Three-Phase-Measurement-Based Load Modeling Technique Using Unbalanced Fault Data

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ABSTRACT This study presents a load modeling technique using unsymmetrical fault data. Typically, three-phase balanced fault data are prerequisite for load modeling; however, the existing technique utilizes only positive sequence data. Obtaining symmetrical data from a real power system is very difficult as three-phase faults are very rare. In this study, I aimed to improve existing methods designed for estimating load parameters from three-phase symmetrical fault data via load modeling of unsymmetrical faults. The proposed method corrects the existing algorithm using positive sequence data along with three-phase data, namely phases-A, -B, and -C. The equation for each phase of the load model is obtained and subsequently used for load parameter estimation. The load model parameters are estimated using the data obtained from phases-A, -B, and -C, unlike in existing load models that use only positive sequence data. Unsymmetrical faults occur more frequently in a system than symmetrical faults, and numerous opportunities for load model parameter estimation are available. Applying this algorithm to the three-phase data collected using phasor measurement unit-like data acquisition devices is expected to considerably increase both the parameter estimation accuracy and frequency during load modeling parameter estimation in the future.

INDEX TERMS Load modeling, measurement-based approach, parameter estimation, three-phase data, unbalanced disturbances, asymmetrical fault.

I. INTRODUCTION

Load models are used for power system analysis, and they significantly influence the results of system assessment. Load modeling involves the estimation of parameters such as the ZIP ratio of a load model and the slip of an induction motor model [1]. If the load model is inaccurate, the power system planning and operation would be based on incorrect simulation. This could change the load shedding amounts in special protection systems, rendering the stability and extent of blackouts in the power system variable [2].

For these reasons, obtaining accurate parameters of load models is essential. Currently, measurement-based load modeling, which uses measurement units such as fault recorders or phasor measurement unit (PMU), is actively researched to improve accuracy.

To estimate parameters based on measurement in load modeling, previous studies proposed a method of adding a transfer function to the load model to reflect the time delay

in the load model estimation [3], [4]. In this method, the estimation accuracy of the load model parameters is relatively increased by reflecting both continuous and discontinuous changes; however, this method is generally difficult to implement in simulation because the load model itself is a new type of load model.

To reduce error in a measurement-based load model, a composite model comprising the conventional ZIP model and a dynamic model can be employed. Some researchers have used this composite model to increase the accuracy and speed of parameter estimation by selecting highly sensitive parameters. This significantly affects the load model, among many other estimated parameters [5]–[15]. Although the estimation speed generally increases, the accuracy of estimation is limited.

To increase the accuracy of the measurement data, researchers have installed a PMU in the microgrid of a university to estimate the load model parameters [10], [16]–[26]. The static and dynamic load models were combined to construct a composite load model, and an event-oriented online load model was constructed using parameter sensitivity

analysis. However, parameter estimation was still difficult because events very rarely occurred and voltage variation was very small in the microgrid built in the university.

While research efforts to improve the composite load model parameter sensitivity analysis have continued [27]–[37], such efforts have not improved the accuracy, although the efficiency of estimating the load model parameters increased. Improving accuracy is difficult when data acquisition is difficult because a huge amount of data is needed to increase accuracy.

Therefore, to address this problem, methods to estimate load model parameters using unsymmetrical faults have been studied, focusing on transforming the equations of the active power and reactive power to the dq plane using Park's transformation [38]–[43]. Although using unsymmetrical fault data improved parameter estimation, it yielded minimal improvement in the accuracy of parameter estimation.

In [44]–[46], three separate fifth-order dynamic models were introduced to define the ZIP load model in unsymmetrical faults, and a method of adding a general induction motor model to estimate parameters in unsymmetrical faults was proposed. However, the above models are difficult to implement in simulation because a new type of model was used in these studies.

Obtaining the parameters of a load model is difficult as a typical load model uses only positive sequence data. Thus, a typical load model only needs data at a symmetrical fault, but not at an unsymmetrical fault. However, obtaining data on three-phase symmetrical faults is difficult as most faults in a power system are unsymmetrical faults. A symmetrical fault occurs at most once or twice annually in one substation. To acquire fault data, a device for measuring and storing fault currents such as a fault recorder or a PMU should be installed in the substation. However, if a three-phase fault does not occur where such a device is installed, the load model parameters cannot be estimated using existing techniques. Therefore, most fault data measured in measurement-based load modeling are discarded, and the load model parameter estimation fails.

