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RESEARCH ARTICLE

WaveLines: Towards Effective Visualization and Analysis of Stability in Power Grid Simulation

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Abstract Closely related to the safety and stability of power grids, stability analysis has long been a core topic in the electric industry. Conventional approaches employ computational simulation to make the quantitative judgement of the grid stability under distinctive conditions. The lack of in-depth data analysis tools has led to the difficulty in analytical tasks such as situation-aware analysis, instability reasoning and pattern recognition. To facilitate visual exploration and reasoning on the simulation data, we introduce WaveLines, a visual analysis approach which supports the supervisory control of multi-variate simulation time series of power grids. We design and implement an interactive system that supports a set of analytical tasks proposed by domain experts and experienced operators. Experiments have been conducted with domain experts to illustrate the usability and effectiveness of WaveLines.

Keywords Stability, Visual Analysis, Power Grid, Simulation Data

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1 Introduction

Studying the stability of power system is a fundamental problem in the electric industry [1] because severe blackouts and huge economic loss can be caused by system instability [2]. Based on the definitions proposed by CIGRE Study Committee and the IEEE Power System Dynamic Performance Committee [3], the stability of power system can be roughly classified with respect to three fundamental variables: rotor angle stability, frequency stability, and voltage stability.

Power grids [4] are a typical form of power systems and can be abstracted as networks. Figure 2 illustrates a typical configuration of a power grid. The nodes in the network are denoted as $V = \{v_i, r_j | i \in [1, n], j \in [1, m]\}$ where v_i and $r_j \in V$ indicates buses and generator buses respectively. Buses (v) allocate and deliver electricity generated by generator buses (r). The links are transmission lines connecting the nodes in V. A power grid is a complicated, dynamic and multi-faceted system. Controlled experiments on real power grids might result in unexpected loss, making simulation the unique acceptable way to test the system capability of recovering from accidents and to facilitate electric power planning. It has been verified that simulation can achieve comparable accuracy with the real situation [5, 6]. Our focus is the simulation data of the *transient stability*, which simulates the occurrence of electrical faults and the response of the power grid. The input of the simulator is the simulation time length $T = \{t_k | k \in [1, l]\}$, a electrical fault, its occurrence time $t_O \in T$ and its location $v_F \in V$. The output is a multi-variate time series set that records the temporal changes of the bus set V in multiple monitored variables (e.g., voltage) during time T.

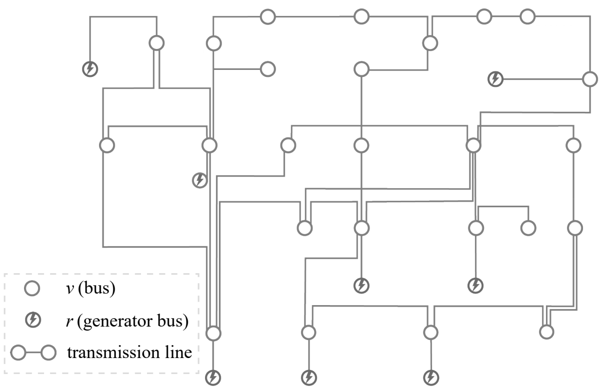

Fig. 1: A power grid consisting of 33 buses.

Different stability issues might occur in the simulation data when the power grid attempts to recover from a fault [3]. Traditional physical models are proved to be useful for analyzing the stability [7, 8]. However, it is still quite cumbersome for the analyst to identify the occurrences of faults, study the patterns, and inference the causes. Challenges for that include:

- There is a lack of models to quantitatively describe the stability state of a power grid. Conventional statistical methods only draw simple conclusions about whether a power grid is stable or not [9, 10], but are inefficient for characterizing global trend and fuzzy variations.
- The simulation data of a power grid contains multiple variables. The stability state is a comprehensive consequence of the evolution of all variables. Analyzing the stability demands reliable presentations of evolving details and expressive visual evidences.

The motivation of this work is three-fold. First, being the core of the simulation analysis of power grid, transient stability analysis is directly and closely related to the safety of the power grid. Second, the lack of quantitative models in electrical domain makes it difficult to bring advanced analytical tools into online inference. The analyst can hardly reason the system stability by solely observing the simulation result. Third, although visual forms like line charts, scatterplots and bar charts have been widely employed in analyzing simulation data of power grid, an effective visual analytical tool for depicting visual evidences are still missing.

In this paper, we focus on the visual analysis of power grid stability based on transient stability simulation data. We target at two main research problems: (1) How can be combine the human expertise with the computing ability of computers to provide a more efficient tool to judge the stability of a power grid after different faults take place? (2) How will the power grid behave when different kinds of faults take place? Our work is cooperated closely with domain experts of power system simulation. They provide domain experiences, simulation programs, datasets, and analytical tasks. Through detailed discussions in one year, we design and implement a visual analytics system to support visual exploration and analysis of power grid dynamics and stability, and to identify salient stability patterns. In summary, our contributions are as follows:

- We identify and formulate the design tasks and requirements for interactive visual diagnostics of power gird stability guided by domain knowledge.
- We design a suite of visual designs for numerical time-series that empowers the analyst with capabilities of visual inspection of global trends, local variations and correlations of multiple variables over time.
- We propose a new visual analysis approach, WaveLines (explained in Section 1), that supports the exploration, identification and inference of abnormality, stability, and fault of a power grid.

2 Related Work

2.1 Visual Analysis of Power Systems

Nowadays, visualization techniques have been widely applied in the manufacture domain [11, 12]. Advanced infrastructures and new policies in power systems together result in increasingly complex power grid structures and simulation data [13]. To achieve more efficient and convincing supervisory control of power systems, visual analysis approaches has been applied to deal with such complex simulation data [14].

However, till now, only a few visual analysis solutions have been developed. Tools like GreenGrid [15] and Grid-IE [16] provide a visual interface to solve situational awareness problems. Overbye et al. [17] visualize power flow for transmission analysis. These works introduce novel algorithms and models to improve their scalability and usability, tackling on real-world power system problems. Wong et al. [18] devise a large-scale visual analytics pipeline for power grid contingency analysis and develop an end-to-end solution.

