static load models are polynomial and exponential models [2]. Static load models state load power at each instant in the form of an algebraic function in terms of voltage amplitude and bus frequency at the same instant; whereas, in dynamic models voltage amplitude and bus frequency are considered in previous instants and usually the present instant [3].

Dynamic load models might be categorized in two groups; input-output models and physical models. The former is similar to a black box demonstrating a mathematical representation of input and output relation.

The inputs are bus voltage and bus frequency while the outputs are active and reactive powers [4]. Inappropriate or imprecise load models might adversely influence on power-flow calculations, short circuit calculations and stability analysis.

According to reference [4], load modeling is essential in the following cases:

- Transient stability analysis in power systems
- Voltage stability analysis
- Small disturbance phase stability analysis
- Power-flow analysis

If load models are not correctly selected and adjusted, simulator system definitely cannot achieve results close to actual system behavior. For instance, in WSCC system of US, the impact of electric load on power system damping was investigated using composite load model and sensitivity of model parameters were analyzed. The results showed that the percentage of motor load exploited in the model has the most sensitivity. System damping is decreased by increasing percentage of motor load in total load model [5].

Although the importance of load model in simulation and analysis of power system is well known, load modeling has remained a difficult process due to complicated characteristics of the loads. First, variety of loads results in different dynamic properties. For example, a sample bus bar in steady state is connected to lots of consumers such as fluorescent and normal lamps, refrigerator, warmer, compressor, motor and furnace; hence, precise estimation of load composition is really difficult. Second, variations in amount and structure of the load, which depend on factors such as time, hour, season, climate and economic situation, cause load modeling to become even harder. Even if precise load composition was clear, it would not be practical to demonstrate all of them in analysis as there are millions of various

types of loads in the whole grid. Therefore, load representation in power systems requires so many simplifications [4].

Load modeling is divided into two generic groups:

1. Feeder load modeling
2. Load modeling for whole power system

Overall, there are two approaches to feeder load modeling and deriving its parameters and characteristics:

- Component-based approach
- Measurement-based approach

The steps of component-based approach might be briefly mentioned as follows:

1. Determining percentage of each load class in total active power of bus bar
2. The percentage of each load component in consumed active power of a specific load class
3. Electrical characteristics of each load component (power factor, voltage and frequency sensitivity and so on).

In [6] voltage and frequency dependent static load model is utilized to determine parameters. Load modeling which is suitable for power-flow and transient stability is investigated in [7]. The authors introduce LOADMOD software and obtain static and dynamic load models. This method suffers from a few drawbacks including time consumption; error resulted from continuous load variations and data collection error. In recent years, measurement-based load modeling has become more important owing to its advantages such as [4]:

1. It illustrates load dynamics of actual system; thus, it provides more precise load characteristics.
2. It is able to solve parameter identification problem using system identification theory.
3. When there is new measured data, known load parameters can be modified or updated.

In this study, WAMS measurement system is utilized. Phasor Measurement Units (PMUs) constitute the main parts of WAMS. They are able to precisely measure voltage and

current phasors as well as frequency simultaneous with a shared time reference which is provided by GPS.

In [8] they used this modeling technique in feeder with 65 kV voltage level. They utilized ZIP-IM composite load model with 14 parameters. It is the same as the method employed in [9] where PMUs are used to measure load parameters. In both of them voltage variations and power variations are respectively considered as input and output parameters.

As mentioned in [10] measurement-based load modeling has shortcomings as it just consider balanced conditions. So to address this problem in [10], a load model reference is presented which makes this method applicable to unbalanced disturbance conditions.

Reference [11] uses input-output load model structure. Bus voltage and frequency are set to be input of the model; whereas, active and reactive powers are the outputs. Also nonlinear regression analysis is performed on the model using Support Vector Machine (SVM).

In [12] static load models are used and PMUs are exploited as measurement devices. They utilized online measurements for load modeling. The parameters are derived applying nonlinear squares sum. Input-output models usually use measurement-based methods to determine their parameters, e.g. fuzzy models, neural-fuzzy models [13] and Volterra series [14].

Lots of research works have been conducted on feeder load modeling; however, load modeling for whole power system has not been vastly investigated. That is why it is discussed in this paper. The paper is organized as follows. In section 2 studies performed on load modeling in whole power systems are explicated. Sensitivity analysis is introduced in section 3. In section 4 the desired method is implemented on 14 bus system based on different load models.

Finally, section 5 concludes the paper.

Load modeling for whole power system

In the previous section load modeling was introduced for a feeder using various component-based and measurement-based methods; nevertheless, applying this model to whole system is not correct as the characteristics of different loads are completely divergent. It might seem reasonable to achieve load model of each feeder via measurement or other approaches. Yet in a wide power system, which includes lots of feeders, this is impractical. If load characteristics registers are supposed to be placed in each feeder, a huge investment is needed. Moreover, obtaining and updating load parameters may face problems and difficulties.