This study proposes a load modeling technique that can increase the accuracy of using unbalanced fault data with modified load model equations. Unbalanced faults, such as a ground fault in a single line, occur approximately 100 to 200 times a year. If the load model parameters can be estimated using unbalanced failure data, then, the accuracy of estimation can be improved. Instead of using data obtained from the commonly used load voltage level (base kV: 22.9 kV in the KEPCO system), the transmission-grade voltage level (base kV in the KEPCO system: 154 kV) was used for load modeling because the system data used in KEPCO is abbreviated data with an installed load of 154 kV. In addition, the loads of Phases-A, -B, and -C are symmetric at the transmission voltage level such that the voltage and current are also symmetric, and the ZIP load and induction motor model parameters have the same values in each phase. The load model parameters were estimated using the data of Phases-A,

-B, and -C, unlike existing load modeling methods in which only the positive sequence data are used. Unsymmetrical faults occur more frequently than symmetrical faults in a system; therefore, numerous opportunities for load model parameter estimation are available.

The rest of this manuscript is structured as follows. Section II presents equations for load modeling. The equations were then verified through a case study, as presented in Section III. Section IV summarizes the main conclusions from the study.

II. EQUATION OF LOAD MODEL
A. MODIFIED ZIP LOAD MODEL
The modified ZIP load model considers each individual phase load equation, unlike the conventional ZIP load model that uses only a positive equation. Equations (1)–(6) can be formulated as the measurement units could obtain both positive sequence data and phase information of each phase.

$$P_{zip,A} = P_{zip,A0}\left\{a_A\left(\frac{V_A}{V_{A0}}\right)^2 + b_A\left(\frac{V_A}{V_{A0}}\right)^1 + c_A\left(\frac{V_A}{V_{A0}}\right)^0\right\}$$
$$(1)$$

$$P_{zip,B} = P_{zip,B0}\left\{a_B\left(\frac{V_B}{V_{B0}}\right)^2 + b_B\left(\frac{V_B}{V_{B0}}\right)^1 + c_B\left(\frac{V_B}{V_{B0}}\right)^0\right\}$$
$$(2)$$

$$P_{zip,C} = P_{zip,C0}\left\{a_C\left(\frac{V_C}{V_{C0}}\right)^2 + b_C\left(\frac{V_C}{V_{C0}}\right)^1 + c_C\left(\frac{V_C}{V_{C0}}\right)^0\right\}$$
$$(3)$$

$$Q_{zip,A} = Q_{zip,A0}\left\{a_A\left(\frac{V_A}{V_{A0}}\right)^2 + b_A\left(\frac{V_A}{V_{A0}}\right)^1 + c_A\left(\frac{V_A}{V_{A0}}\right)^0\right\}$$
$$(4)$$

$$Q_{zip,B} = Q_{zip,B0}\left\{a_B\left(\frac{V_B}{V_{B0}}\right)^2 + b_B\left(\frac{V_B}{V_{B0}}\right)^1 + c_B\left(\frac{V_B}{V_{B0}}\right)^0\right\}$$
$$(5)$$

$$Q_{zip,C} = Q_{zip,C0}\left\{a_C\left(\frac{V_C}{V_{C0}}\right)^2 + b_C\left(\frac{V_C}{V_{C0}}\right)^1 + c_C\left(\frac{V_C}{V_{C0}}\right)^0\right\}$$
$$(6)$$

where a_A, b_B, and c_C are the ZIP load model parameters of Phase-A, that is, constant impedance, constant current, and constant power, respectively, and $a_A + b_A + c_A = 1.0$. P_{A0} is the initial value of the active power for Phase-A and V_{A0} is the initial value of the voltage for Phase-A. Phases-B and -C have similar parameters.

Now, the load model parameters are assumed to have the same values for each phase. This is hypothesized based on the assumption that the load obtained at the transmission level achieves three-phase symmetry and that the load parameters in each phase will also have the same value. Accordingly, the following equations are obtained.

$$a_A = a_B = a_C = a \qquad (7)$$
$$b_A = b_B = b_C = b \qquad (8)$$
$$c_A = c_B = c_C = c \qquad (9)$$

Equations (1)–(6) can be modified to the equations shown below.

$$P_{zip,A} = P_{zip,A0} \left\{ a \left(\frac{V_A}{V_{A0}} \right)^2 + b \left(\frac{V_A}{V_{A0}} \right)^1 + c \left(\frac{V_A}{V_{A0}} \right)^0 \right\} \tag{10}$$

$$P_{zip,B} = P_{zip,B0} \left\{ a \left(\frac{V_B}{V_{B0}} \right)^2 + b \left(\frac{V_B}{V_{B0}} \right)^1 + c \left(\frac{V_B}{V_{B0}} \right)^0 \right\} \tag{11}$$

