Non-intrusive monitoring and disaggregation of industrial load based on Petri net theory

Wei Zheng¹,*, Jie Yu¹, Hongjie Tian², Peng Li³, Chenning Wu² and Mengfu Tu⁴,⁵

¹School of electrical engineering, Southeast University, Nanjing 210096, China
²Ningxia Power Exchange Center Company, Yinchuan 750001, China
³Nanjing SAC Power Grid Automation Co., Ltd, Nanjing 210096, China
⁴NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing 211106, China
⁵State Key Laboratory of Smart Grid Protection and Control, Nanjing 211106, China

*Corresponding author e-mail: 1005065985@qq.com

Abstract. In this paper, the non-intrusive monitoring and disaggregation method of industrial load based on Petri net theory is studied. First, the basic concepts of Petri nets are introduced. On the basis of prototype Petri nets, time factor is added. Then, the Petri net with time factor is combined with industrial load production process. Considering the production sequence, start-stop time and production time constraints of industrial load, a non-intrusive monitoring and disaggregation model of industrial load is constructed. Finally, according to the actual production process of industrial load, the electricity consumption situation of each production link is calculated, and the detailed analysis results of industrial user's electricity consumption behavior are obtained. The research could provide an important reference for realization of friendly interaction between industrial users and power grid.

1. Introduction

With the development of society and the continuous growth of electricity demand, power saving has direct and critical effects on the sustainable development of the economy and the environment. In the fields of high efficiency, saving and optimizing power consumption, the equipment platforms which carry these technologies in hardware and equipment have broad market demand and development prospects. In recent years, the rapid development of smart grids has also triggered a research boom on "smart power" technology[1-3]. Document No. 9 of Electric Power Reform clearly states that demand side management and energy efficiency management should be actively carried out to promote supply-demand balance and energy saving. From this point of view, detailed analysis and in-depth mining of user energy consumption information will provide basic information reference for the above related research. For example, the premise of implementing demand response scheme in smart grid is to collect and analyze load data[4-6].

From the perspective of existing demand, load monitoring and energy analysis have received more attention. Electric load monitoring refers to monitoring the operation status and energy consumption of different loads through real-time acquisition of load’s electrical parameters. It is a key basic technology for user-side energy management[7]. By understanding the state mode, power consumption period, power consumption level of various loads, it can help the energy users to distribute electricity reasonably and optimize the mode of energy consumption, so that the whole
power system is always in a state of efficient operation, which is of great significance in today's emphasis on energy saving and emission reduction.

The existing research divides load monitoring into intrusive and non-intrusive according to the way the load data is obtained. In terms of non-intrusive monitoring, the literature [8] uses the pattern recognition method to design Fisher's supervisory load identification method, but only classifies the electrical appliances and cannot identify specific electrical appliances. According to the principle of load feature superposition, the literature [9] uses the genetic algorithm to realize the decomposition of the total signal, which is based on the characteristics of load active power and 3rd harmonic current amplitude. In the literature [10], a load decomposition algorithm for sparse underdetermined solution is proposed, which decomposes the running electrical appliances from the total load signal. However, the algorithm has a large amount of calculation, and it is difficult to realize real-time monitoring when the load is large. In the use of non-intrusive monitoring for power behavior analysis, the current domestic research [8-10] mainly stays on the exploration of resident load identification algorithms, and few studies on industrial load identification algorithms.

This paper first introduces the basic concepts of Petri net and defines a mapping from transition set to some time factor set on the basis of prototype Petri net. Then, the Petri net with time factor is combined with the industrial load production process. Considering industrial load production process sequence, start-stop time and production time constraints from the perspective of time, a non-intrusive monitoring and disaggregation model of industrial load is constructed. Finally, according to the actual production process of industrial load, the electricity consumption of each production link is calculated. The research could provide an important reference for realization of friendly interaction between industrial users and power grid.

2. Petri net theory

Petri net theory is a model for describing distributed systems. It can describe the structure of the system and simulate the operation of the system[11-13]. Petri net theory has strict mathematical expressions, intuitive graphical representations, rich system description methods and system behavior analysis techniques. Here we only give a few concepts that are closely related to this article.