In the literature, three approaches have been proposed for load modeling in power systems:

1. Compressed load regions method
2. Conventional modeling approach
3. system-wide approach

In [15-17], the first method is introduced based on Pahsor Measurement Units. In these papers a part of system is assumed to be load region from the perspective of the other parts. Then, this region is tried to be simply modeled for the rest of the power system. One of the disadvantages associated with this method is that WAMS application in power system load modeling where load model dynamics are also included is not perfectly reviewed. Conventional method relies on the basis that in practice various bus bars might share some features and characteristics such as load classes ratios, similar load changes, load location and so on. This method suggests that bus bars might be classified in several groups using a few criteria. Afterwards, in each group one bus bar can be chosen as the representative of the whole class and load characteristics registers are installed on that bus bar. Then, the model obtained by measuring

characteristics of selected bus bar might be used for all bus bars in corresponding group. In this case number of load models used for dynamic simulations will decrease significantly. In this method a few steps should be taken so that the bus bars could be clustered [18]:

1. Determining properties

Agricultural, industrial, commercial and residential load classes might be chosen as an index. If it is necessary to take further details into account some of load classes might be divided into smaller groups. As an example, industrial load might be divided into two groups; light and heavy industrial loads. Furthermore, as loads are time variant, classification indices might even include seasonal and time changes.

2. Voltage level

Voltage levels should not be too low in clustered bus bars. Both precision of measurement-based modeling and optimal cost of modeling should be taken into considerations. Usually in a 500kV transmission grid, loads which are connected to 220kv/110kv or 220kv/66kv buck transformers can fulfill this requirement [18].

3. Determining number of classes

The maximum optimal number of classes (C_{max}) should be adjusted so that [18]:

$$2 \leq C_{opt} \leq C_{max} \qquad (1)$$

Based on a rule of thumb calculation C_{max} should be in the following range [18]:

$$2 \leq C_{max} \leq \sqrt{n} \qquad (2)$$

Where n is the number of loads needed to be classified.

4. Selecting a substation

The bus bar which is closer to the center of cluster should be selected as sample bus bar in order to install load characteristics register.

The third method, system-wide method, was introduced by Ping Ju in 2011 [19]. In this method load modeling is performed using WAMS and Phasor Measurement Units. It is selected as the basis of our article. Some of its shortages are overcome. In our study, this method is also implemented on static load models where some suggestions are provided to address problems regarding output variable selection. System-wide load modeling aims to make simulation results more similar to and consistent with measured dynamic behavior in actual system. It is assumed that for other components of power system other than loads, precise and evaluated models are utilized. Definitely, if variations of all variables including bus voltages, bus phases, active power and reactive power of lines are the same as simulation results all over the power system, the ideal state is obtained. In this case simulation results can be trusted. Nevertheless, amount of data, processing load, number of measurement devices all over the system, number of buses in the grid, telecommunication facilities and capability of measurement device to choose output variable should be considered. In [19] they either did not presented a specific choice for output variable or utilized inappropriate variables. Since PMU might not be able to measure all current phasors (dependent on it manufacturer), in this study we use voltage phasors of different points of the system as output variable. Additionally, even if it is possible to measure all current phasors, communication facilities and process load must be considered before employing this method. On the other hand, current flow is caused by voltage so if voltage phasors are modified, current and power are modified automatically. Another lack of [19] is that it did not include static load models and diverse actual grids. They did not provide a proper comparison between their method and conventional one. Here, these issues are investigated using proper indices which include all variables of the grid. The steps of this method include:

- classifying bus bars to several classes so that modeling become easier similar to first method.

- choosing appropriate output variables; amplitude and phase of bus voltages are selected in our study.

- determining sensitivity of various parameters of each class to output variable(s) during disturbance event. Load classification reduces the number of parameters which should be estimated. Usually, even if small number of classes is chosen for load model, tens of parameters need to be estimated. Thus, the number of parameters should be decreased even more. In order to reduce number of parameters, another tool is needed. Sensitivity Analysis (SA) is a tool by which it is possible to specify the parameter which mostly impacts on output value. High sensitivity parameters are easier to be estimated using parameter estimation algorithm comparing to low sensitivity parameters. It might be said that parameters with very low sensitivity could not be identified in parameter estimation process.

- Choosing the most sensitive and identifiable parameters to start parameter estimation step.

-using output variable(s) measured by WAMS in actual power system, employing optimization algorithm, achieving parameters corresponding to time span and modifying system dynamics in simulator.

Sensitivity analysis

Sensitivity analysis helps us to determine sensitivity of outputs of the model to its inputs. When input factors are relatively certain and definite, we may consider partial derivative of output variable of function in terms of input. Sensitivity measurement is carried out using numerical computations and several simulations while input factors are changed in the vicinity of nominal values. In fact local influence of input factors on output of the model is found out.