These studies focus on regular operational data. In this work, we design and implement a visual analytic approach for simulation data of transient stability calculation. We address fundamentally different analytic tasks from those described above.

2.2 Visual Analysis of System Stability

Stability analysis can be summarized into a process of feature abstraction, computation, exhibition and most importantly, knowledge discovery. Interactive visual analytic techniques allow a better insight into the obscure computation results, contributing to the last two steps.

A large variety of visualization techniques for stability analysis have been applied in distinct fields, including finance [19], biology [20] and mathematics [21].Existing solutions for visualizing stability in power grid data mainly focus on voltage stability [22, 23]. Visual forms are employed to display the difference between the current operation point and the computed stability area or the stability margin. Cokkinides et al. [24] go one step further by not only monitoring system transient stability, but also visualizing the real-time state with system energy computation.

The aforementioned studies uses only one or two features. Stability of power grids, however, is a sophisticated result of interactions between multiple features (behaving as variables) in a complex dynamic system. Therefore, we hope the system presented in this paper can help experts in electric domain to break the curse of limited feature analysis and to depict the combined effect of multiple relevant factors.

2.3 Visualization of Time-series Data

Time-series visualization can be categorized into three types [25]. The first category is the typical linear and cyclic time [26]. The former is always visualized on the horizontal time axis and the latter is encoded on the spiral-shaped time axis to reveal periodic characteristics. The second category includes visualizations of discrete time points, such Marey's Graph [27] and Sankey diagram [28], and time interval visualizations aiming to present temporal relationships [29]. The third category includes visualizations of ordered time [30] and branching time [31].

Among all these categories of visualizations, efforts have been made to extend these approaches to more complex multivariate time series. For instance, TimeWheel [32] represents the value of different variables at discrete time points, but it causes serious visual occlusion with the increasing amount of time points and are not suitable for continuous time. Instead, ThemeRiver [33] indicates the continuous temporal evolution of multiple variables in a stacked form. Other visualizations like dynamic graph and matrix can also be used to represent temporal changes. For example, Zhao et al. [34] proposed the MatrixWave to organize ordered event sequences by matrix sequence connected in a zig-zag manner. Particularly, connected scatterplot [35] visualized pairwise time series in a two-dimensional coordinate system. It can reveal the correlation between pairs of variables.

However, a visual representation that not only supports intuitive correlation analysis of multivariate time series generated by an individual, but also facilitates the legible comparison among a group of such individuals in limited resolution and screen space is still missing.

In summary, there is still a lack of visualization-based power grid stability analysis among all kinds of the previous works. As a result, enlightened by the analysis pipelines from power system visualization studies, the knowledge discovery processes from the stability visualization studies and the human-machine interactions from the time-series visualization studies, we decide to implement an visual approach that supports not onlythe supervisory control, but also the stability analysis of power grids.

3 Tasks and Approach Overview

3.1 Working with Domain Experts

Two domain experts from China Electric Power Research Institute (CEPRI) were closely involved in this study. They are both senior engineers engaged in power grid simulation and analysis. Their responsibilities include predictive simulation of regular operations, preventive simulation of possible faults and abductive simulation of already-occurred accidents. For decades, their team has been developing simulation tools to solve large-scale non-linear differential simulation equations. From their perspective, the limitation of analysis methods has blocked the way for computational methods to further progress. Therefore, a visual analytics system is needed to fill the gap between numerical calculation and data analysis.

We followed the Sedlmair's design study methodology [36] and conducted three formal interviews with domain experts. In the first interview, experts introduced basic domain knowledge and described the problem of stability analysis. Based on this, we characterized the visual analytical tasks in the following. Before the second interview, we introduced our prototype to experts. After that, we interviewed the experts to collect feedback. Some confusing cases are discovered and examined during the interview. In the last interview, a complete version of Wavelines was provided.

3.2 Task Analysis

We characterize the following visual analytical tasks based on the interviews with the domain experts.

T1. To gain situational awareness of the power grid after a fault is triggered. When answering the question of how they judge the stability of a power grid during the interview, experts said that they needed to know the connectivity between nodes and a summarization of changes on all nodes. In other words, a full picture of the grid is needed.

T2. To discover frequent patterns when a fault takes place. During the interview, we asked the question that how faults affected the operation of the power grid. Experts explained that different kind of faults resulted in different changes of power grid states. They were interested in distinguishing and classifying frequent patterns of power grid states.

T3. To distinguish between stable and unstable cases. As the experts mentioned during the interview, the major goal of stability analysis was to identify unstable cases from most of the stable ones.

3.3 Approach Overview

Our approach consists of three major components: a data module, a data processing module and a visual analysis module. The data module abstracts the transient simulation data, including the structure and time-varying states of the power grid. Among hundreds of time-varying variables in the mathematical model, we choose the voltage, frequency, and rotor angle (RA) to represent the states of the power system according to our collaborated experts. These variables are the most meaningful features used to support stability analysis and are also the most commonly used ones. The data processing module performs a set of computations to the input data, including distance computation for graph construction, and similarity computation for node ranking. The visual analysis module provides multi-faceted presentation of the raw time-series and identified frequent patterns within an integrated visual design framework, WaveLines (Section 4). A suite of visual analytics views and user-interactions is provided to augment the decision-making process (Section 5).

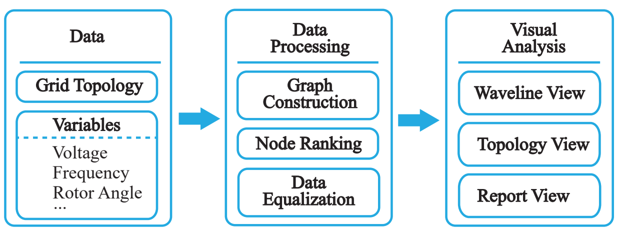

Fig. 2: An overview of the WaveLines architecture.

4 The WaveLines Representation

4.1 The Representation

The WaveLines representation consists of two components: the time series and the grid topology.

