Recent developments in load model parameter identification via ambient PMU signal

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Abstract. Load modelling has a significant impact on operation mode arrangement, transient stability analysis, small disturbance stability calculation and other aspects in power system. It is an important basis and issue for the decision-making of dispatching operation department. As a novel research field of measurement-based identification method, load model parameter identification via ambient PMU signal has gained some developments. This article reviews the current research status of ambient data-based load parameter identification, outlines its basic principle and typical framework, and expounds three technical routes. By summarizing the characteristics of various methods, the future research direction is prospected.

1. Introduction
The main purpose of load model research is to provide accurate load models for power system stability calculations. The use of optimistic or conservative load models will adversely affect the safety and economic operation of the power grid [1]. In the research of load modelling, people have proposed many modelling methods. At present, the methods are mainly concentrated into two categories: one is the "component-based method" and the other is the "measurement-based method" [2]. The component-based method is based on statistical principles. Its idea is to treat the load as a collection of individual users, and each user is a collection of various types of electrical equipment. The electrical appliances are classified and the average characteristics of various types of electrical appliances are determined, and then a comprehensive load model is obtained. Afterwards, the composition and capacity ratio of various typical electrical equipments are calculated. Finally, the researchers summarize these data to get a load model. Meanwhile, the measurement-based method is based on system identification theory, taking the comprehensive load as a whole. First, the measurement data is collected from the field, and then the comprehensive load model structure and model parameter are identified based on these data. The core of this method is to determine model parameter based on the measured post large disturbance data, so that the model response is well fitted to the measured load data [3-4]. In general, this method makes the load model parameter identification an optimization problem, that is, how to obtain the optimal solution of the model according to the known conditions. After years of research, commonly used optimization algorithms for load identification are: least squares method, genetic algorithm, particle swarm optimization algorithm, etc.

In the process of measurement-based method, if you want to identify the dynamic parameter in the load model effectively, the voltage fluctuation range of the load node needs to be at least 10% of the
steady state value. In the actual operation of the power system, the number of large disturbances is very small. The normal operation of the power system is always affected by various small random disturbances, the most important of which is the random load fluctuation. Under these excitations, all signals in the system have small fluctuations similar to noise signals. This noise-like signal reflects the operating characteristics of the system; Pierre et al. first use it for the identification of low-frequency oscillation mode [5]. Ledwich et al. study the key properties of ambient data, and point out that the small variations in power system open a new field of load identification [6]. With the simplified first-order load model, a method to estimate load parameter via ambient signal is proposed [7]. This method does not require large disturbance data, and is verified by a simulation model. However, there is still some distance away from actual use.

In recent years, although the related research via ambient signal to identify load parameter is only in its infancy, some researchers have made good progress [8-18]. This paper is organized as follows. After Section 1 introduces the topic, Section 2 describes the basic idea of ambient PMU signal-based identification. Section 3 provides three different types of technical routes for parameter identification. Section 4 summarizes the characteristics of the three methods, and concludes the paper.

2. Ambient PMU signal-based load modelling

With the widespread use of wide-area measurement system (WAMS) and phasor measurement unit (PMU) in power system, it is convenient to obtain high-precision grid operation data, which provides mature conditions for load online dynamic modelling. The operating data collected by PMU mainly includes the following signals: ring-down signal, probing signal and ambient signal. The ring-down signal has two sources, one is the fluctuation caused by the primary equipment switching, and the other is the fluctuation after the system fault. The probing signal refers to the response obtained after a small signal is input to the electrical secondary control equipment, which is required for specific tests. There is random switching of loads in the system at all times, which will stimulate the power system to oscillate. Such signals are called ambient signals, as shown in Figure 1. Ambient signals exist all the time, and the use of ambient signals for load modelling can meet the time-varying requirements of load models.

![Figure 1. Schematic diagram of ring-down signal and ambient signal.](image)

The ambient signal-based load model parameter identification is a branch of the measurement-based approach, which is trying to identify the load parameter from ambient signals. The continuous random switching in load will excite the ambient voltage signals of the load buses, which will lead to the ambient power signals of the load buses, as shown in Figure 2. Then, the relationship between the
ambient voltage signals and the ambient power signals can be used to identify the load model parameter [13].

![Figure 2. The idea of ambient signal-based load identification [13].](image)

3. The ambient signal-based load identification methods

3.1. Composite load model: Z+M

Since the existing methods are difficult to use the small disturbance PMU signal to identify the load model parameter, Ji et al. proposed a load parameter identification method based on small disturbance data measured by PMU for the first time [8], whose load model adopts the traditional “Z+M” model in PSASP software package. In Figure 3, the constant impedance and induction motor constitute the static and dynamic parts of the composite load model respectively. The dynamic part is an induction motor equivalent circuit that considers the electromagnetic transient process of the rotor circuit, while the steady-state equivalent circuit of an induction motor is shown in Figure 4. The definitions of equivalent circuit parameter can be found in the Literature [8-11], and we will not introduce them in detail here.