Hence such techniques are called Local S.A. The undergoing equations illustrate a simplified version of sensitivity analysis calculations [19]:

$$\frac{\partial y_i(\theta,k)}{\partial \theta_j} = \lim_{\Delta\theta_j \to 0} \frac{y_i(\theta_1,...\theta_j+\Delta\theta_j,...\theta_m,k) - y_i(\theta_1,...\theta_j,...\theta_m,k)}{\Delta\theta_j} \quad (3)$$

Where y_i is ith output variable, θ is model parameters vector, θ_j is jth parameter, k is time samples, and Δ is parameter variations. Normalized sensitivity of parameters is calculated as shown below [19]:

$$\frac{\partial [y_i(\theta k)/y_{i0}]}{\partial [\theta_j/\theta_{j0}]} = \lim_{\Delta\theta_j \to 0} \frac{[y_i(\theta_1,...\theta_j+\Delta\theta_j,...\theta_m,k)-y_i(\theta_1,...\theta_j,...\theta_m,k)]}{\Delta\theta_j/\theta_{j0}} \quad (4)$$

Where y_{i0} is the initial value of output variable. As for simplicity of comparing sensitivity of parameters, average sensitivity is derived as follows [19]:

$$A_j = \frac{1}{k}\sum_k \left| \frac{\partial [y_i(\theta,k)/y_{i0}]}{\partial [\theta_j/\theta_{j0}]} \right| \quad (5)$$

Implementation of proposed method on a 14 bus system for diverse load models

To conduct our research and implement modeling techniques a loop system is needed which consists of different voltage levels similar to power system. IEEE 14 bus system is exploited in modeling process as sample system. There are 11 loads in this system. According to the equation presented for calculating number of clusters, this system should be divided into two or three classes. Thus, system is able to implement worst case of system-wide method while it implements the best case for conventional method. In this network, buses are divided into three classes. As a result each group of three or four buses will have one representative. It is the best condition for conventional method as one of the error sources in conventional method is applying

load model of representative to all other members of the group. By considering small number of buses in each group this problem is overcome. The following figure depicts the system implemented in PSAT software.

In the following subsections system-wide modeling approach is implemented for each load model separately and the results are presented.
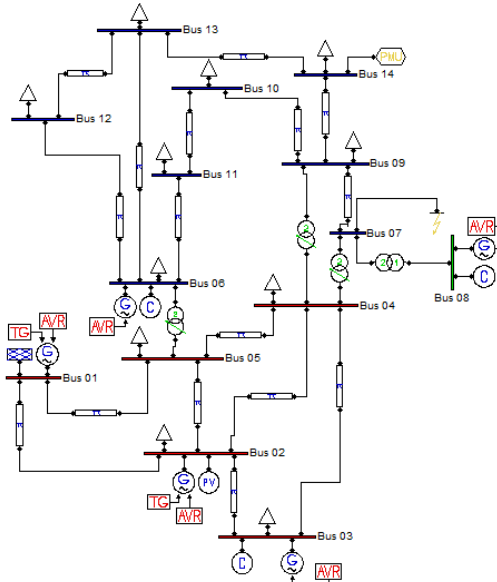

Fig.1: 14 Bus System

Frequency dependent static load model

In this model existing bus bars are divided into three classes; industrial, commercial and residential. Bus bars number 2,3,4 and 5 constitute industrial class. Commercial class includes bus bars number 6, 9 and 12. Finally, 10, 11, 13 and 14 are considered as residential bus bars.

In addition:

1. Bus bar 4 is representative of industrial class
2. Bus bar 12 is representative of commercial class
3. Bus bar 14 is representative of residential class

Three above mentioned bus bars are selected as the sample on which load dynamics registers are installed. Here, PMUs are selected as measurement device in these bus bars. The load model used in this section is as follows [2]:

$$P = P_0 \left(\frac{V}{V_0} \right)^{a_P} \left(1 + \Delta\omega \right)^{b_P}$$

$$Q = Q_0 \left(\frac{V}{V_0} \right)^{a_Q} \left(1 + \Delta\omega \right)^{b_Q}$$

(6)

V_0 constant value is initial value of bus voltage determined by power-flow results. $\Delta\omega$ denotes frequency variations in bus bar. a_P and b_P are load parameters regarding active power which demonstrate dependency of load on voltage and frequency, respectively. a_Q and b_Q are load parameters representing dependency of reactive power on bus bar voltage and frequency. It is assumed that before system-wide modeling, parameters of different classes are derived and exist for desired time span. These parameters might be obtained using an arbitrary method. They could be calculated using measurement-based methods and applied to the whole system (conventional method). Also, they might be obtained

exploiting component-based methods (in this case bus bar classifications and choosing representatives should be performed). They might be even achieved from a previous system-wide method. Load parameters associated with mentioned load

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model are presented in the undergoing table. These are selected from reference [20]. It is given that load modeling is performed in summer and using proposed parameters in summer

Table 1: Comparing values of summer parameter

Model	Residential(3)	Commercial(2)	Industrial(1)
Parameter			
a_P	1.2	0.5	0.1
b_P	0.7	1.2	2.6
a_Q	2.7	2.5	0.6
b_Q	-2.3	-1.6	1.6

A fault is assumed to occur at 0.5s which is automatically cancelled after 50ms. The fault occurs with 0.5+0.5j impedance in bus number 7. The operating frequency is equal to 50 Hz and all simulations are performed with constant simulation pace.

