

A Study on the Measurement Based Approach Techniques for Static Load Modeling

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Abstract— In this paper, Static load models are developed using the measurement based approach which is fundamental for on-line load modeling. The measurement data can be acquired from PMU(Phasor Measurement Units). On the assumption that we have on-line measurement data, a scheme which is for Static load model capable to apply SCADA/EMS is developed. The Least Squares criterion is used for minimizing between measured and simulated data. And we suggest the method which uses the only parts of the acquired data. In this manner, Static load modeling algorithm can be developed. In this paper, a scheme that simple Static load model is applied for On-line load modeling is studied.

Keywords - Load Modeling, Parameter Estimate, Measurement Based Approach

I. INTRODUCTION

Accurate computer modeling of power system is essential for reliable simulation about power system stability. However, typical load is composed of a large number of devices such as refrigerators, heaters, motors, furnaces, and so on. So the task of load modeling is very complicated. Techniques representing load as an aggregated form is necessary. It is important to represent the load model as a simple aggregated form and not to distort the characteristics of loads.[1] Loads are constantly changing from time to time. To represent the load characteristics correctly, the On-line load modeling algorithm is needed.

In this paper, the algorithm estimating correct parameters of load model structure is suggested. To establish a method which applying On-line load modeling algorithm to real power system is a purpose of this paper. To do the task of load modeling in real time, the technique of the Off-line measurement based load modeling is necessary.

The task of modeling a physical object is composed of determining the model structure of the object under study and of deriving the associate parameter values of the model structure.[2] In the past, the issue of how to accurately model power system components such as synchronous generators[3], excitation systems[4], and loads has received a great deal of attention from the power industry. Several IEEE standard model structures have been proposed for load model. These model structures are commonly used in current power system

analysis and control programs. So it is at the heart of the area of parameter estimation in system identification.

Using the technique of the measurement based load modeling, On-line load modeling is possible. Using this, it is possible to estimate the parameters of load model in real time, so the load characteristics changing time to time can be represented. The concept of the on-line load modeling is introduced by Rehtanz. With the concept of “sliding window”, he showed the changing parameter of the dynamic load.[5] Using the real time measurement equipments such as a PMU(Phasor Measurement Units), it is possible to acquire data in real time and to estimate the parameters of the load model in real time.

In this paper, we suppose that the data acquired from digital simulator Hypersim is the measurement data. Using this, the measurement based approach is applied. The parameters of static load model are estimated. In general power system analysis programs, some load models are valid only when the voltage is around the normal operation range. To overcome this, the programs adjust the load models automatically at low voltage. So we suggest the plan estimating the parameters using only data over the assigned voltage level and it is tried to apply On-line load modeling algorithm

II. THE MEASUREMENT BASED APPROACH

A. Basic principle

In the measurement based approach, the load characteristics are measured at representative substation and feeders directly using the measure equipment. With this data, we can estimate the parameters of the static load model. Composite load characteristics are normally measured at the highest voltage level for which the voltage of connected load can be adjusted by transformer tap changers. The measured responses of voltage, active power, and reactive power are fitted to the polynomial and exponential expressions.[6]

The task of load modeling is to decide appropriate mathematical relationship between power consumption and voltage/frequency at power delivery buses. The load model is very important to represent the power system dynamics.[7], [8] The actual data is the data recorded by DSP or PMU device. To improve the estimation engine, preprocessing work such as

noise filtering can be done to the recordings. The parameters of the static load models are estimated based on on-line measurement data. The parameters of the assigned load model structure are estimated in order to make the square error between recorded data and simulated results minimum.[9] The basic algorithm for the measurement based approach is described as follows:

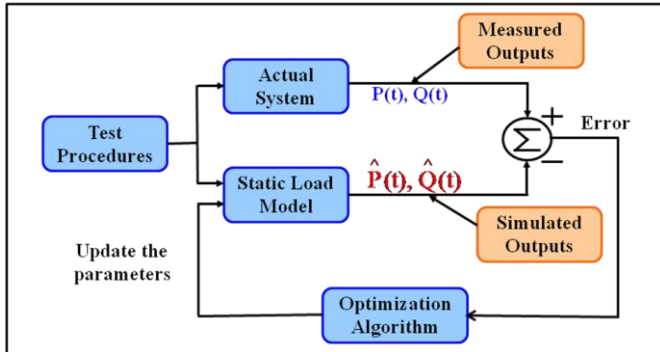


Figure 1. The Algorithm for the Measurement based Approach

B. Input and Output data Preparation

Above Fig. 1 is the first step for the static load modeling is acquiring the data in power system. When trivial or serious contingency occurs in various circumstances, we can acquire the data representing the load characteristics. It is the merit of the measurement based approach that we can produce the load model as demanded form by power system analysis programs. For load model structure under study real and reactive power consumption is influenced by the change of voltage and frequency. So we need the data such as voltage, frequency, real and reactive power of the load. We can acquire all essential data only measuring three data. Input and output data are as followed:

- Input data (The measured data)
 - Positive sequence bus voltage magnitude V , $v(t)$
 - Positive sequence bus current magnitude I , $i(t)$
 - Frequency f , $f(t)$
- Output data (The calculated from V and I)
 - Real and Reactive power P , Q

Voltage, real and reactive power at initial operating condition, V_0 , P_0 and Q_0 , must be also measured and calculated. In this work, measured three-phase voltage and current data are used to calculate real and reactive power. The complex power in a three-phase transmission line can be calculated by follow two method[10]:

• Phasor method

$$S = V_a I_a^* + V_b I_b^* + V_c I_c^* \quad (1)$$

• Positive sequence method

$$S = 3(V_a^+ (I_a^+)^* + V_a^- (I_a^-)^* + V_a^0 (I_a^0)^*) \quad (2)$$

The measured data should be examined for its suitability in load modeling task. Measured data without sufficient information showing the relationship among voltage, frequency, P and Q should be excluded. Some guideline for filtering out measurement data are as follows:

1. The transient changing must be maintained at least 0.5 sec. the change within 0.5 sec cannot show the relation among the voltage, frequency, real and reactive power.
2. After transient period all measured values should be at the condition around steady-state. In some cases frequency increases continuously after a disturbance while V , P , and Q return to their original operation point. This type of measurement should be discarded.
3. The change of voltage, frequency, P and Q should be greater than 10% of its original value.
4. The cases where P , Q vary due to current deviation while V , f remain relatively flat should be excluded.

C. Load modeling using the Parameter Estimation Technique

First we must determine the structure of the static load model. With the data such as voltage, current, frequency, real and reactive power measured at the load bus, we can estimate the parameter of the load model. The objective of our estimation task is to make the simulation model response match the measured response by iterating on the parameters to be estimated. The basic idea is to minimize the error between the model response and the measurement data. The cost function is as follows:

$$\text{Min}_{p \in P} E(p) = \sum_{k=1}^N (z_{act}(t_k) - z_{cal}(t_k, p))^2 \quad (3)$$

where

- $E(p)$: Error Function of parameter p
- $z_{act}(t_k)$: Actual data at t_k
- $z_{cal}(t_k, p)$: Calculated data at t_k with parameter p
- N : Total number of sampling points
- P : Parameter space

A Least Square Method is used to optimize the match the measured and model responses as the model parameters are adjusted. We can define the parameter space P to be the permissible range of all parameters to be estimated. The minimizing point for (3) in P is considered to be the desired solution to the estimation program. For minimizing the error $E(p)$, a good optimization technique is needed. In [6], a simple gradient-based method was used to show the effectiveness of the proposed approach. And other techniques such as BFGS method, Downhill simplex method, Genetic Algorithm and so on, are developed.

III. STATIC LOAD MODELING ALGORITHM

A. Idea

In order to estimate the parameters of the static load model we first determine the window size and using the data within the window the parameters of the load model are estimated continuously. With the concept of “sliding window” the parameters are estimated, so we can check up the changing parameters representing the changing load characteristics.

In the general commercial power system analysis program such as PSS/E, the static load models such as Exponential model, ZIP model and PSS/E Static Load model are used. The Static load models represent the real and reactive power as a function of voltage/frequency and are applied power system simulation. However, the load model function is not always valid in almost commercial power system analysis programs. The function of the load model is valid over the assigned voltage level such as 0.7 [pu], however, under the assigned voltage level the load models are represented as a different function.

In the Digital Simulator Hypersim, the load model function is represented differently according to the voltage range.[11] Generally static load model function is valid only when the voltage is around the normal operation range. And in ETMSP, the program adjusts the models automatically at low voltage. Constant current load and constant MVA load are converted to constant impedance load when the bus voltage is under the assigned voltage level.