$$P_{zip,C} = P_{zip,C0} \left\{ a \left(\frac{V_C}{V_{C0}} \right)^2 + b \left(\frac{V_C}{V_{C0}} \right)^1 + c \left(\frac{V_C}{V_{C0}} \right)^0 \right\} \tag{12}$$

$$Q_{zip,A} = Q_{zip,A0} \left\{ a \left(\frac{V_A}{V_{A0}} \right)^2 + b \left(\frac{V_A}{V_{A0}} \right)^1 + c \left(\frac{V_A}{V_{A0}} \right)^0 \right\} \tag{13}$$

$$Q_{zip,B} = Q_{zip,B0} \left\{ a \left(\frac{V_B}{V_{B0}} \right)^2 + b \left(\frac{V_B}{V_{B0}} \right)^1 + c \left(\frac{V_B}{V_{B0}} \right)^0 \right\} \tag{14}$$

$$Q_{zip,C} = Q_{zip,C0} \left\{ a \left(\frac{V_C}{V_{C0}} \right)^2 + b \left(\frac{V_C}{V_{C0}} \right)^1 + c \left(\frac{V_C}{V_{C0}} \right)^0 \right\} \tag{15}$$

In this case, the number of equations exceeds the number of parameters being estimated as there are two more effective power equations and two more ineffective power equations, unlike in the existing parameter estimation method that exclusively uses positive sequence data; thus, parameter estimation is much easier. Even if unsymmetrical data is used, parameter estimation can still be performed because each phase has different equations.

B. MODIFIED INDUCTION MOTOR MODEL
The induction motor model is modified exactly like the zip load model. There are six parameters in the induction motor model: Rs, Rr, Xs, Xr, Xm, and H. Rs and Xs represent the stator resistance and leakage reactance, respectively, whereas Rr and Xr represent the rotor resistance and leakage reactance, respectively. Xm is the magnetizing reactance, and H is the inertia constant. Expanding the current–flux equation in the d- and q-axes [47], I obtain the following equations:

$$\varnothing_{ds} = X_s i_{ds} + X_m(i_{ds} + i_{dr}) \tag{16}$$

$$\varnothing_{qs} = X_s i_{qs} + X_m(i_{qs} + i_{qr}) \tag{17}$$

$$\varnothing_{dr} = X_r i_{dr} + X_m(i_{ds} + i_{dr}) \tag{18}$$

$$\varnothing_{qr} = X_r i_{qr} + X_m(i_{qs} + i_{qr}) \tag{19}$$

$$\frac{dE_d}{dt} = \frac{1}{T'} \left[E_d + (X_{ss} - X')i_{qs} \right] - (\omega - 1)E_{qs} \tag{20}$$

$$\frac{dE_q}{dt} = \frac{1}{T'} \left[E_q + (X_{ss} - X')i_{ds} \right] - (\omega - 1)E_{ds} \tag{21}$$

$$\frac{d\omega}{dt} = \frac{1}{2H}(T_m - T_e) \tag{22}$$

where

$$T' = \frac{X_r + X_m}{R_r}$$

$$X_{ss} = X_s + X_m$$

$$X' = X_s + \frac{X_r X_m}{X_r + X_m}$$

$$T_m = (A\omega^2 + B\omega + C)T_0$$

If the active and reactive powers of the induction motor are expressed as d-axis and q-axis voltage and current, I obtain

$$P_m = v_{ds}i_{ds} + v_{qs}i_{qs} \tag{23}$$

$$Q_m = v_{qs}i_{ds} - v_{ds}i_{qs} \tag{24}$$

Here, Phases-A, -B, and -C can be substituted into each formula to obtain,

$$P_{m,A} = v_{ds,A}i_{ds,A} + v_{qs,A}i_{qs,A} \tag{25}$$

$$P_{m,B} = v_{ds,B}i_{ds,B} + v_{qs,B}i_{qs,B} \tag{26}$$

$$P_{m,C} = v_{ds,C}i_{ds,C} + v_{qs,C}i_{qs,C} \tag{27}$$

$$Q_{m,A} = v_{qs,A}i_{ds,A} - v_{ds,A}i_{qs,A} \tag{28}$$

$$Q_{m,B} = v_{qs,B}i_{ds,B} - v_{ds,B}i_{qs,B} \tag{29}$$

$$Q_{m,C} = v_{qs,C}i_{ds,C} - v_{ds,C}i_{qs,C} \tag{30}$$

Assuming that the parameters of the induction motor model are the same in each phase, then, there is no change in the number of parameters for the load model; however, the probability of success of the parameter estimation increases because the number of equations increases.