4.1.1 Time series

To discover frequent patterns of power grid states (**T2**), we need to compare between three dimensions, namely, *(time, bus, variable)*. Conventional solutions always consider one *variable* each time [37, 38]. However, this might lose the coherence between different *variables*. The connected scatterplot design [35] reveals the correlation between pairwise *variables* but always takes too much space. Therefore, we propose the *wavelines*, which can not only reveal the joint evolution of two variables in a single visual element, but also compare the difference between time series of multiple buses.

As for WaveLines, the input is a three dimensional array, *(time, bus, variable)*. The length of the *variable* dimension is limited to two to support clear perception and effective comparison after repeated trials. The output is a set of vertically juxtaposed color bars, namely, wavelines, and is provided in two optional representations: the wavelines (*wl*,Figure 3 (a)) and the stacked wavelines (*swl*,Figure 3 (b)). As shown in Figure 3 (a), the *time, bus* dimensions are encoded by the horizontal and vertical axis respectively. The values of the two variables (*variable* dimension) are encoded by the color and the height of the color bar. Both the *wl* and the *swl* preserve temporal coherence, but the former is less efficient in presenting the coherence among buses because color bars are separately placed. Instead, the latter compensates this problem and easily discloses local disturbance.

Alternative designs Several alternative visualization designs have been considered before we finally decide to adopt the wavelines. First, line chart is a direct way to visualize multivariate time series. Correlations can be easily distinguished in a line chart, but the comparison of a group of line charts requires too much valuable screen space and is less effective when the number of line charts is more than a dozen. Second, heatmap is a possible approach to compare the time series of a group of buses, but a single heatmap can hardly be applied to interpret pairwise variables with acceptable modification. Third, streamgraph is suitable for time series of pairwise variables and performs better on the issue of space-saving than line charts. However, it cannot support negative values.

***Wavelines* Representations of Discovered Patterns** We now introduce the identified patterns from the *wavelines* and summarize them into three categories: substructure pattern (Figure 4 A), correlation pattern (Figure 4 B) and propagation pattern (Figure 4 C).

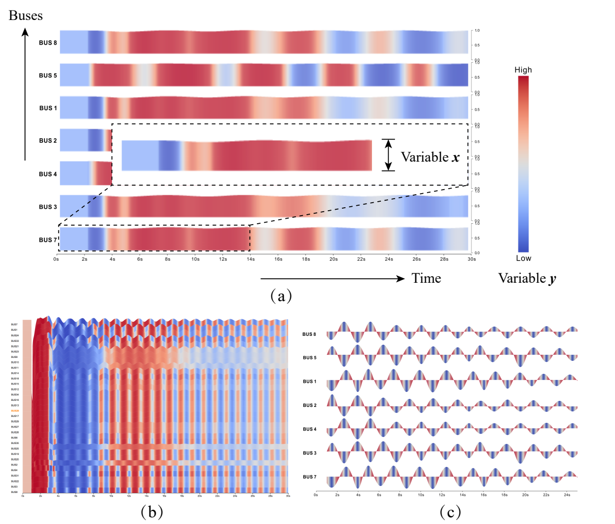

Fig. 3: Different forms of the WaveLines design presenting periodic fluctuations of the voltage(height)-frequency(color) pair. (a) The wavelines. (b) The stacked wavelines. (c) The deviation time-series.

- **Substructure Patterns**.The stable pattern is the most common one, behaving as gradually smaller amplitude in shape and increasing intervals between red-and-blue in color. Unstable patterns can be divided into four categories: the periodic instability, the first-swing instability, the multi-swing instability and the coherent-swing instability. The periodic one behaves as dense waves with changeless amplitude in shape and frequent red-and-blue intervals in color. The first-swing instability behaves as a tremendous wave with continuously increasing/decreasing amplitude in shape and increasingly redder/bluer in color. The multi-swing instability refers to trajectories which oscillate several cycles first and then become unbounded, behaving as wave with increasingly larger amplitude and increasingly deeper color intervals. The coherent-swing instability illustrates devices in a sub-grid coherently lose synchronism with the rest after being subjected to a finite disturbance, behaving as opposite shape and color behaviors of the wavelines for sub-grid devices.
- **Correlation Patterns**.Positive and negative correlations can be easily recognized. Positive correlations behave

as matching shape and color in a both increasing or both decreasing pattern, while negative correlations behave as mismatched.

- **Propagation Patterns**.Propagation patterns are reflected by juxtaposed wavelines. The propagation of the fault starts from the fault center to its nearby buses, behaving as increasingly shrinking shape or weaker color from the fault center waveline to the others.

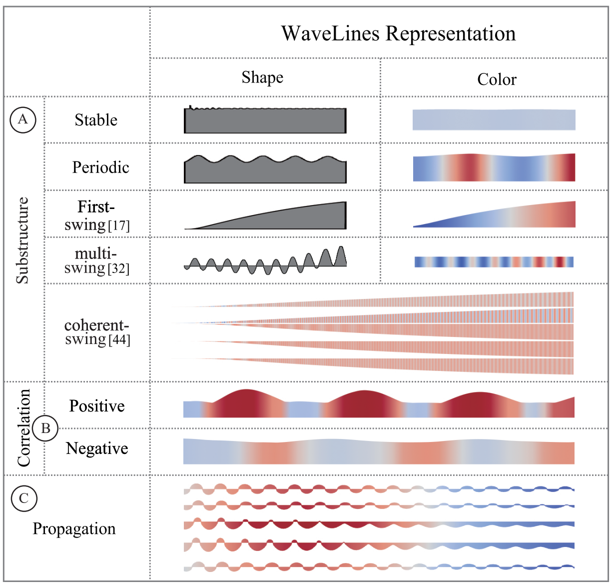

Fig. 4: Frequent substructure, correlation and propagation patterns. The shape and color feature are provided separately for patterns involving only a single variable.

4.1.2 Grid topology

Given the topological structure of the power grid, we need to further summarize the state changes of all buses to help experts gain the situational awareness of the power grid (**T1**). We apply a novel 'light bulb' glyph to summarize the features of the buses because it not only reveals how the connectivity between buses influences the propagation of a fault, but also corresponds to the metaphor that buses connected in the power grid are functioning like a light bulb.