Sensitivity analysis

According to aforementioned facts, output

variables for sensitivity analysis are considered to be voltage and phase of bus 14, 4 and 12 as representatives of residential, industrial and commercial classes, respectively. The following table shows sensitivity of bus 14 voltage angle to load parameters:

Table 2: Sensitive Values for angle of bus 14

Parameter	Sensitivity	Parameter	Sensitivity
a_{P1}	5.7073e-4	a_{Q1}	0.0011
b_{P1}	3.7500e-4	b_{Q1}	2.5792e-5
a_{Q1}	4.1792e-4	a_{P3}	0.0092
b_{Q1}	1.9164e-5	b_{P3}	2.1245e-4
a_{P2}	0.004	a_{Q3}	0.0012
b_{P2}	2.8721e-4	b_{Q3}	4.9689e-5

After conducting sensitivity analysis, sensitive parameters are chosen as demonstrated in table below:

Table 3: Sensitive Parameters

α_{P1}	b_{P1}	α_{P2}	α_{Q2}	α_{P3}	α_{Q3}

It is noteworthy that theses sensitive parameters are selected for mentioned transient event (balanced three-phase fault in 7th bus). For another transient state other parameters might be derived as sensitive ones. Consequently, in each time when we perform load modeling using system-wide method, sensitivity analysis must be performed.

Parameter estimation

In actual system which is the reference for PMU measurements, all of the loads inside a class are assumed to have the same model. Another assumption regarding actual system is that merely obtained sensitive parameters changes in the system. The latter is necessary to acquire final results which should be achieved by optimizer. These results are required to demonstrate precision of parameter estimation and improve precision of the conventional method to its maximum value. The goal function is as follows and genetic algorithm is used for this purpose.

$$objective\ function\ wide-node =$$
$$\sum_{\substack{t \\ i=4,12,14}} \left(V_{im}(t)-V_{ic}(t)\right)^2 + \sum_{\substack{t \\ i=4,12,14}} \left(\theta_{im}(t)-\theta_{ic}(t)\right)^2 \quad (7)$$

Where θ_{im} and V_{im} are phase and amplitude of measured bus voltage in actual system, θ_{ic} and V_{ic} are phase and amplitude of modeled bus voltage. The output variables are simultaneously collected from the whole system and measured with constant pace. Afterwards, genetic algorithm is applied for parameter estimation which results in the following values:

Table 4: Results of Parameter Estimation

parameter	Default	Real	Estimated	Margin
α_{P1}	0.1	0.3	0.279	0.05-0.35
b_{P1}	2.6	2.9	2.832	2.55-2.95
α_{P2}	0.5	0.7	0.708	0.45-0.75
α_{Q2}	2.5	2.2	2.217	2.15-2.6
α_{P3}	1.2	1.4	1.401	1.15-1.45
α_{Q3}	2.7	2.1	2.109	2.05-2.75

Comparison with conventional method

In conventional method, variations of active and reactive powers are measured for changes in time of fault, voltage values and **bus** frequency. Subsequently, effort goes into deriving parameters in such a way that output of model for active and reactive powers are equalized to actual values. The goal function in conventional method is as follows:

$$A = \sum_{\substack{t \\ i=4or12or14}} \left(P_{im}(t) - P_{ic}(t) \right)^2 \qquad (8)$$

$$B = \sum_{\substack{t \\ i=4or12or14}} \left(Q_{im}(t) - Q_{ic}(t) \right)^2 \qquad (9)$$

Where P_{im} and Q_{im} are actual measured values for active and reactive power while P_{ic} and Q_{ic} are corresponding values obtained from the model. The undergoing table includes parameter estimation results for all classes using conventional method:

objective function traditional load modeling = A + B

Table 5: Results of Parameter Estimation in Bus Bar Represent

Model	Residential(3)	Commercial(2)	Industrial(1)
Parameter			
a_P	1.376	0.735	0.302
b_P	0.674	1.043	2.581
a_Q	2.113	2.192	0.617
b_Q	-1.911	-1.793	2.003

Two indices are calculated as comparison index. The first one is voltage index including voltages of all buses during transient phenomenon and the second is phase index consisting of voltage phases of all buses during transient phenomenon. These indices, which are selected to assure that in all variables actual and modeled results are close, are calculated as shown below:

Voltage index:

$$\sum_{i=1}^{14}\sum_{t} \left(V_{im}(t) - V_{ic}(t) \right)^2 \qquad (10)$$

Phase index:

$$\sum_{i=1}^{14}\sum_{t} \left(\theta_{im}(t) - \theta_{ic}(t) \right)^2 \qquad (11)$$

Table.6 represents these indices calculated for two modeling methods:

Table 6: Comparing index of modeling method

conventional	Phase index	0.0065
….	**Voltage index**	2.6674e-6
System-wide	**Phase index**	4.6153e-4
…..	**Voltage index**	1.3351e-6

As can be seen in the table, system-wide method achieves better performance in equalizing actual system and simulator outputs. This property is more sensible in case of bus phase as can be seen in the next load model, as well.