C. COMPOSITE LOAD MODEL
The active and reactive power equations for the composite load model can be formulated by combining the zip load and induction motor models.

$$P = P_{zip} + P_m \tag{31}$$

$$Q = Q_{zip} + Q_m \tag{32}$$

Substituting P and Q in the conditions for phases-A, -B, and -C in each equation, I obtain,

$$P_A = P_{zip,A} + P_{m,A} \tag{33}$$

$$P_B = P_{zip,B} + P_{m,B} \tag{34}$$

$$P_C = P_{zip,C} + P_{m,C} \tag{35}$$

$$Q_A = Q_{zip,A} + Q_{m,A} \tag{36}$$

$$Q_B = Q_{zip,B} + Q_{m,B} \tag{37}$$

$$Q_C = Q_{zip,C} + Q_{m,C} \tag{38}$$

The objective function for parameter estimation using the least squares method is given as follows:

$$F_{P,A}(t) = P_{A,measured} - P_{A,3alculated} \tag{39}$$

$$f_{P,B}(t) = P_{B,measured} - P_{B,3alculated} \tag{40}$$

$$f_{P,C}(t) = P_{C,measured} - P_{C,3alculated} \tag{41}$$

$$\text{minimize} \sum \left(|f_{P,A}(t)|^2 + |f_{P,B}(t)|^2 + |f_{P,C}(t)|^2 \right) \tag{42}$$

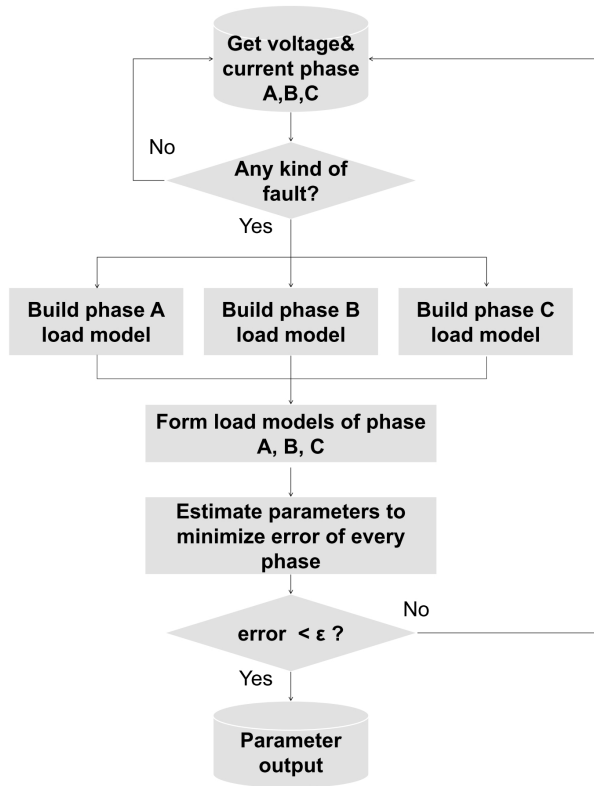$$\text{error} = \sum \left(|f_{P,A}(t)|^2 + |f_{P,B}(t)|^2 + |f_{P,C}(t)|^2 \right) \tag{43}$$

These equations utilize the complete voltage and power of each phase, and hence yield a least-squared error that is less than that obtained using existing methods that utilize only positive sequence data. In addition, the load model parameters can be estimated from unsymmetrical fault data.

A flowchart of the process of parameter estimation using the above equations is shown in Fig. 1. The parameters estimated in this study are those of the ZIP load model and the induction motor model. ZIP parameters include a, b, and c in the active power section and a, b, and c in the reactive power section, which are specified in equations (10)–(15). The parameters of the induction motor model are Rs, Rr, Xs, Xr, Xm, and H.

A comparison of the existing and proposed load modeling methods shows that although the existing load model yields three-phase data, it only uses positive sequence data extracted from the three-phase data for load modeling. In addition, in terms of the type of fault, the existing method only performs parameter estimation for three-phase faults, instead of performing parameter estimation for all types of faults. Accordingly, only the load model parameter for positive sequence data is estimated.

In contrast, in the proposed load modeling method, three-phase data is used for parameter estimation, and all types of faults can be used for parameter estimation; thus, the load model parameter for each phase is estimated.
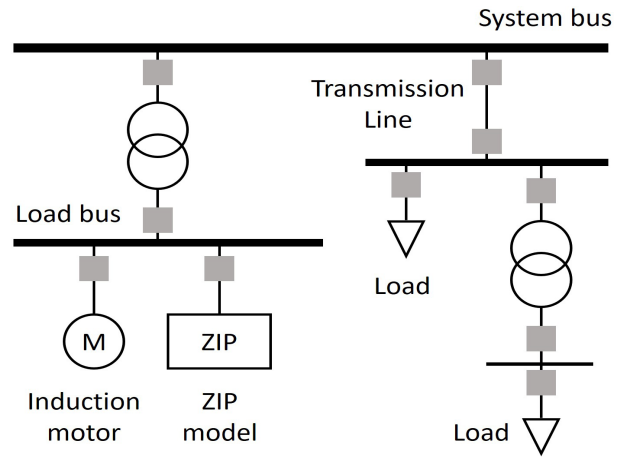

FIGURE 2. One-line diagram of power system with composite load structure.