The glyph of each bus follows a consistent design with the wavelines, using the metaphor of a light bulb (Figure 5). The reference voltage of each bus is represented as a circle in the middle, whose color and size indicate its value, surrounded by two layers of concentric arc areas. The reference voltage value indicates the power delivery ability of buses. The larger the reference voltage, the more electricity can be delivered by this bus. The timeline of the inner and outer arc areas records the temporal evolution of two variables in a clockwise order. Instead of drawing the timeline as a complete circle, we use a circular arc with a gap at the bottom to differentiate the starting and ending time. The bus index is encoded at the bottom of the glyph with orange color indicating a fault center. To summarize the fluctuation of each variable, we separate the entire time period into time windows of fixed length. The default length is set to 40 time points because it is found after many experiments that such aggregation granularity can better preserve the evolution trend of most variables. Each time window is represented as a bar rising from the baseline arc, with height indicating the average value of that variable in this time window. Negative average values of each time window are all flipped to the outward side of the baseline arc to save spaces. Green and yellow are used to indicate negative and positive values respectively. We map green to negative values because it has a cold hue.

Design Considerations We now explain the design choices we made when designing the 'light bulb' glyph. First, a circular-shaped time axis allows the concentric arcs design. For concentric arcs of the same time length, the outermost one possesses the biggest area and the leading position. Therefore, analysts will naturally look for the outer-to-inner influence, instead of being lost in the A-to-B or B-to-A causality analysis. Second, we use two layers of concentric arcs rather than use both height and color on a single arc to represent two variables because the color transition is obscure within very limited pixels.

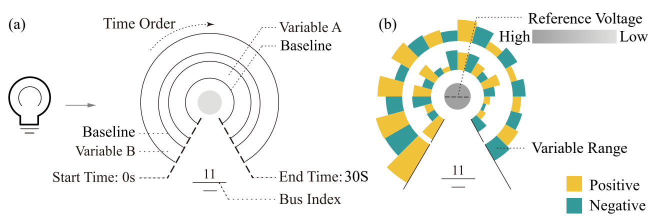

Fig. 5: Glyph design of a single node. (a) The concept map of the design, indicating the metaphor of a light bulb. (b) Visual encodings of the design.

4.2 Auxiliary Designs

To support more effective analysis and pattern discovery, the following transformations are made to the WaveLines representation. Users can also decide to enable or disable these transformations interactively.

Buses are ranked according to the electrical distance. An ordered arrangement is more likely to uncover meaningful patterns. The ranking operation is performed in three steps. First, the electrical distance is computed to measure the similarity between buses, denoted as:

$$E(v_i, v_j) = \sqrt{R^2(v_i, v_j) + X^2(v_i, v_j)}\ , v_i, v_j \in V,$$

where $E(v_i, v_j)$ denotes the electrical distance between bus v_i and v_j, $R(v_i, v_j)$ and $X(v_i, v_j)$ denote the positive sequence resistance and reactance respectively. Second, we construct an undirected weighted graph $G = (V, E)$ of the power grid, in which E indicates the edge set consisting of electrical distances. The Dijkstra algorithm [39] is employed to compute the shortest path between the fault location v_F and other buses. Finally, the buses are ranked in two optional modes. One places v_F in the center of the vertical axis and other buses upwards or downwards according to their distance to v_F. The other places v_F at the bottom.

Variables encoded by the color are additionally interpreted by a luminance map. We employ a linear luminance map to enhance the original blue-to-red color map [40, 41] so that colorblind users are also welcomed.

Variables encoded by the height are normalized and scaled. For some variables, the range of different buses may vary significantly and even for a single bus there may exist extreme values. We apply a linear $[0, 1]$ normalization and a square root/log operator to alleviate these two problems respectively.

The deviation time series is computed for variables. The limited screen space for juxtaposed wavelines and the diminished numerical values caused by normalization lead to manually indistinguishable variation of wavelines. We compute the difference between the reference value (a constant value that a bus will keep if no fault is triggered) and actual value, yielding a deviation time-series to amplify the numerical difference (Figure 3 (c)).

Transformation Trade-offs We now discuss trade-offs of the last two transformations. First, by applying normalization, the evolution trend of less important nodes with low average values is amplified. Therefore, the importance of nodes get obscured. Because our major task is to explore the stability, being a global state that requires a balanced observation of every node, we choose to normalize the raw data. Second, we also apply the deviation time series to emphasize the deviation from the reference value, which amplifies the numerical difference. However, it may become less intuitive to perceive the actual value of the variable. Since the stability analysis focuses more on the difference rather than the original value, the deviation time series is adopted. Third, non-linear scaling turns extreme values to a perceptible level at a price of changing the data distribution and value. As a result, users are only suggested to apply non-linear scaling when the existence of extreme values causes difficulty in perceiving most of the normal values. Users are not suggested to apply non-linear scaling when the evolution trend is smooth without extreme values and can be clearly perceived.

5 Visual Analysis with the WaveLines

5.1 Visual Interface

The WaveLines interface consists of three views: the topology view (Figure 6 a), the wavelines view (Figure 6 b) and the report view (Figure 6 c). The topology view and the wavelines view show the topology and the temporal evolution of the power grid respectively. The report view provides a list of observation items and their possible answers, including the stability state, the patterns and the evolution of variables. Users choose the answers and make annotations during the exploration. The following interactions are provided:

Details-on-demand WaveLines can be browsed by free zooming. Users are allowed to zoom in and out by scrolling the mouse wheel. In the topology view, the zooming level decides the amount of information shown on each glyph. Zooming in provides more exploration space for the focused area, which makes it possible to increase the amount of time windows and shrink the time length for each time window. In the wavelines view, zooming on the time interval enables more precise reading of the time stamps.