Static comprehensive load model

In this model only voltage dependency is considered. It is defined as follows:

$$P = P_o \left[P_{ZIP} + P_{EX} \right] \qquad (12)$$

$$Q = Q_o \left[Q_{ZIP} + Q_{EX} \right] \qquad (13)$$

$$P_{ZIP} = z_p (V/V_0)^2 + i_p (V/V_0) + p_p \qquad (14)$$

$$P_{EX} = p_e (V/V_0)^a \qquad (15)$$

$$Q_{ZIP} = z_q (V/V_0)^2 + i_q (V/V_0) + p_q \qquad (16)$$

$$Q_{EX} = q_e (V/V_0)^b \qquad (17)$$

Here z_p, i_p, p_p and p_e are percentage of constant impedance, constant current, constant power and exponential loads in active power of the bus, respectively; while, z_q, i_q, p_q, q_e are percentage of constant impedance, constant current, constant power and exponential loads in reactive power of the bus, respectively. *a* and *b* are voltage exponents in exponential load model corresponding to active and reactive power.

Among these ten parameters p_e and q_e are omitted due to dependency and 8 parameters are utilized in next steps.

Bus bars number 2, 3, 4 and 5 constitute industrial class. Commercial class includes bus bars number 6, 11 and 12. Finally, 9, 10, 13 and 14 are considered as residential bus bars.

The representatives are selected similar to previous model:

1. Bus bar 4 is representative of industrial class
2. Bus bar 12 is representative of commercial class
3. Bus bar 14 is representative of residential class

As for exponential load, default parameters are taken from [20] which are measured in summer and night. There are not enough information about ZIP load parameters for different classes and time spans. It is imagined that in industrial class the highest percentage belongs to constant power load model as a consequence of large number of motors. Moreover, it is assumed that residential class mostly consists of constant impedance loads. The other remained load type (constant current) which is not included in two previously mentioned classes is considered as model of commercial class.

Default values of parameters can be found in the following table:

Table 7: Parameter Values Corresponding To Summer Season evening

Model Parameter	Industrial(1)	Commercial(2)	Residential(3)
z_p	10	10	60
i_p	10	75	20
p_p	70	10	15
a	0.18	0.99	0.92
z_q	10	10	60
i_q	20	70	15
p_q	60	10	10
b	6	3.95	4.04

Sensitivity analysis

As well as previous model output variables for sensitivity analysis are voltage and phase of bus 14, 4 and 12 as representatives of residential, industrial and commercial classes, respectively.

The following table shows average sensitivity of load parameters to phase of bus 14:

Table 8: Angular Sensitivity Value for bus 14

parameter	Sensitivity	parameter	Sensitivity	parameter	Sensitivity
z_{p1}	$9.9981e^{-4}$	z_{p2}	$2.1869e^{-4}$	z_{p3}	0.0079
i_{p1}	$4.7778e^{-4}$	i_{p2}	$1.7541e^{-5}$	i_{p3}	$2.2140e^{-4}$
p_{p1}	$7.8052e^{-4}$	p_{p2}	$2.5148e^{-4}$	p_{p3}	0.0022
a_1	$1.0947e^{-4}$	a_2	$1.1495e^{-4}$	a_3	$6.3488e^{-4}$
z_{q1}	$2.6341e^{-4}$	z_{q2}	$3.5333e^{-5}$	z_{q3}	0.0010
i_{q1}	$6.9193e^{-4}$	i_{q2}	$4.0965e^{-4}$	i_{q3}	$4.2722e^{-4}$
p_{q1}	0.0026	p_{q2}	$8.6228e^{-5}$	p_{q3}	$4.7005e^{-4}$
b_1	$3.3082e^{-4}$	b_2	$6.0380e^{-5}$	b_3	$3.9946e^{-4}$

For this transient event and in this load model, parameters of commercial class do not have high sensitivity. As a result, they are not identifiable and they will not pass to parameter estimation step. The significance of sensitivity analysis is more evident in this model, because using 24 classes of parameters in optimization algorithms could lead to divergence. Furthermore, low sensitivity parameters are not properly identifiable and may generate unacceptable results. The sensitive parameters which pass through sensitivity analysis step are included in the following table:

Table 9: Sensitive Parameters

z_{p1}	i_{p1}	p_{p1}	i_{q1}	p_{q1}	z_{p3}	p_{p3}	a_3	z_{q3}

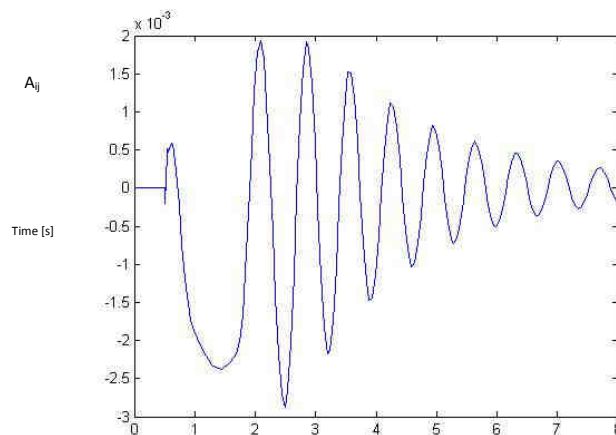For instance, the undergoing figure illustrates sensitivity path of iq_1 parameter:

Fig.2 : Sensitivity path of i_{q1} parameter

Parameter estimation

In this step sensitive parameters are utilized to estimate the parameter. Parameter estimation is performed by PMU measurement to improve simulator behavior so that it matches the actual system. Contrary to previous section actual system is presented more completely where loads existing in one class have small differences. The main index of load classes is assumed to be maintained e.g. percentage of constant power load in industrial class is still the highest percentage. As will be seen in the following paragraphs, it cause system-wide method to become more superior to conventional method; because, in conventional methods there is a simplifying assumption which states that all load models in one class are the same. Using this simplifying assumption the load model derived from representative bus bar is applied to all of them. Considering actual behavior of the system this assumptions impose considerable error. The results of parameter estimation are demonstrated in the follow table.

Table 10: Results of Parameter Estimation

parameter	Default Value	Real Value	Estimated Value	Estimate Interval
z_{p1}	10	……	9.521	$5-25$
i_{p1}	10	……	6	$5-15$
p_{p1}	70	……	56	$55-85$
i_{q1}	20	……	26.45	$5-30$
p_{q1}	60	……	59.031	$50-70$
z_{p3}	60	……	57.935	$50-70$
p_{p3}	15	……	5	$5-25$
a_3	0.92	……	0.831	$0.7-1.5$
z_{q3}	60	……	53.949	$50-70$

Comparison with conventional method

In this section load model in the system is calculated using conventional method; then, the results are compared. In the following table results of parameter estimation for all load classes using conventional method are presented.

Table 11: Results of Parameter Estimation in Bus Bar Represent

Model Parameter	Industrial(1)	Commercial(2)	Residential(3)
z_p	19.274	5	79.937
i_p	8.504	61.814	24.088
p_p	69.192	14.512	10.944
a	0.251	0.703	0.747
z_q	14.279	10.634	71.253
i_q	23.522	73.339	7.69
p_q	50.134	9.182	13.706
b	5.575	3.089	5.445

Exploiting indices introduced in previous section, the comparison results are as follows:

Table 12: Comparing index of modeling method

Conventional	Phase index	0.3021
	Voltage index	$5.9351e^{-4}$
System-Wide	Phase index	$9.6493e^{-4}$
	Voltage index	$5.1835e^{-5}$

As can be observed in the above table, considering overall grid variables, system-wide method and its estimated parameters, provide better results comparing to conventional method. This will lead to more precision and matching between actual system and simulation results.

Dynamic load model of induction motor with constant impedance (Z-IM)

As the last model, dynamic load model of induction motor together with static part is investigated. In recent publications and in measurement-based methods this model has attracted great attention. It has shown acceptable performance in increasing generality of the model.

The induction motor load model with static constant impedance part is utilized for system-wide method. The dynamic part includes induction motor model where transient states of stator are ignored and its third order model is achieved [21], [22]. The static part consists of constant impedance load model in the form of following equation:

$$P = P_{mn}\left(\frac{V}{V_0}\right)^2$$

$$Q = Q_{mn}\left(\frac{V}{V_0}\right)^2$$

(18)

Where V_0 is the initial voltage of bus bar calculated after power-flow. Parameters of induction motors are presented in the following table:

Table 13: Induction Motor Parameters of Order 3

R_s	X_s	R_r
X_r	X_m	H

Additionally, percentage of motor load is another parameter of this model defined as follows:

$$K_{pm} = \left(\frac{P_{motor}}{P_0}\right)$$

(19)

Where P_{motor} is initial power of motor load

.

as dynamic section and P_0 is the initial bus bar power calculated by power-flow. As for torque, constant torque model is exploited. Here, loads are divided into two groups; small industrial and large industrial. The default values of parameters are chosen from [23] and shown in table 14

Table 14: Values of Parameters Corresponding to Small And Large Industrial Grade

Model Parameter	Large industrial(1)	Small Industrial(2)
R_s	0.013	0.031
X_s	0.067	0.1

R_r	0.009	0.018
X_r	0.17	0.18
X_m	3.8	3.2
H	1.5	0.7
K_{pm}	0.4	0.2
Q_{mn}	−0.25	−0.2

High voltage bus bars are considered as large industrial loads class and low voltage bus bars are categorized as small industrial loads class:

- Buses number 2, 3, 4, 5 in large industrial class.