Definition 1 A triple \( N=(P,T;F) \) that meets the following conditions is called a net:

1. \( P \times T \neq \emptyset \);
2. \( P \cap T = \emptyset \);
3. \( F \subseteq (P \times T) \cup (T \times P) \);
4. \( \text{dom}(F) \cup \text{cod}(F) = P \cup T \)

where

\[
\text{dom}(F) = \{ x \in P \cup T \mid \exists y \in (P \cup T) : (x,y) \in F \} \quad (1)
\]

\[
\text{cod}(F) = \{ x \in P \cup T \mid \exists y \in (P \cup T) : (y,x) \in F \} \quad (2)
\]

P and T are two disjoint sets, which are called the basic elements of network N, the elements of P are called places, the elements of T are called transitions, and F are the flow relations in the network.

Definition 2 Set \( N=(P,T;F) \) be a network. For \( x \in P \cup T \),

\[
\tilde{x} = \{ y \mid \exists y \in P \cup T \land (y,x) \in F \} \quad (3)
\]

\[
x^\prime = \{ y \mid \exists y \in P \cup T \land (x,y) \in F \} \quad (4)
\]

where \( \tilde{x} \) is the input set of \( x \); \( x^\prime \) is the output set of \( x \); \( x \cup x^\prime \) is the extension of \( x \).

Definition 3 A network system \( \sum = (N,M) = (P,T;F,M) \) is a marked network and has the following transition firing rules.

1. For \( t \in T \), if \( \forall p \in \tilde{t} : M((P) \geq 1 \), then say M authorization t fires, recorded as \( M > t \).

2. If marking M authorization t fires, the transition t can fire under M. If the new marking obtained by authorizing is \( M^\prime \), then for \( \forall p \in P \), the following formula is established
3. Non-intrusive monitoring and disaggregation model of industrial load

Traditional load monitoring takes an intrusive approach, in which sensors are installed on each user's electrical equipment to record their usage. The advantage of this method is that the monitoring data is more comprehensive. The disadvantages are poor practical operability, high implementation cost and high maintenance cost. Generally, multiple data acquisition equipment and sensors are arranged to monitor the load equipment at a fixed point, and the installation work needs to enter the interior of the building. On the other hand, because this method uses more sensors, there are more interference factors and errors, which will also affect the reliability of load operation and data integrity[14,15]. In this paper, the non-intrusive monitoring method is used to install the data acquisition device at the initial end of the industrial load. Its advantages are low economic cost, little disturbance to the production and life of industrial users, low installation cost and convenient maintenance of equipment.

3.1. Industrial load production workflow model

As shown in Fig.1, a process is represented by two transitions and a place; where $t_{i1}$ is defined that the beginning of the process $i$, $t_{i2}$ is defined that the end of the process $i$, a mark in the place $s_i$ is defined that the process $i$ is in progress. A time value $a_i$ is assigned to the place $s_i$, indicating that it takes at least $a_i$ unit time from the $t_{i1}$ occurrence before $t_{i2}$ can occur.

![Figure 1. A process is represented by Petri net model](image1)

For the whole project, the following steps can be used to construct the time-delay Petri net workflow model.

(1) If the process $i$ is the premise process of the process $j$, then add a place $s_j$ between $t_{i2}$ and $t_{j1}$, which makes

$$\{s_j\} = \{t_{i2}\}$$

and $s_j$ is endowed the time value of 0.

![Figure 2. The relationship between processes are represented by a net model](image2)

(2) For those processes without premise processes, merge their transitions as transition $t_b$.

Introducing the initial place $s_0$, which makes
and $s_0$ is endowed the time value of 0.

(3) For those processes without follow-up process, merge their transitions as transition $t_e$. Introducing the closing place $s_e$. Introducing the closing place $s_e$, which makes
\[
\begin{align*}
\{ t_e \mid \text{process } j \text{ has no follow-up process} \}, \\
\{ s_e \} \\
\end{align*}
\]

(4) Setting the initial mark $M_0$, which makes
\[
M_0(s_0) = 1, \
M_0(s) = 0 \quad (s \neq s_0)
\]

An engineering problem Petri net workflow model can be expressed as
\[
\begin{align*}
\sum = (S, T; F, W, M_0)
\end{align*}
\]

Where $N = (S, T; F)$ is an appearance network,
\[
\exists !s_0 \in S \land \exists !s_e \in S : \{ s_0 \} = \emptyset \land \{ s_e \} = \emptyset, \quad \forall t \in T : \{ t \} \neq \emptyset \land \{ t^* \} \neq \emptyset
\]

\[
W : S \rightarrow R_0
\]

\[
M_0(S) = \begin{cases} 
1, & \text{if } s = s_0 \\
0, & \text{other}
\end{cases}
\]