TABLE 1. Cases corresponding to the fault types and ZIP ratios of the composite load model.

ZIP ratio Fault type	0.35/0.50/ 0.15	0.10/0.25/ 0.65	0.70/0.30/ 0.00
Single-line-to-ground (SLG)	Case A	Case D	Case G
Double-line-to-ground (DLG)	Case B	Case E	Case H
Three-phase-to-ground (TPG)	Case C	Case F	Case I

III. CASE STUDY

A. TEST SYSTEM DATA CASE

To test the performance of parameter estimation of the proposed composite load model, I used a single-machine infinite bus and composite loads. The base power is 154 kV, and the powers of the loads are 100 MW and 50 MVAr per phase. Three types of faults and three sets of ZIP loads and induction motor parameters are analyzed for the case study. In this analysis, the ratio and parameters of the induction motor are fixed, but the ZIP load ratio is varied. Changes in the graph may not be noticeable even if the value changes because the sensitivity of each parameter of the induction motor model is not very large [5]. Fig. 2 shows the system used for the case study. A fault occurs on a line based on the fault type presented in Table 1. Each phase of the voltage and power were measured for the load modeling. There are three loads, which are represented as an exponential load model, with a constant impedance, constant current, and constant power.

The results for each test case are shown in Fig. 3, whereas Table 2 lists the result of the parameter estimation.
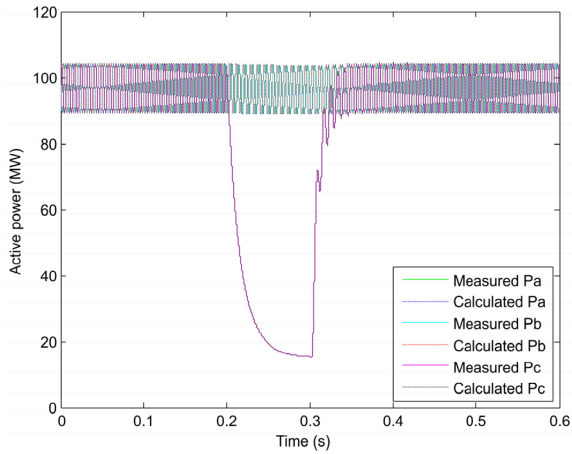
FIGURE 3. Results of measured and calculated powers for SLG (Case A).

TABLE 2. Results of parameter estimation of ZIP ratios with cases corresponding to the fault types.

ZIP ratio / Fault type	0.35/0.50/0.15	0.10/0.25/0.65	0.70/0.30/0.00
SLG	0.349/0.500/0.151	0.101/0.251/0.648	0.700/0.300/0.000
DLG	0.350/0.500/0.150	0.100/0.250/0.650	0.700/0.300/0.000
TPG	0.350/0.500/0.150	0.100/0.250/0.650	0.700/0.300/0.000

Fig. 3 shows the active power graphs of the measured and calculated parameters from phase-C-to-ground fault, where the zip ratio is 0.35:0.50:0.15. A single-phase fault (Phase-C) generates single-phase voltage and power dip; hence, the others do not vary much. Parameter estimation using these data successfully determined the load parameters with an estimation error of less than 0.01%. Fig. 4 shows the same graphs for Phases-B and -C-to-ground fault (DLG). A double-phase fault produces a voltage drop in these phases. The estimation
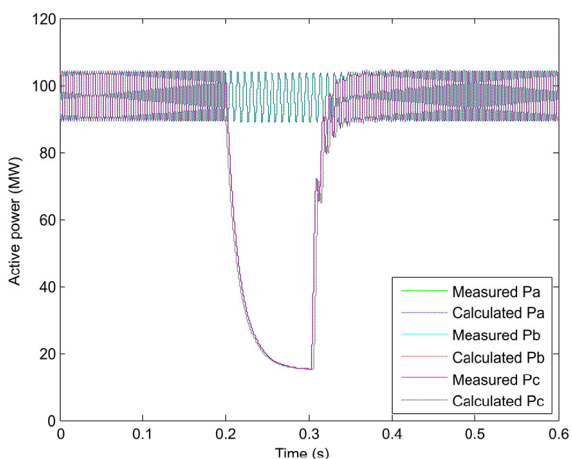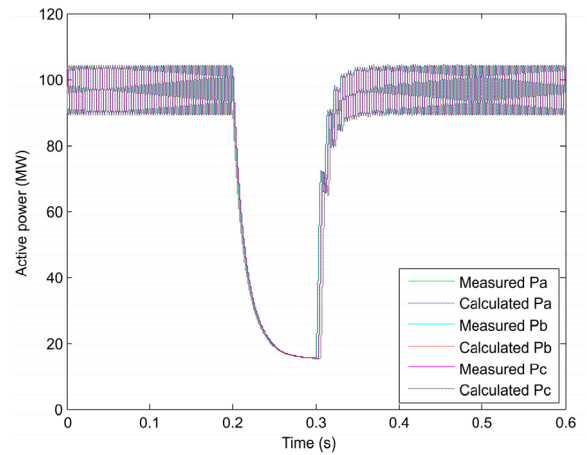