- Buses number 6,9,10,11,12,13 and 14 are classified in small industrial class.

- Bus number 4 is the representative of first class

-Bus number 12 is the representative of second class

Thus, goal function is used as follows with only two voltage phasors:

$$objective\ function\ wide-node = \qquad (20)$$

$$\sum_{\substack{t \\ i=4,12}} \left(V_{im}(t)-V_{ic}(t)\right)^2 + \sum_{\substack{t \\ i=4,12}} \left(\theta_{im}(t)-\theta_{ic}(t)\right)^2$$

C.1. Sensitivity analysis

Sensitivity analysis is performed on parameters of this load model with respect to output variables. The results are demonstrated in table 15. for voltage amplitude of bus number 4.

Table 15: Sensitive Values For Amplitude of Bus 4

Parameter	Sensitivity	Parameter	Sensitivity
R_{s1}	$4.5172\,e^{-5}$	R_{s2}	$3.3584\,e^{-4}$
X_{s1}	$4.7995\,e^{-4}$	X_{s2}	$5.6601\,e^{-4}$
R_{r1}	0.0018	R_{r2}	0.0019
X_{r1}	0.0011	X_{r2}	$4.6724\,e^{-4}$
X_{m1}	0.0166	X_{m2}	0.0131
H_1	$7.1133\,e^{-4}$	H_2	0.0025
K_{pm1}	$7.0310\,e^{-4}$	K_{pm2}	$1.3224\,e^{-4}$
Q_{mn1}	0.0159	Q_{mn2}	0.0082

After sensitivity analysis for three other variables, sensitive parameters during the previously mentioned fault are selected to be used in parameter estimation step. These are listed in the following table:

Table 16: Sensitive Parameters

X_{m1}	H_1	Q_{mn1}	R_{s2}	R_{r2}	X_{m2}	H_2	Q_{mn2}

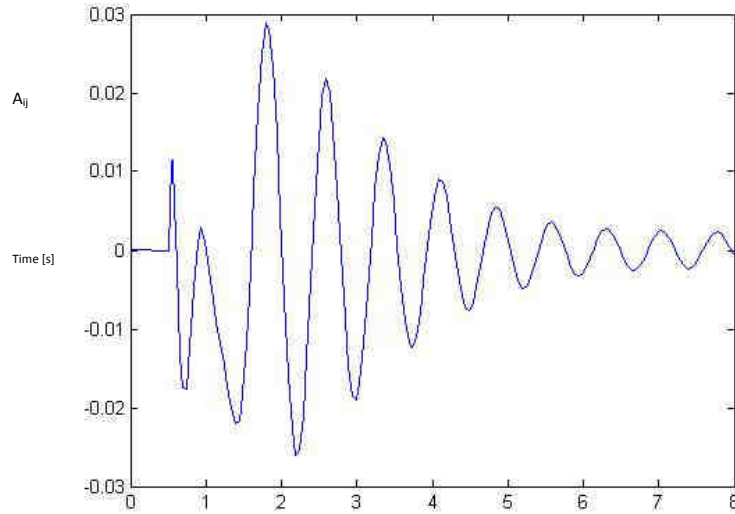For instance, the undergoing figure illustrates sensitivity path of R_{r1} parameter:

Fig.3 : depicts sensitivity path of R_{r1} parameter as an example.

Parameter estimation

When sensitivity analysis is carried out and identifiable parameters are determined, selected sensitive parameters pass to parameter estimation step. In contrast with previous models, here we aim to schematically compare actual system variables and system-wide results. In this section loads inside a class have equal parameters shown in the appendix. The result of parameter estimation can be found in table 17.

Table 17: Results of Parameter Estimation

Parameter	Default Value	Estimated Value	Estimate Interval
X_{m1}	3.8	3.639	$3.5 - 3.9$
H_1	1.5	1.408	$1.3 - 1.6$
Q_{mn1}	-0.25	-0.23	$(-0.27) - (-0.23)$
R_{s2}	0.031	0.038	$0.02 - 0.04$
R_{r2}	0.018	0.033	$0.01 - 0.04$
X_{m2}	3.2	3.292	$3 - 3.4$
H_2	0.7	0.547	$0.5 - 0.8$
Q_{mn2}	-0.2	-0.159	$(-0.25) - (-0.1)$

In the following figures some variables of actual system are compared to those of the system whose parameters are estimated using genetic algorithm.