Dynamic Linking Instead of highlighting selected items, we employ dynamic linking among the topology view and the wavelines view to build direct and comprehensible cognitive

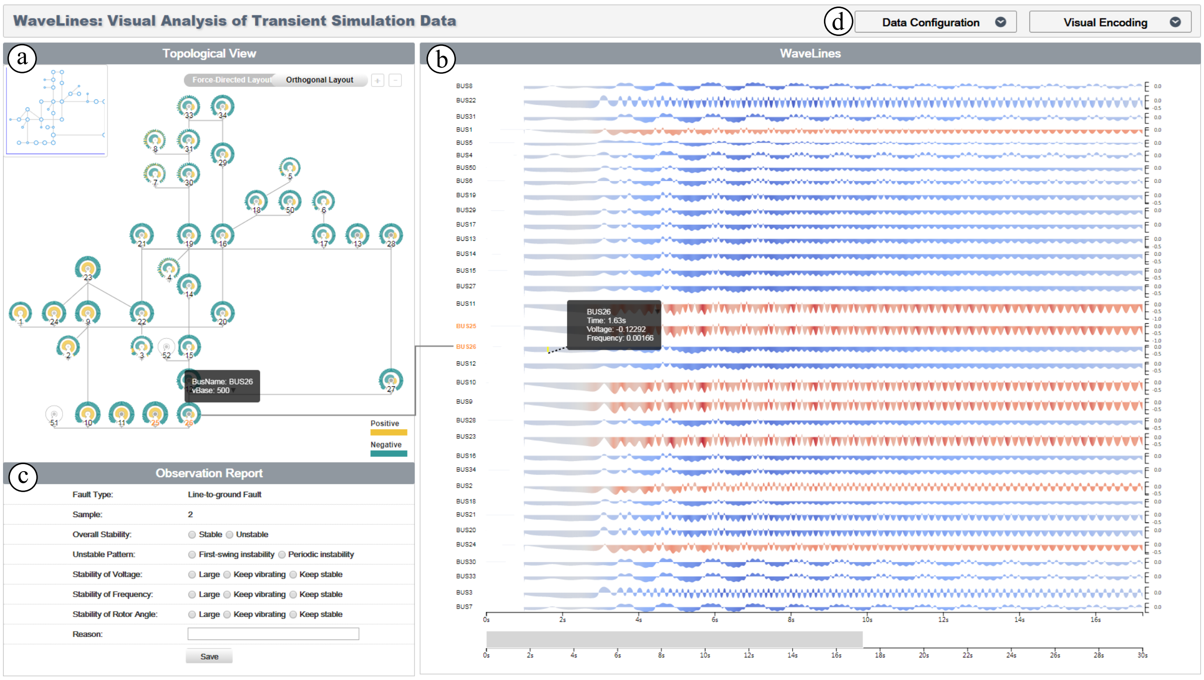

Fig. 6: The interface of WaveLines, showing the simulation of a power system after being affected by a three-phase grounding fault. (a) The topological view illustrates the topological structure of the power grid. (b) The wavelines view depicts time-series of one or two variables of buses in the power grid. (c) The report view allows for annotating and saving observations in the analysis process. (d) The control panel offers options of visual encodings and parameter adjustments.

connection between the waveline of a specific bus and its location in the power grid topology.

Reordering Despite two automatic ranking modes of buses, we encourage users to manually adjust the order of buses in the wavelines view to support easy comparison.

5.2 The Visual Analysis Pipeline

Figure 7 illustrates the general visual analysis pipeline of WaveLines. To trigger the visualization, users first need to select a data configuration. For example, a fault type will be selected and users can change the fault locations and variables. In particular, users are allowed to select the same variable twice to construct WaveLines for a single variable.

Then users can interactively explore the stability and the patterns in the WaveLines interface. First, users receive an overview of the global state of the power grid in the topology, according to which users decide whether this data sample worth further investigation. Users will go back to the data selection step and change the data configuration if the selected sample is of less research value. In practice, we find users are more interested to further investigate data samples with outliers, communities and drastic changes. When an interesting sample is discovered, users are able to analyze the stability in the more detailed wavelines view and identify fault propagation with the help of the topology view.

During the exploration, users make annotations in the report view to record stability patterns and the report file is saved. Users are allowed to directly compare the textualized patterns in the reports or generate statistical results.

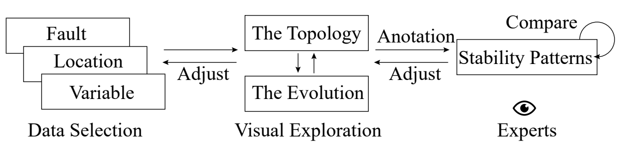

Fig. 7: The general pipeline of WaveLines.

5.3 Compare to Other Tools

In this section, we compare the WaveLines interface with other two designs focusing on the supervisory control of power grids, namely, Grid-IE [16] and GreenGrid [15] (Table 1). Grid-IE integrates heterogeneous real-time data into an explicit geographical-based map. It displays variations by animation but lacks the support for correlation and comparison analysis. GreenGrid applies force-directed algorithm to visualize the outputs of steady-state simulations. However, patterns are not addressed. In comparison, Wavelines allows in-depth stability analysis by offering the following advantages. First, the combination of the grid topology and the dynamic variation of the wavelines assure the accuracy of power grid supervisory control(**T1**). Second, the design of the wavelines makes it easier to identify pairwise correlations and to compare different nodes. Therefore, analysts would be more likely to discover frequent patterns (**T2**) and unstable cases(**T3**).

Table 1: Comparing WaveLines with Grid-IE [16] and GreenGrid [15].

	Grid-IE [16]	GreenGrid [15]	WaveLines
Topology	Geographic	Force-directed	Force-directed + Orthogonal
Analyzing Time-series	No	No	Yes
Correlation	No	No	Yes
Stability Analysis	No	No	Yes
Visual Form	Graph	Graph	Graph + WaveLines

6 Experimental configurations

To evaluate the effectiveness and usefulness of WaveLines, we conduct case studies (Section 7) and expert interviews (Section 8) in collaboration with domain experts from CEPRI. The two experts participated in the case study and the pilot study of the expert interview are the experts mentioned in Section 1. The other experts participated in the expert interview will be described in Section 8.