![Figure 3. “Z+M” model and its equivalent circuit.](image)

The equivalent circuits of Figures 3 and 4 constitute the mathematical model of measurement-based method, and the state equation is shown in (1) ~ (5) with \( R_s = 0 \). In [8], the load node voltage measured by PMU and the parameters to be identified in the load model are substituted into the mathematical model, and the state Equation (1) is solved by the improved Euler method. The weighted error between PMU measured currents and calculated total currents of “Z+M” model is selected as the objective function, which can be solved with the genetic algorithm to determine the load model parameter. The work of Ji et al. led to the core problem of the ambient signal-based load parameter identification: how to select the identification data set? Furthermore, Ma et al. focused on the selection of small PMU disturbance in [9]. For a load node, if the center line of the bus voltage and current fluctuation curve is a straight line in a certain period of time, it means that the fluctuation of the bus...
voltage and current is mainly caused by the external system disturbance. The load can be regarded as constant during the period, and the PMU data is suitable for parameter identification. Therefore, an important principle for selecting the identification data set is that the voltage and current fluctuation of the load bus node is caused by the disturbance of the external network, rather than the load change in the bus. According to the sensitivity analysis, Ji et al. mainly identify the parameter in the load model: stator leakage reactance $X_s$, initial slip $s_0$ and proportion of dynamic load $P_{mp}$.

![Steady-state equivalent circuit of induction motor.](image)

**Figure 4.** Steady-state equivalent circuit of induction motor.

\[
\begin{aligned}
\frac{ds}{dt} &= \frac{T_M - T_E}{T_j} \\
\frac{dE_d}{dt} &= -E_d + K_z (X - X') I_q + T_{d0} E_d s \\
\frac{dE_q}{dt} &= -E_q - K_z (X - X') I_d - T_{d0} E_q s \\
T_{hi} &= K_L \left[ \alpha + (1 - \alpha)(1 - s)^p \right] \\
T_E &= -\text{Re}(\hat{E}^r \hat{I}) \cdot K_p = -(E_d I_d + E_q I_q) \cdot K_p \\
I_d &= \frac{E_d - U_q}{K_z X'} \\
I_q &= -\frac{(E_d - U_d)}{K_z X'} \\
\end{aligned}
\]

(1) (2) (3) (4) (5)

With

\[
\begin{aligned}
X' &= X_s + \frac{X_s X_m}{X_r + X_m} \\
X &= X_s + X_m \\
X_m &= T_{d0} R_r - X_r \\
\end{aligned}
\]

(6) (7) (8)

3.2. Improved composite load model: $R+M_{new}$

In order to solve the time-varying tracking problem of load model, Tsinghua University proposed a complete set of ambient signal-based load parameter identification method [12-15] including basic principles, improved load model, identification framework, optimization algorithm robustness, and actual power grid verification method. In [12-13], Zhang et al. used a “Z+M” load model to identify
the corresponding parameter by minimizing the power deviation between the PMU measured output and the model predicted output. Different from [8-11], an alternative “Z+M” load model shown in Figure 5 is employed, whose static part is made up of constant resistance and reactance in parallel. On the other hand, the dynamic part of the model uses a different induction motor transient equivalent circuit, which is the same as the PSD-BPA software package. The state equation of induction motor transient equivalent circuit in PSD-BPA is shown in (9) ~ (12) with $R_s = 0$, and the parameter definitions can be found in [12-13].

$$\begin{align*}
\frac{ds}{dt} & = \frac{T_m - T_e}{H_2} \\
\frac{dE_d}{dt} & = -E_d - (X - X')I_q + T_{d0}E_q s \\
\frac{dE_q}{dt} & = -E_q + (X - X')I_d - T'_{d0}E_d s \\
T_e & = E_d I_d + E_q I_q \\
I_d & = \frac{U_q - E_q'}{X'} \\
I_q & = \frac{-(U_d - E_d')}{X'}
\end{align*}$$

(9) ~ (12)

To reduce the number of parameters to be identified, the steady-state “Z+M” model in Figure 5 is converted to “R+M_{new}” model according to Y-Δ transformation in Figure 6. The relationship between the original parameters and the equivalent parameters is given as:
Replace the parameters $X, X'$ and $T_{d0}$ in (9) ~ (12) with new parameters, then the parameters to be identified are $X_{\text{new}}, X'_{\text{new}}, T_{d0\_\text{new}}, H_2$ and $T_m$ of the dynamic part and the resistance $R$ of the static part. The criterion to select the identification data set is choosing the ambient PMU signal with a relatively larger disturbance magnitude, where the active power fluctuates more than 1% for example. Compared with “$Z+M$” model in [8-9], Zhang’s proposal selected a simplified “$R+M_{\text{new}}$” model [12-13] and identifies different parameter sets. There are differences between these two methods in dealing with the active power distribution of the static and the dynamic parts.