The operation process of $\sum$ reflects the construction process of the project, when the $\sum$ runs to the termination mark $M_f$:
\[
M_f(S) = \begin{cases} 
1, & \text{if } s = s_e \\
0, & \text{other}
\end{cases}
\]

3.2. Non-intrusive monitoring and disaggregation model based on Petri net theory

The steady-state power of the load can reflect the energy consumption state and energy consumption level of the load, which is the most intuitive feature type among many load characteristics. When different loads are put into use or exited from operation or even switched to the working state, their corresponding power characteristics will be changed, thereby changing the total power consumption or total power consumption. The steady-state power characteristic of load satisfies superposition and is easy to analyze and process. Regardless of noise interference, when the total load power changes, along with the occurrence of load events, the goal of non-intrusive load disaggregation is to monitor and identify the working state of the power load, and complete the total load to the timing. The running track of the load is reproduced.

The target of load identification is the load equipment working sequence combination based on the process operation mark of the Petri net with minimum distance to the measured total load power, which can be expressed as
\[
\begin{align*}
\min F = P_t(t) - \sum_{i=1}^{n} M_i(s_i) P_i(t)
\end{align*}
\]

where $P_t(t)$ is the measured total load steady state active power at each moment; $M_i(s_i)$ is the running mark of the process $i$; $P_i(t)$ is the steady state active power of process $i$.

The constraints are as follows:

1) Process start time constraint
\[
E(s_i) \leq t_{i_0} \leq L(s_i)
\]

where $E(s_i)$ is the earliest start-up time of the process $i$; $t_{i_0}$ is the actual start-up time of process
i; L(s_i) is the latest start-up time of the process i.

2) Process closure time constraint

\[ E(s_i) + T_i \leq t_{ic} \leq L(s_i) + T_i \]  \quad (18)

where \( T_i \) is the operation time of the process \( i \); \( t_{ic} \) is the actual closing time of the process \( i \).

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**Table 1.** Three Scheme comparing.

| Numble | Scheme 1 | Scheme 2 | Scheme 3 | Scheme 4 | Scheme 5 |
|--------|----------|----------|----------|----------|----------|
| 1      | 456      | 456      | 123      | 123      | 123      |
| 2      | 789      | 213      | 644      | 644      | 644      |
| 3      | 213      | 654      | 649      | 649      | 649      |

**4. Simulation example**

Setting a production process of the industrial load consists of 12 processes. The connection relationship between each process code, running time and process is shown in Table 2.

**Table 2.** Industrial load production process timing information

| Process code | a | b | c | d | e | f | g | h | i | j | k | l |
|--------------|---|---|---|---|---|---|---|---|---|---|---|---|
| Running time | 8 | 15| 21| 3 | 7 | 12| 27| 5 | 18| 14| 4 | 10|
| Premise      | no| a | b | b | c | c | e | e | c | f | g | g, h, d, i |

Based on the industrial load production workflow model proposed in part 3.1, a Petri net with time weights in the place can be constructed. After eliminating some zero-weight places by simplification, the workflow Petri net model is shown in Figure 3.

**Figure 3.** Industrial load workflow Petri net model

This section uses a production process cycle of the industrial load to verify the power consumption information. The power consumption curve of a production process cycle is shown in Figure 4. It can be seen that as the industrial load production process advances, its power consumption curve is constantly changing.
Figure 4. The power consumption curve of a production process cycle

According to the industrial load Petri net workflow model, starting from \( s_0 \), one by one, the earliest possible start time \( E(s_i) \) of each process is obtained, and then the minimum time \( T(E) \) required to complete the whole project is obtained \( (T(E) = E(s_f)) \). Finally, starting from \( s_e \), trace back one by one to get the latest start time \( L(s_i) \) of each process, as shown in Table 3.

Table 3. \( E(s_i) \) and \( L(s_i) \) values for each process place of the industrial load

| \( s_i \) | \( s_0 \) | a | b | c | d | e | s_1 | f | g | h | i | s_2 | j | k | l | s_e |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| \( E(s_i) \) \((\text{min})\) | 0 | 0 | 8 | 8 | 23 | 23 | 29 | 30 | 30 | 29 | 42 | 57 | 57 | 57 | 60 | 71 |
| \( L(s_i) \) \((\text{min})\) | 0 | 0 | 8 | 9 | 58 | 23 | 30 | 31 | 30 | 62 | 43 | 67 | 57 | 67 | 61 | 71 |

The non-intrusive load monitoring technology can conveniently monitor the electricity consumption of each production link, and get accurate electricity usage behavior of industrial users. Based on the Petri net theory, the non-intrusive monitoring and disaggregation model analyzes the power consumption of a production cycle, and the input time, cut-out time and power of each production link are shown in Table 4.