FIGURE 5. Results of measured and calculated powers for TPG (Case C).
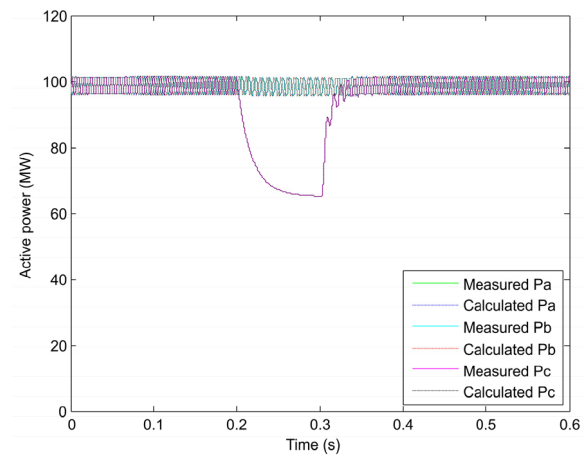

FIGURE 6. Results of measured and calculated powers for SLG (Case D).

error was also below 0.01%. From Figs. 3 and 4, it can be inferred that parameter estimation was performed properly in SLG and DLG, which are associated with unbalanced faults. Fig. 5 shows plots of a three-phase-to-ground fault, and hence, all phase voltages and voltage drop during the fault. In this case, the estimation error was also below 0.01%. Fig. 5 shows that the proposed algorithm can estimate the parameters regardless of the type of failure. These results imply that the algorithm and load model presented in this paper can be employed to determine load parameters regardless of the fault type.

Figs. 6–11 show the plots for the cases listed in Table 1. The estimation error of the load parameters, that is, the difference between the specified and estimated values, is small as the difference between $P_{measured}$ and $P_{calculated}$ is small. The low error can be attributed to the simple and ideal nature of the system where the data was collected. These results suggest that parameter estimation can be performed not only for three-phase faults but also for single-line- and double-line-to-ground faults. In addition, parameter estimation was successfully performed for various load conditions.
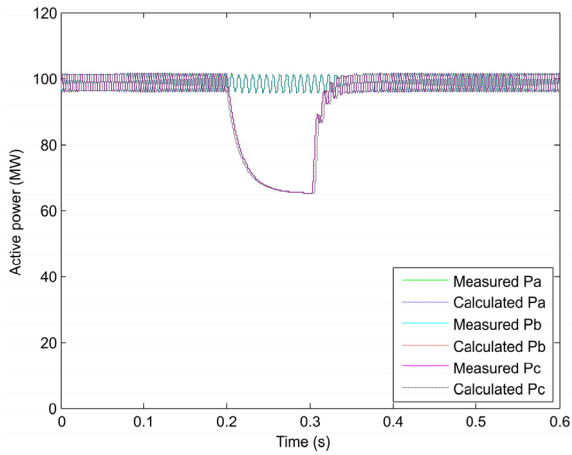

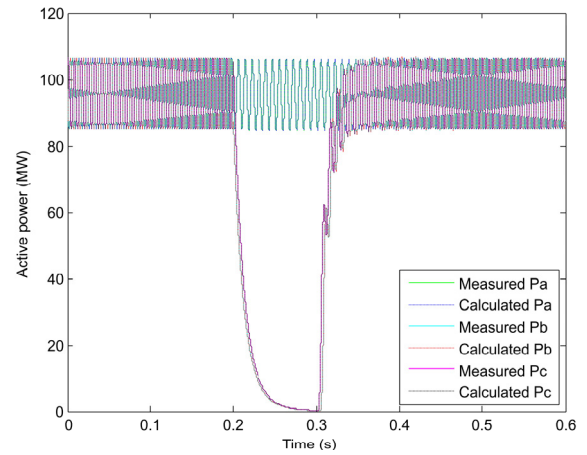**FIGURE 4.** Results of measured and calculated powers for DLG (Case B).