Transient simulation results run on one power grid of 39 nodes are used to testify the performance of Wavelines. As shown in Figure 8, four different types of faults (grounding of bus, disconnection of AC line, exit of generator and line-to-ground) are imposed on different nodes of the power grid in the simulation to generate various simulation data samples, resulting in 60 simulation samples in total. 8 generators locate on eight of the nodes that have rotor angle values. Each time series records the value of a variable in a time length of 30 seconds. The fault is triggered at 1 second and the sampling interval is 0.01 second. Thus the time series contains 3,000 time points.

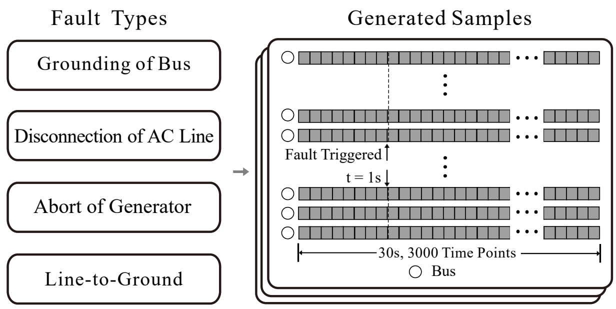

Fig. 8: The data includes simulation samples affected by four types of faults (listed on the left side). For each sample , the entire simulation length is 30 seconds and the fault is triggered on a specific bus at the end of the first second.

The back-end part is deployed on a server with a 3.40GHz Intel Core i7 CPU, 8GB memory PC and users could get access to the system through the web browser. All case studies and expert interviews are conducted with a 23 inches monitor whose optimum resolution is 1920×1080. Before the data can be explored in the system, it is processed at the back-end with Python. The whole data processing takes about 9 minutes. The initial front-end rendering for each sample takes about 1.2 seconds. It is optimized to 0.6 seconds by reducing the size of the color gradient map for frequency.

7 Case Studies

In this section, we present typical use cases that are identified by the expert. To avoid risks of confirmation bias, none of the cases in this Section is used in the following user study or expert interview. The domain expert aims to examine whether the power grid is able to keep stable under different situations. Particularly, he focuses on exploring the unstable cases indicating the power grid will break down, so that he is able to adjust the real-world dispatch of the power grid to avoid potential breakdowns.

7.1 Case 1: Three-Phase Grounding Fault

Line-to-ground fault is one of the most common faults that take place in power grid. It will trip off the circuit breaker and lead to a power down situation. Focusing on this kind of faults, the expert discovered two typical examples of a system gradually regaining stability (Figure 9) and becoming unstable (Figure 6). Wavelines with height indicating voltage and color indicating frequency is applied in both cases.

Case 1.1: Stability Recovery Deviation time series was applied to examine the overall state of the power gird after the fault took place (**T1**). Starting from the topology view, a dramatic voltage drop was noticed on most nodes, behaving as a long blue bar at the beginning of the outer arc (Figure 9 (a)). Then, the expert turned to the wavelines view. By zooming in to the beginning of the timeline, he discovered this sudden change had happened at the exact moment when the fault occurred (1 second). Then at the next moment (1.01 second), voltage rose again, accompanied by fluctuations of both voltage and frequency. This behaved as periodically changing wave shape and red-blue-intervals (Figure 9 (b)). However, the suppressed shape and color of color bars prevented the expert from further identifying interesting patterns. So he applied nonlinear scaling (Figure 9 (c)), and clearly noticed that voltage (amplitude) and frequency (color) gradually diminished (**T2, T3**).

The expert then applied the original time series to complete his inference. Two buses, bus 24 and 1, were identified due to their distinctive frequency evolution patterns (Figure 9 (d)). He then checked the data and found this was caused by the grounding of bus 24 and 9. Given that bus 24 directly connects with bus 9 and 1 in the power grid topology, the analyst further noticed that this was a three-phase grounding fault, which was a specific kind of line-to-ground faults. The frequency pattern is caused by the speed adjustment of the generator on bus 1 after the fault took place.

Based on these observations, the expert concluded that the power grid gradually became stable and recorded his findings in the report view.

Case 1.2: Becoming Unstable Figure 6 depicts another case of a line-to-ground fault. The expert noticed the voltage kept fluctuating and the frequency of several buses increases to an abnormal value (**T2**). The analyst confirmed that this case is a typical unstable case (**T1, T3**).

In this case, the faulty part gradually influences the entire grid. The expert applied the fault-bus-centered ranking method to understand the propagation pattern. He discovered buses near the fault received greater impacts, exhibiting a severer change in voltage and a similar frequency evolution. He then drew out the recorded log of case 1.1 and compared these two cases. He noticed that the faulty buses in case 1.1 were 220 KV lines while the faulty buses in this case were 500 KV lines. This meant that the faulty buses in this case were more significant ones and transferred more electricity. Therefore, the impact of the fault in this case is too strong to recover, resulting in an unstable case.

7.2 Case 2: Generator Exiting Fault

Generator analysis is an essential part of power grid stability analysis. The analyst selected a case in which the generator on bus 6 exited and applied the frequency (height) and voltage (color) pair of the deviation time series. An obvious increase of frequency could be seen in the topology view, accompanied by huge decrease of voltage on bus 6. The red-and-blue color intervals on wavelines further suggested there existed voltage fluctuations on some nodes(**T1, T2**).

To explore the impact of generators on the two different voltage performances, the expert applied RA (height) and voltage (color) pair. Wavelines of the eight generators indicated a drop-to-zero behavior of RA and a huge voltage drop on bus 6, which is understandable because the generator on bus 6 had stopped working. But all other generators exhibited a continuous increase of rotor angle because they need to work faster to compensate the ceased work on bus 6, leading to unstable voltage fluctuations on these generators. Buses far away from a generator didn't show obvious voltage changes. Based on the joint behavior of all variables, the power grid is recognized as an unstable one (**T3**).

8 Expert Interview

We used the same dataset described in Section 7 and conducted an expert interview to demonstrate the efficiency and effectiveness of the WaveLines. Guided by [42], the expert interview consisted of three components: a pilot interview, a formal interview and an afterward interview.