In this paper, we suppose that power system is decoupled into many subsystems. So we use the decentralized formulation. In decentralized formulation, the relationship among voltage and power at each bus is decoupled. The commercial simulation program cannot be used directly. The decentralized formulation greatly lessens the computing burden. It make possible the parallel estimation of the load model of all the bus. So in the measurement based approach, we should consider that load response is not determined according to the intended load model function under the assigned voltage level such as 0.7 [pu]. In this manner we suggest the method estimating the parameters of the Static load model only using the data over the assigned voltage level such as 0.7 [pu].

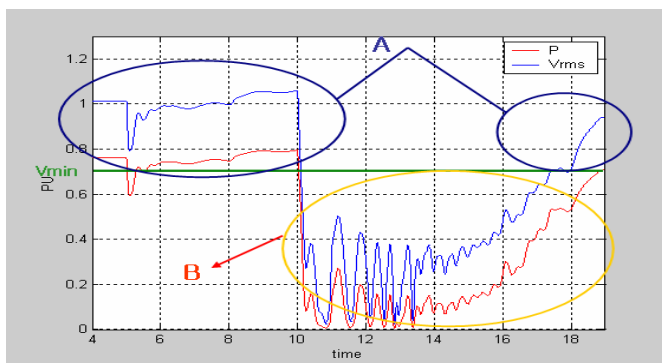


Figure 2. A division of the measured data in power system analysis program

In Fig. 2, ‘A’ part of the data is represented in the form of the general Static load model function, however, ‘B’ part of the data is represented in other different function.

B. Proposed Real-time Static Load modeling Algorithm

With the measurement based approach technique, we suggest the method estimating the parameters of the load model in real time. The parameters of the load model should be produced continuously, so the calculation speed should be fast and the load model structure should be simple. So we suggest not the dynamic load model but the static load model should be used in the real time load modeling task. In this proposed algorithm, we suppose the function of the load model is valid only over the assigned voltage level and the assigned voltage is 0.7 [pu]. The proposed algorithm is as follows:

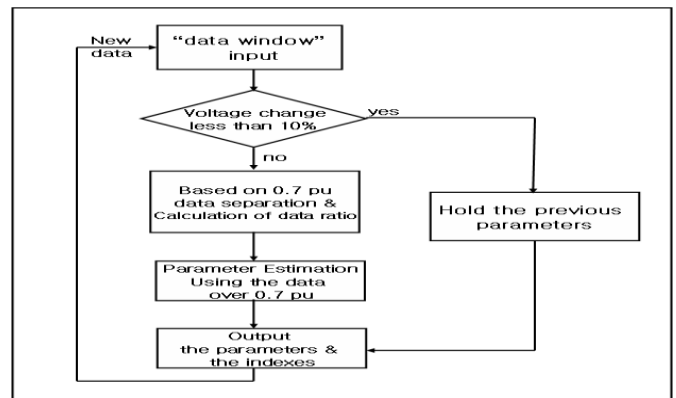


Figure 3. A proposed algorithm of the on-line static load modeling

First we receive the data within the “data window” and inspect whether there are voltage changes less than 10% of the original voltage level. If the voltage changes greater than 10%, the parameters of the static load model are estimated in real time with the data over the assigned voltage.

IV. SIMULATION EXAMPLES

A. Simplified test System

We tried to apply the load modeling algorithm using the data acquired from digital simulator Hypersim instead of the measured data in the real power system. We suppose that the data from Hypersim is similar to the measured data in real power system. Fig. 4 is a simplified test system used to test the algorithm. There are three generators and ten lines in the test system. And additional one substation system is built.

In order to make voltage change, two contingencies occur in the test system. Three-phase fault occurs at 5 sec and the line trips at 5.05 sec. After 0.02 sec the line is reconnected. Short-term oscillations occur in the system. At 10 sec, same fault occurs again, however, it takes more time to trip the line. So the longer oscillations occur. We can acquire the data using this contingency scenario. The simplified test system of Hypersim and the scenario of the contingency are as follows:

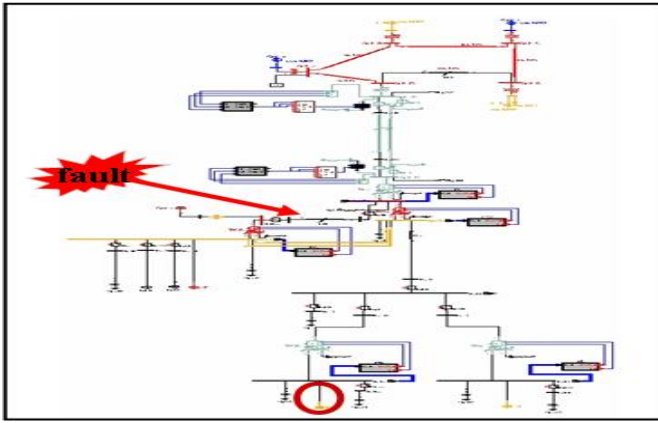


Figure 4. Test system

Table I. Contingency scenario

| Time | Scenario | Remark |
|-----------|----------------------|----------------|
| 5.00 sec | 3 ϕ fault Occur | |
| 5.05 sec | Trip the line | Contingency I |
| 5.07 sec | Reconnect the line | |
| 10.00 sec | 3 ϕ fault Occur | |
| 10.09 sec | Trip the line | Contingency II |
| 11.00 sec | Reconnect the line | |
| 19.00 sec | Stop the Simulation | |

B. Parameter Estimation of the Static Load Model

1) Exponential Load Model

First we try to verify the measurement based algorithm estimating the parameter of the exponential load model. We have the real parameter of the exponential load model. Using the measured data such as voltage, real power the parameter of the exponential load model is estimated. The structure of the Exponential model is as follows:

$$P = P_0 \left(\frac{V}{V_0} \right)^{np} \quad (4)$$

The value of parameter ‘np’ which satisfy the function (4) is estimated. The estimating task is composed with two case: one is the task using the data in whole voltage level and the other is the task using only the data under the voltage level of 0.7 [pu].

The results of the Exponential model are as follows:

Table II. Estimated parameters of Exponential model

| | Real np value | Initial np value | Estimated np value | Error |
|--|---------------|------------------|--------------------|--------------------------|
| Using all data | 1 | 0.5 | 1.4506 | 2.6410 |
| | 1.5 | 0.5 | 1.6937 | 0.3930 |
| | 2 | 0.5 | 1.9950 | 0.0076 |
| Only using data over the voltage level of 0.7 pu | 1 | 0.5 | 1.0000 | 3.4452 $\times 10^{-12}$ |
| | 1.5 | 0.5 | 1.4998 | 1.2214 $\times 10^{-7}$ |
| | 2 | 0.5 | 1.9995 | 1.7949 $\times 10^{-6}$ |

In the exponential load modeling we have known the real value of the parameter. So we can compare the result between two cases. The results of the case using the data over the voltage are more reliable. The square errors is smaller and the estimated parameter more similar to real value.

2) PSS/E Static Load Model

We have verified the measurement based approach algorithm estimating the parameter of the Exponential model. So we suppose the algorithm estimating the parameter of the load model is correct. In Hypersim, we cannot use the PSS/E Static load model or ZIP model. So there are no real values of the parameters. In PSS/E static load model we try to find the parameters makes the least error using same algorithm. The structure of the PSS/E Static Load Model is as follows:

$$P = P_0 (a_1 V^{n1} + a_2 V^{n2} + a_3 V^{n3}) \quad (4)$$

Using the measured data the 6 parameters (a1 a2 a3 n1 n2 n3) of the PSS/E Static Load Model are estimated. The results of the PSS/E Static Load Model are as follows:

Table III. Estimated parameters of PSS/E Static Load Model

| | Initial value [a1 a2 a3 n1 n2 n3] | Estimated value [a1 a2 a3 n1 n2 n3] | Error |
|--|-----------------------------------|--|--------------------------|
| Using all data | [1.3 -1.5 1.2 3.4 6.0 3.4] | [1.3058 -1.4795 1.2058 2.2978 2.9157 2.2978] | 0.0621 |
| | [0 0 0 0 0 0] | [0.3451 0.3451 0.3451 1.6942 1.6942 1.6942] | 0.3928 |
| | [0 0.6 0.3 0.7 0.7 0.7] | [0.0176 0.6589 0.3589 1.6923 1.6947 1.6948] | 0.3928 |
| | [0.1 0.7 0.3 0.2 1] | [-0.2846 0.8650 0.4533 0.7223 1.4139 1.4140] | 0.2130 |
| Only using data over the voltage level of 0.7 pu | [1.3 -1.5 1.2 3.4 6.0 3.4] | [1.3066 -1.4823 1.2066 1.5256 1.5428 1.5247] | 1.5491 $\times 10^{-12}$ |
| | [0 0 0 0 0 0] | [0.3436 0.3436 0.3436 1.4998 1.4998 1.4998] | 1.1934 $\times 10^{-7}$ |
| | [0 0.6 0.3 0.7 0.7 0.7] | [0.0396 0.6456 0.3456 1.2993 1.5080 1.5080] | 1.5250 $\times 10^{-7}$ |
| | [0.1 0.7 0.3 0.2 1] | [0.0625 0.6836 0.2847 1.3660 1.5300 1.4574] | 1.9582 $\times 10^{-7}$ |

We have obtained multiple local solutions from a single set of measurement. The parameters of the load model are reasonable. The errors are very small. The multiple local solutions were obtained using different initial guesses.

3) ZIP Model

The parameters of the ZIP model can be estimated in the same way. The ZIP model is a static load model that represents the power relationship to voltage magnitude as a polynomial equation. The structure of the ZIP Model is as follows:

$$P = P_0 (a_1 V^2 + a_2 V^1 + a_3 V) \quad (5)$$

Using the measured data the 3 parameters (a1 a2 a3) of the ZIP Model are estimated. The results of the PSS/E Static Load Model are as follows:

Table IV. Estimated parameters of ZIP Model

| | Initial value [a1 a2 a3] | Estimated value [a1 a2 a3] | Error |
|--|-----------------------------|-------------------------------|---------------------------|
| Using all data | [-4 6 -1] | [0.6414 0.4149 -0.0564] | 0.4541 |
| | [1 1 -1] | | |
| | [0.7 0.1 0.2] | | |
| Only using data over the voltage level of 0.7 pu | [-4 6 -1] | [0.3891 0.7211 -0.1101] | 4.6963 × 10 ⁻⁶ |
| | [1 1 -1] | | |
| | [0.7 0.1 0.2] | | |

The parameters of ZIP model represented same results regardless of the initial value. However, the results in real power system can be different according to the initial value. In parameter estimation of three static load model, the case only using the data over the voltage level of 0.7 [pu] was more reasonable.

C. Proposed the On-line Static Load Modeling Method

With the measurement based approach technique we tried to apply the algorithm of the on-line static load modeling. When the variation of voltage and power occur, the parameters of the assigned static load model are estimated in real time. The basic concept is the sliding window. With this concept the parameters of the load model are produced continuously using the data only within the window.

- The exponential model : $P = P_0 \left(\frac{V}{V_0}\right)^{np}$ (np = 1)
- Window size : 2 sec (400 Sample)

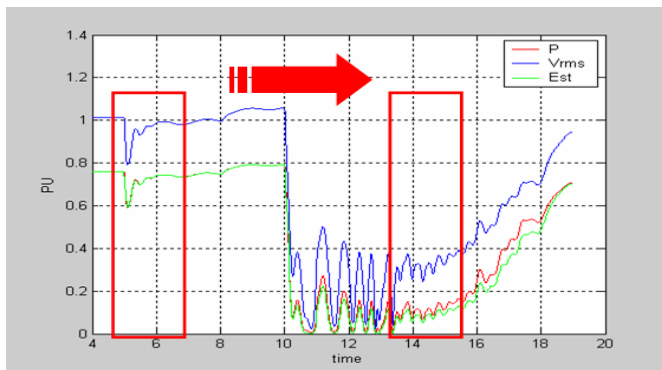


Figure 5. Sliding window (whole voltage level)