Undergoing figure comparison between voltage of bus 6 in actual and estimated system.
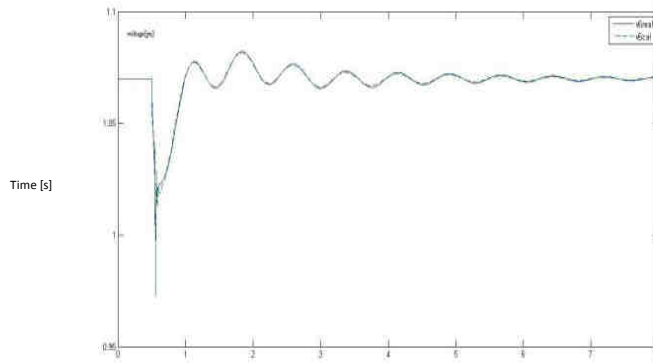
Fig.4 : Comparing voltage of bus 6 In Real System And Estimated System.

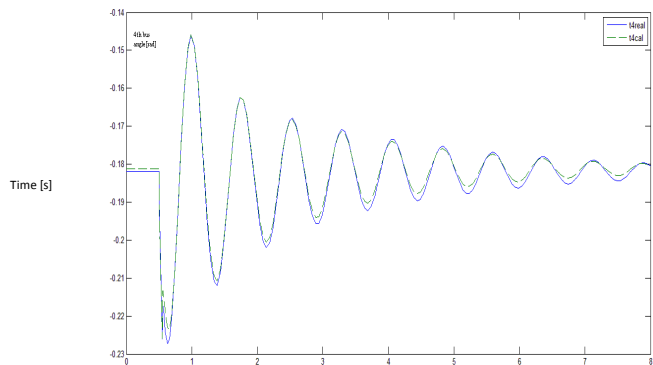Undergoing figure comparison between phase of bus 4 in actual and estimated system.

Fig.5: Comparing 4th bus Angle In Real System And Estimated System.

The following figure comparison between the active power which passes from bus 2 to bus 3 in actual and estimated systems.
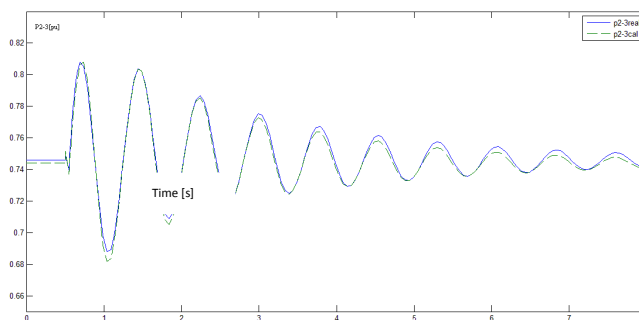

Fig.6: Comparing Active And Passed Power From Bus 2 to Bus3 in Real System And Estimated System.

The following figure comparison between the reactive power which passes from bus 2 to bus 3 in actual and estimated systems.
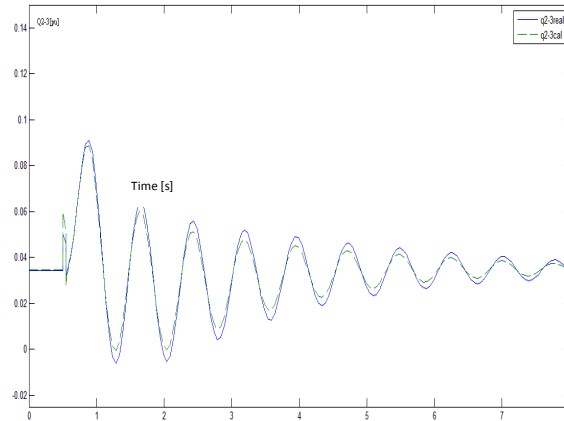
Fig.7: Comparing Reactive And Passed Power From Bus 2 to Bus 3 in Real System And Estimated System.

Conclusion

In this paper load modeling in power systems was investigated due to its importance. There are numerous and redundant research works which focus on load modeling on one bus bar of the grid and try to show other parts of the grid such as lines, transformers and consumers using a mathematical model with respect to that bus. However, in this article we left aside those research works and investigated load modeling for whole power system. The conventional method for power system load modeling and its steps were completely described. In this paper a novel modeling technique was utilized which needs WAMS. Voltage phasors of different parts of the system were chosen as output variables. Furthermore, this method was investigated in worst cases and for various models and systems. We did not mention number of voltage phasors needed in this method to achieve results better than conventional method; because, it depends on number of classes used in conventional methods as well as number of buses. Finally, it was demonstrated that only by choosing small number of synchronized voltage phasors this method achieves better results comparing to conventional method.

Appendix

Values of actual system parameters of Z-IM model:

Appendix Values of the real system.

Parameter	Real Value	Parameter	Real Value
R_{s1}	0.02	R_{s2}	0.05
X_{s1}	0.03	X_{s2}	0.15
R_{r1}	0.01	R_{r2}	0.03
X_{r1}	0.1	X_{r2}	0.25
X_{m1}	3.5	X_{m2}	3.4
H_1	1.3	H_2	0.5
K_{pm1}	0.35	K_{pm2}	0.3
Q_{nn1}	−0.23	Q_{nn2}	−0.15

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