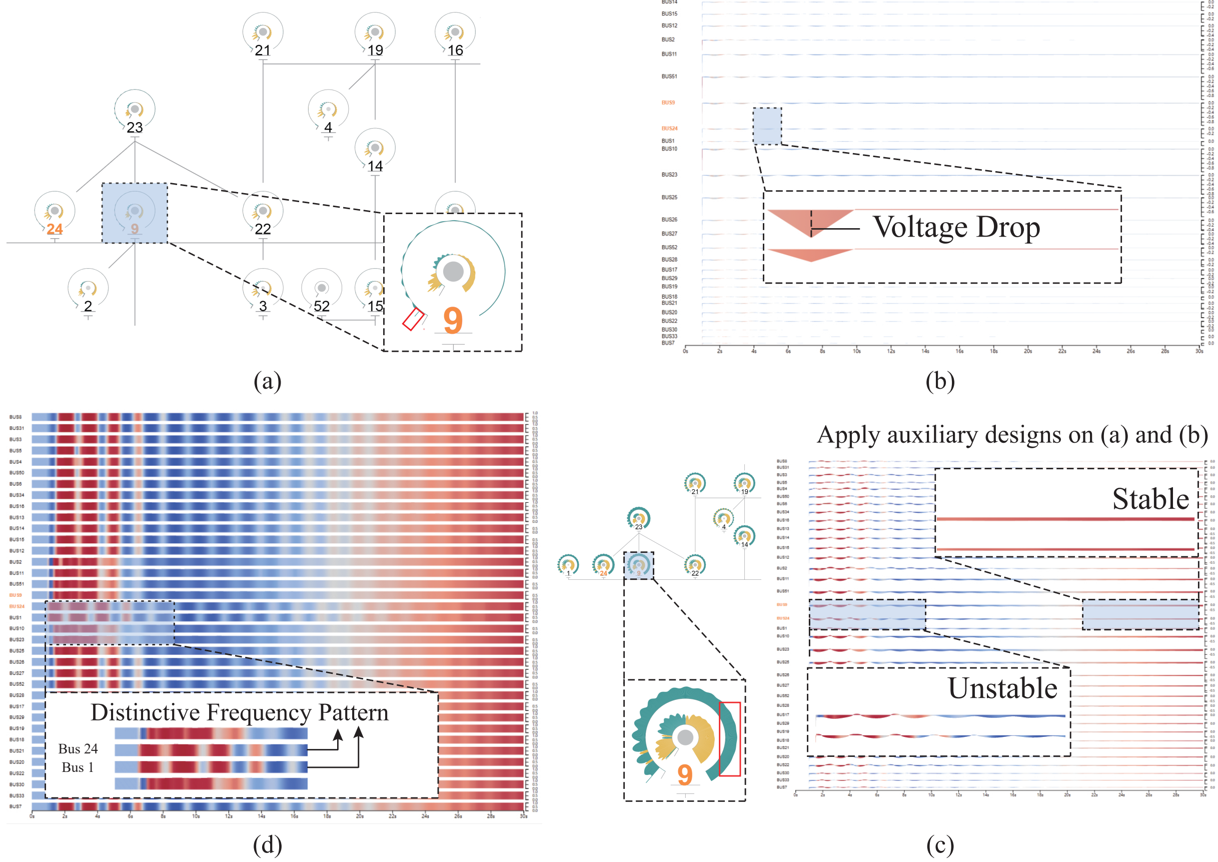

Fig. 9: A power system regains its stability after being affected by a TPH fault, in which the voltage(height)-frequency(color) pair is applied. (a) The topology view indicates a voltage drop. (b) More detailed voltage behavior shows in the wavelines view. (c) Non-linear scaling is applied to enhance readability. (d) Distinctive frequency patterns showed by the original times series.

8.1 Participants

We invited sixteen target users from the power system simulation department of CEPRI, including engineers working on simulation program and software development, and data analysts focusing on the power system simulation data. Among them, two engineers were the same experts mentioned in Section 1 and they were invited to the pilot interview. To avoid risks of confirmation bias, the other fourteen users, including ten engineers and four data analysts, were invited to the formal interview and the afterward interview. None of them had used our system before or had knowledge of visualization techniques except traditional statistical charts.

8.2 Procedure

We first conducted the pilot interview, during which we presented the first version of the WaveLines and asked the two participants to explore the system and to identify usability issues. According to their suggestions, we refined the system and conducted the user study and the afterward interview one month later.

During the formal interview, the fourteen participants were evenly divided into two groups: an experiment group and a control group. Both groups were asked to answer a set of questions (Table 2) according to five randomly selected data samples. The difference was that the experimental group answered such questions by exploring the WaveLines interface while the control group by exploring traditional line charts they always used. Time for each user study was limited to 10 minutes and the time for each participant to answer each question was also recorded.

Immediately after the formal interview, we conducted an interview for each participant. They were first asked to score 1-5 points for the questions in Table 3, with each question pointing to a specific task (**T1,T2,T3**) in Section 3. Then we gathered their feedback on the usability, visual design and interactions of the system as well as suggestions for potential improvements. The interview lasted about 25 minutes.

8.3 Feedback

8.3.1 The pilot interview

During the pilot interview, although the WaveLines designs received encouraging comments, usability issues are also raised. First, initially there was only the force-directed layout in the topology view. The participants commented that it was not easy to understand and the dynamic layout would confuse users in topology identification. Therefore, we added an option of the static orthogonal layout which is more familiar to our target users. Second, the glyph in the topology view was initially designed as simple rectangles. The participants recommended that more information, for example, the variation trend, should be displayed. We then proposed the light bulb glyph design to meet this requirement.

8.3.2 The formal interview

Since our participants are all experienced domain experts, their answers for each question are all reasonable and convincing. Therefore, we only evaluate the efficiency rather than the accuracy. Figure 10 shows the average time that both group used to answer each question. The experimental group is marked as blue and the control group is marked as yellow. The answering time of the experiment group is significantly less than the control group for most of the questions, indicating the effectiveness and efficiency of the WaveLines. In particular, the results of question 2 and 3 indicate that the topology view and the 'light bulb' design achieves equal performance with the line charts in overall state analysis, but performs much better in identifying significant buses. The results of question 5-6 indicate that the wavelines representation is a more efficient tool used to identify frequent patterns, especially the propagation patterns. This is contributed by the bus ranking method provide in the WaveLines interface.