FIGURE 7. Results of measured and calculated powers for DLG (Case E).

FIGURE 8. Results of measured and calculated powers for TPG (Case F).

FIGURE 9. Results of measured and calculated powers for SLG (Case G).

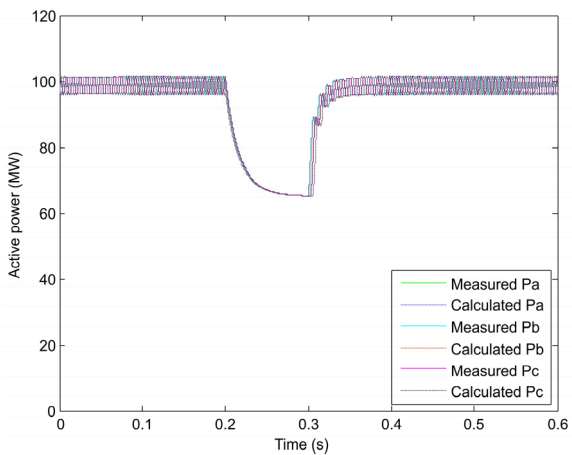**FIGURE 10.** Results of measured and calculated powers for DLG (Case H).

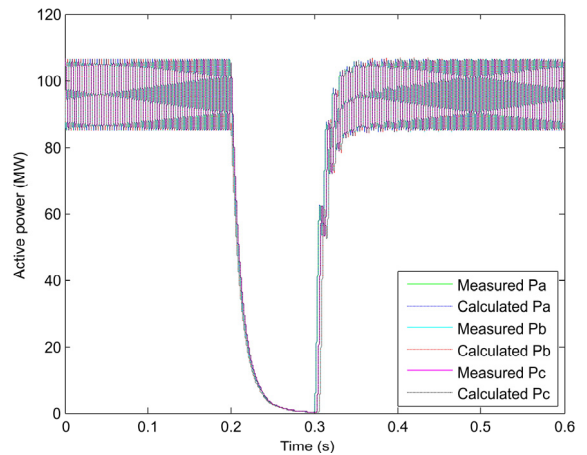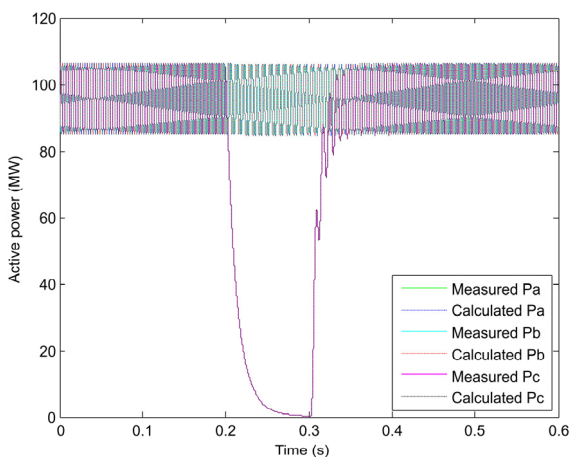**FIGURE 11.** Results of measured and calculated powers for TPG (Case I).

The analysis results demonstrate that for the nine cases shown in Figs. 3–11, all the parameters were successfully estimated. It should be noted that parameter estimation can be realized even for unbalanced faults such as SLG and DLG.

In the past, parameter estimation was possible only with TPG data. However, if unbalanced fault data are obtained from measurement devices such as PMUs, immediate parameter estimation may be possible.

B. ACTUAL SYSTEM DATA CASE

I verified the performance of the proposed algorithm using actual data acquired from the system in Busan in 2013 and data on unbalanced faults. Fig. 12 shows the voltage waveform at the time of the fault; it can be observed that the voltage drop due to this fault is not so large (approximately 0.03 pu) as it is an SLG-type fault. Existing models did not accurately estimate the parameters from this unbalanced fault. However, the parameters can be estimated using an improved algorithm, and the errors are considerably reduced.