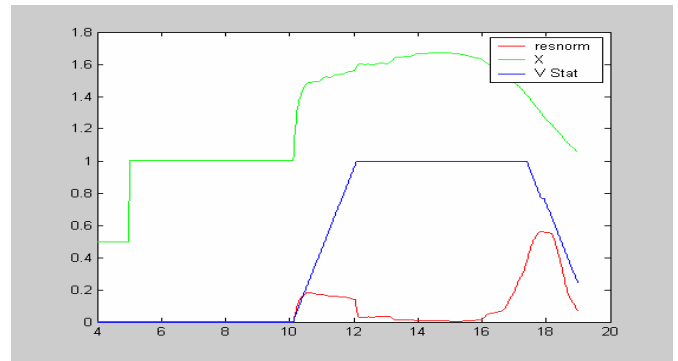


Figure 6. A graph from the On-line static load modeling

From 5 sec when first contingency occurs to 10 sec (in Fig. 5), the value of the estimated parameter is “1” which is the true value of the parameter. However, we can recognize that the parameter is changing and the errors are also great after 10 sec. After 10 sec there are many data under the voltage level of 0.7 [pu]. So the method represents the reliability of the data is necessary. We suggest the index represents the composition of the data. The index is calculated from ratio between the data over and under the voltage level of 0.7 [pu] within the window. The index increases from “0” when the number of the data under the assigned voltage level increases. The index will be “1” when all data within the window are under the voltage level of 0.7 [pu]. It is expected the index can help to represent the reliability of the estimated parameters.

We can estimate the parameter using the data only over the level of 0.7 [pu] within the window. In the same way we show the estimated parameter continuously. In this case, the index is more crucial. We have neglected the data under the voltage level of 0.7 [pu], so the graph of the parameter is more simple. And in this case it is expected the change of the load characteristics is represented well. The result estimating continuously is as follows:

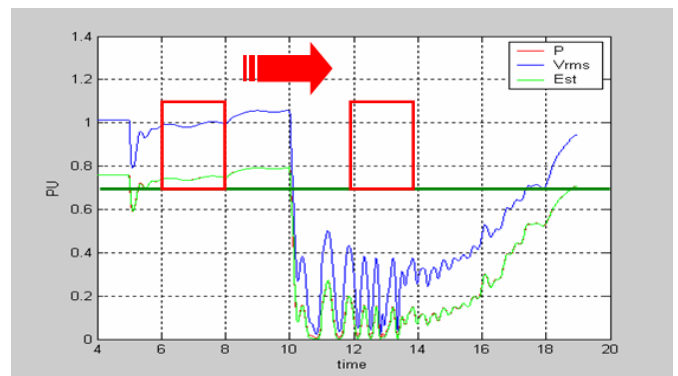


Figure 7. Sliding window (only over the assigned voltage level)

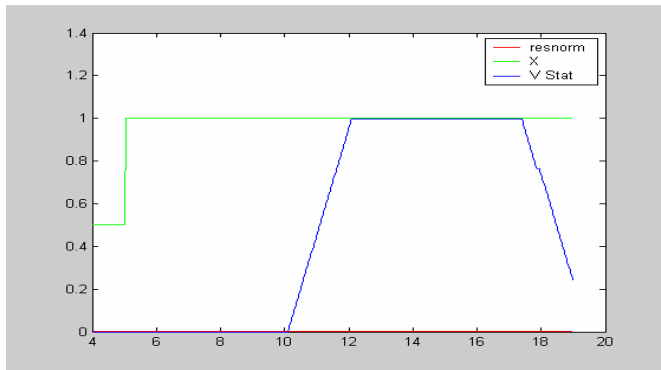


Figure 8. The result from the On-line static load modeling (only using the data over the assigned voltage level)

V. CONCLUSION

This paper introduces the measurement based approach technique and suggests the algorithm of the static load modeling using this technique. For the fast estimation of the parameter, the static load model is suggested. We tried to estimate the parameters of the static load models. And with the concept of “sliding window” this paper suggests the method applying the static load modeling.

In general commercial power system analysis program, the mathematical function of the load model is valid only around normal operating voltage level and it is simulated with converted to constant impedance model under the assigned voltage level. So we suggested the method estimating the parameters using over the assigned voltage level in such a case the parameters are estimated in decentralized formulation

Using the digital simulator Hypersim which can acquire the data as in real power system, we acquired the data and verified the measurement based approach algorithm with the load model of Hypersim. And we tried to estimate the parameters of the PSS/E static load model and ZIP model which have no real value.

In on-line static load modeling the result using the data

under the assigned voltage level was the simpler than the result using the whole data within the window. And we suggested the index representing the reliability of the estimated parameter. The index is calculated from the ratio of the data within the window.

It is expected that the proposed algorithm of the real-time static load modeling can help to estimate the parameters of the static load model used in the general commercial power system programs, when we acquire the measured data in power system. The static load model can be estimated faster than the dynamic load model. So it is also expected that it can present the simple load model in EMS which needs fast calculation.

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