Table 4. The result of industrial load non-intrusive monitoring and disaggregation

| Process code | a | b | c | d | e | f | g | h | i | j | k | l |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Input time | 0 | 8 | 8.5 | 23 | 23 | 30 | 30 | 30 | 42 | 57 | 60 | 60 |
| Cut-out time/ (kW) | 10 | 15 | 8 | 20 | 16 | 18 | 25 | 5 | 14 | 19 | 13 | 27 |
5. Conclusions

In the non-intrusive monitoring and disaggregation of industrial load, the power feature has a poor recognition effect on the load, and the recognition accuracy is low when multiple loads are simultaneously operated. In order to solve the above problems, this paper introduces the time factor based on the study of Petri net theory, aiming at analyzing the industrial load production process from the time level. The experimental results show that the proposed method has good recognition accuracy and stability, and the accuracy of low-power load that is difficult to identify is significantly improved. Through the research of this paper, it is difficult to identify the industrial users' multi-production process based on a set of monitoring devices. Therefore, based on the research of this paper, it is the next research direction of this paper to continue the load identification and disaggregation of industrial users' multi-production processes.

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References

[1] X. Yu, X. Xu, S. Chen, A Brief Review to Integrated Energy System and Energy Internet [J]. Transactions of China Electrotechnical Society, vol. 31, no. 1, pp. 1-13, 2016.
[2] J. Xu, B. Wang, L. Yan, "The Strategy of the Smart Home Energy Optimization Control of the Hybrid Energy Coordinated Control[J]. Transactions of China Electrotechnical Society, vol. 32, no. 12, pp. 214-223, 2017.
[3] L. Fan, Z. Qu, S. Pei, The Evaluation for Maximum Power Supply Capability and Benefit of Increasing Power Supply of Distribution System [J]. Transactions of China Electrotechnical Society, vol. 32, no. S1, pp. 84-91, 2017.
[4] S. Wang, Z. Sun, F. Kong, Online building energy disaggregation orienting to demand response [J]. Electric Power Automation Equipment, vol. 37, no. 3, pp. 1-6, 2017.
[5] C. Wu, W. Tang, M. Bai, Optimal Planning of Energy Internet near User Side Based on Bi-Level Programming[J]. Transactions of China Electrotechnical Society, vol. 32, no. 21, pp. 122-131, 2017.
[6] B. Li, M. Du, Y. Zhu, A State Estimator for Smart Distribution Networks with Quasi-real Time Data [J]. Transactions of China Electrotechnical Society, vol. 31, no. 1, pp. 34-44, 2016.
[7] Y. Li. Comprehensive study of non-intrusive load decomposition algorithm[D]. Beijing: BeijingJiaotong University, 2016.
[8] B. Qi, Y. Cheng, H. Wu. Non-Intrusive Household Appliance Load Identification Method Based on Fisher Supervised Discriminant[J]. Power System Technology, vol. 40, no. 8, pp. 2484-2490, 2016.
[9] Y. Sun, C. Cui, J. Lu, A Non-Intrusive Household Load Monitoring Method Based on Genetic Optimization[J]. Power System Technology, vol. 40, no. 12, pp. 3912-3917, 2016.
[10] H. Wu, X. Han. Non-Intrusive Residential Load Decomposition Algorithm Solving Underdetermined Equations Based on Signal Sparsification [J]. Power System Technology, vol. 41, no. 9, pp. 3033-3040, 2017
[11] W. Liao, T. Gu, Y. Wang. Immune Scheduling Algorithm for FMS Based on Hybrid Petri Nets[J]. Journal of System Simulation, vol. 22, no. 1, pp. 205-209, 2010.
[12] W. Yang, W. Liao, W. Li, Intelligent routing algorithm considering turn delays based on Petri net[J]. Computer Engineering and Design, vol. 34, no. 10, pp. 3643-3648, 2013.
[13] X. Fang, Z. Wu, S. Liu. The Lookahead Study in Distributed Simulation of Timed Petri Nets[J].Computer Science, vol. 2016, no. 4, pp. 240-243.
[14] S. Lin, L. Zhao, Q. Liu, A non intrusive load identification method based on quadratic 0-1 programming[J]. Power System Protection and Control, vol. 44, no. 8, pp. 85-91, 2016.
[15] P. Li. Non-intrusive power load decomposition and monitoring[D], Tianjin University, 2009.