Fig. 13 shows the result of recalculation using measured active power data and parameter estimation. Here, Pcal(old) and Pcal(modi) are results obtained using existing and improved algorithms, respectively. Here, the existing(old) method represents parameter estimation using symmetrical fault data, which is a method of estimating load model
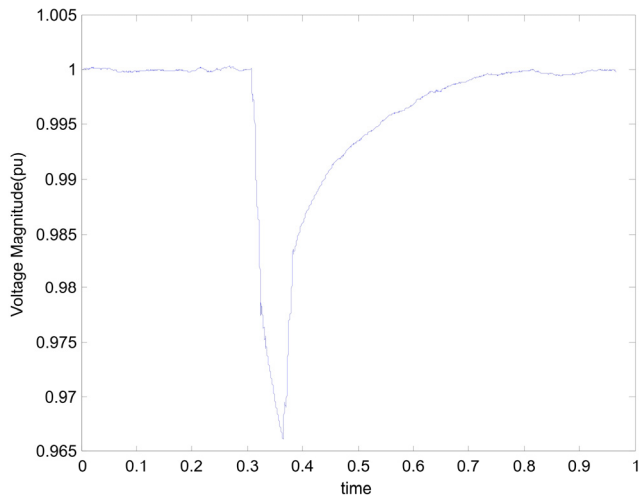
FIGURE 12. Voltage magnitude of actual measurement on September 9, 2013, in Busan.
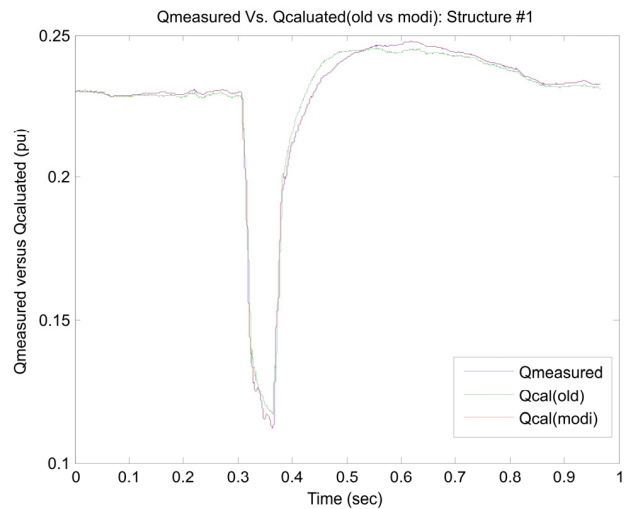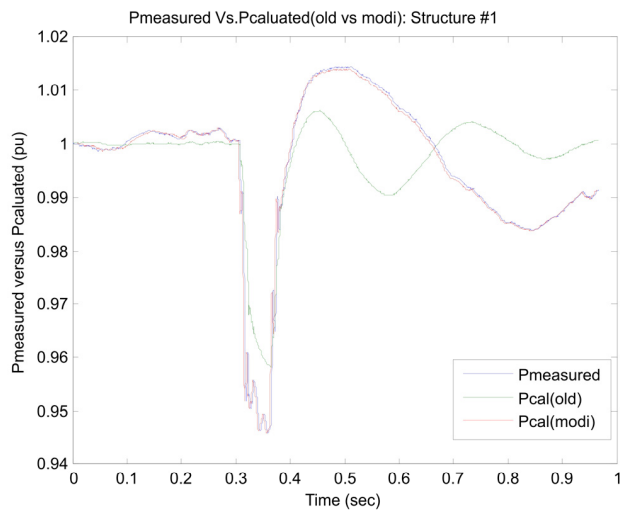

FIGURE 13. Empirically measured power (Pmeasured) versus parameter estimation using existing(old) method (Pcal(old)) and modified method (Pcal(modi)).

FIGURE 14. Empirical reactive power (Qmeasured) versus parameter estimation using existing(old) method (Qcal(old)) and modified method (Qcal(modi)).

IV. CONCLUSION

A load modeling method using unsymmetrical fault data from each phase load model is reported in this article. The proposed method reduced the estimation error for load model parameters and can also be employed for unbalanced fault data. This is because the proposed load model uses three-phase data, unlike existing load models that use only positive sequence data. The algorithm was verified using not only the test system data but also empirical data; I confirmed that parameter estimation is possible using unbalanced fault data, and the estimation accuracy of the parameter improved. In the future, this algorithm will be applied to three-phase data acquired using PMU-like data acquisition devices to significantly increase both the parameter estimation accuracy and frequency during load modeling parameter estimation. In addition, if the measurement data for unbalanced faults are monitored, the algorithm can be improved, and the reliability of the load model parameters can be improved.

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parameters using only positive sequence data from measured data. As shown in the results, the existing algorithm did not accurately estimate the data, whereas results from the modified algorithm are in good agreement with the actual data.

Fig. 14 shows the result of calculating the reactive power using empirical data and parameter estimation; it can be observed that the accuracy of the estimation improved.

The parameter estimation accuracy improved even when empirical data were used. Further, parameter estimation using existing algorithms yielded inaccurate results owing to unbalanced fault data; however, parameters were estimated accurately when the improved algorithm was used. In the future, if unbalanced fault data is continuously monitored, it will be possible to improve the algorithm and ensure the reliability of parameters for the load model.

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