### 3.3. Non-mechanical load model

The non-mechanism load model belongs to the input-output model. The establishment of the non-mechanism model is mainly to describe the input/output characteristics of the load group, and does not demand an explanation of the model mechanism. Common non-mechanical models include transfer function model [16-17] and state-space model [18].

Since the ambient signal indicates that the system is operating in a small disturbance condition, the voltage and power changes of the load node are very weak. Even if it is disturbed, it will still return to the initial operating point. Using this feature, Gao et al. have proposed a linearized composite load model [16], of which the linearized model employs “$Z+M$” model in Figure 5 as the basis. Considering that the environment of load is a small disturbance condition, it can be expanded according to the Taylor series at the operating point, and high-order terms other than the primary term can be ignored to complete the linearization of the model. In [16], the state-space model based on the “$Z+M$” model in Figure 5 is given as:

\[
\begin{align*}
\dot{x}(t) &= A \cdot x(t) + B \cdot u(t) \\
y(t) &= C \cdot x(t) + D \cdot u(t)
\end{align*}
\]

With

\[
\begin{bmatrix}
\Delta P \\
\Delta Q \\
\Delta s
\end{bmatrix} = [\Delta E'_{d}, \Delta E'_{q}, \Delta s]
\]

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} = [\Delta U \Delta \theta]
\]

And $\{A, B, C, D\}$ are matrices determined by the system’s operating balance point $\{U_0, \theta_0\}$ and the parameters to be identified $\{R, X_i, X', T_{d0}, H_2, E'_{d0}, E'_{q0}, s_0\}$. The Laplace transform of (16) can be used to obtain the transfer function between the $\Delta P/\Delta Q$ and $\Delta E'_{d}/\Delta E'_{q}$. According to the input and
output response of the system, the parameters of the load model \{R, X_l, X, X', T_{d0}, H_2, E'_{d0}, E'_q, s_0\} can be obtained after the transfer function parameters are identified.

Among the existing ambient signal-based methods, the Literatures [8-16] all treat load identification as an open-loop identification problem, while [17-18] treat it as a closed-loop identification problem. The small disturbance data of the PMU may be located outside the load to be identified or inside the load. The load to be identified and the remaining components of the power system form a closed-loop system. Scholars in [17-18] believe the schemes in [8-16] are inappropriate to treat the ambient signal-based identification as an open-loop problem, and it’s necessary to identify the internal noise signal while identifying the load parameters. In [18], the state-space model considering noise signal is shown as follows:

\[
\begin{align*}
\dot{x}(t) &= A \cdot x(t) + B \cdot u(t) + G \cdot e_0(t) \\
y(t) &= C \cdot x(t) + D \cdot u(t) + H \cdot e_0(t) + v(t)
\end{align*}
\]

(18)

Where \(e_0(t)\) is unknown internal disturbance, \(v(t)\) is measurement noise, \(G\) is the load model to be identified, and \(H\) is internal disturbance model. Li et al. proposed to use the forecast error method [18] to deal with this closed-loop identification problem in Figure 7. Taking the PMU data in Zhejiang and Chongqing as examples, the closed-loop and open-loop identification schemes are compared, and it is proved that the closed-loop identification scheme can accurately identify internal noise and its load identification results have higher accuracy.

4. Conclusions

As a branch of the measurement-based method, the ambient signal-based load identification method has great potential due to the convenience of obtaining PMU data. The main characteristics of the three methods introduced in this article are summarized as follows:

1) All three methods are based on the most widely used “Z+M” composite load model. The static part of the “Z+M” model has two different expressions, which determine different solution procedures of dynamic and static power distribution. At the same time, the different base values of induction motor model show different equivalent circuits and equations.

2) The first two mechanism models [8-9], [12-13] treat load identification as an open-loop problem and ignore the internal disturbances of load nodes. The final non-mechanical models [17-18] treat load identification as a closed-loop identification problem, and its process is more complicated.

3) For the methods in [8-9] and [16-18], the balance point for system operation is crucial. For the traditional measurement-based method, it is necessary to approximate an operating point as a stable starting equilibrium point in the small disturbance condition. For the state-space model, the operating equilibrium point of the system needs to be removed from the small disturbance data as the mean value.

Although some progress has been made in the load parameters identification of ambient signal, the application of identification parameters to stability analysis of large power grids needs further research.
Treating load identification as a closed-loop identification problem is an effective way to improve the accuracy of parameter identification in a small disturbance condition. However, the identification of load parameters from a single substation is far from enough for the actual grid simulation analysis. It is the future research direction to extend the parameters identified by this method from a single substation to the entire grid.

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