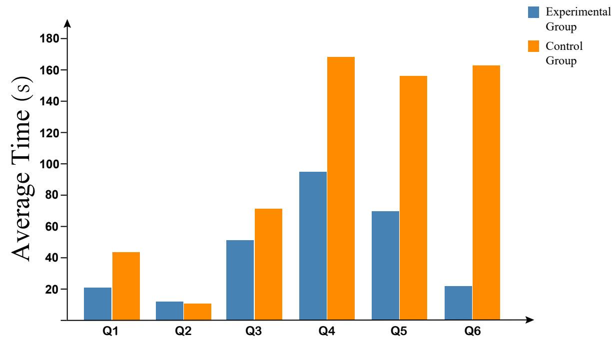

Fig. 10: Evaluation results of the user study, showing the average answering time of each question in Table 2.

8.3.3 The afterward interview

Figure 11 shows the average scoring of questions in Table 3. Most questions receives a positive affirmation with scores higher than 3. Considering that the none of the participants is familiar with visualization techniques, the scoring result is quite encouraging. Particularly, question 6 obtains an average score of 5, indicating the usefulness of the WaveLines representation. Scores of question 8 and 9 ensure that simple understandable visual representations and interactions are provided in the system and preferred by experts. The relatively lower score of question 2 and 4 result from the the glyph design in the topology view. As one of the engineers pointed out, "*It (the glyph of each bus in the topology view) does present a high-level distribution of pairwise variables along the time axis, but the limitation of resolution makes it difficult to compare between different buses.*"

Overall system usability The interviewees confirmed that the system was more effective in displaying the temporal variation of buses than traditional cluttered statistical charts. Therefore, it was more efficient for them to judge the stability and identify frequent patterns by using the WaveLines interface. In particular, they also mentioned that the WaveLines interface could help them reason ustable cases. As one of the engineers commented, *"The WaveLines system makes it more convenient to analyze different aspects of the power grid and can be useful to be integrated with other power grid analysis approaches."*

Visual design and interactions Visual designs, including

Table 2: Questions for the user study.

1. Is the power grid stable or not? (**T3**)
2. According to the topology view, tell the global variation trend of the grid.(**T1**)
3. According to the topology view, list the three most affected nodes.(**T1**)
4. According to the wavelines view, find the existing substructure patterns. (**T2**)
5. According to the wavelines view, find the existing correlation patterns. (**T2**)
6. According to the wavelines view, find the existing propagation patterns. (**T2**)

Table 3: Questions for the afterward interview.

1. Is it easy to discover the joint temporal behavior of different variables? (**T2**)
2. Is it easy to compare changes of different nodes? (**T2**)
3. Is it easy to tell the stability? (**T3**)
4. Is it easy to tell the overall state? (**T1**)
5. Is it easier to locate local disturbance in the stacked wavelines representation? (**T1**)
6. Interactions & optional visual encodings are helpful. (**T3**)
7. The topology view is helpful. (**T1**)
8. I can understand the visual encoding and interactions. (**Readability**)
9. I prefer the analysis process in the system. (**Usability**)

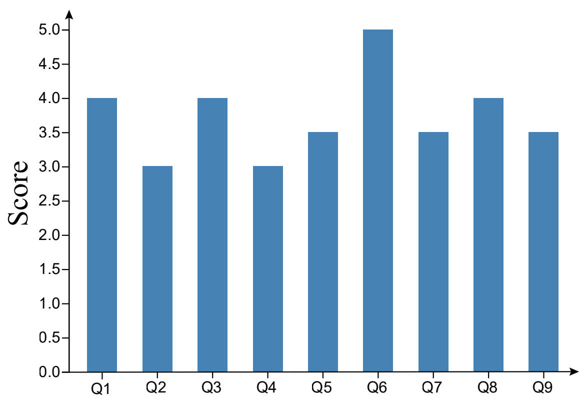

Fig. 11: Evaluation results of the interview, showing the average scores of each question in Table 3

the wavelines representation and the glyph in the topology view, were appreciated by most of the interviewees. They agreed that the wavelines representation revealed the joint evolution between pairwise variables. One of the data analyst commented, *"It could be used to analyze the mutual influence between variables, indicating the sensitivity between these variables as well as between variables and faults."* He also confirmed that although the light bulb glyph took some time to understand and was a little bit too small, it was interesting and informative to summarize the power grid state, *"The glyph provide a temporal overview of the entire power grid. It is easier to associate nodes' behaviors with their locations in the power grid structure by directly exploring the glyph in the topology view."* For the two topology layouts, the orthogonal one is preferred. It is probably because it looks like traditional circuit diagrams and is more familiar to the interviewees. The interviewees are also satisfied with the interactions. A data analyst commented, *"The dynamic linking allows me to quickly locate the interested bus in the topology view. It is convenient to put buses with similar patterns together by dragging and reordering."*

Suggestions The interviewees also mentioned the limitations and provided many valuable suggestions. A data analyst pointed out that it took time to learn the glyph in the topology view and compare between glyphs. He commented, *"The glyph should be bigger to help easy recognition. Moreover, it would be more convenient to provide detailed comparison between glyphs."* Also he suggested although our ranking algorithm had done a great job in aggregating similar wavelines, temporal variation should also be considered.

9 Discussion

In this Section, we discuss the advantages and limitations of the WaveLines.

Generality WaveLines is a general approach for paired time series. It is also a preliminary attempt to apply simple and atomic level visualizations to multivariate time series. Although our work limits the number of variables to two, it is possible to achieve more by adding other visual channels, e.g., texture and density, to the wavelines. However, the number of variables is still limited because too many visual channels causes perception difficulties.

Limitations There are several limitations of the current system. First, the juxtaposition of the wavelines is limited to dozens of nodes, resulting in the scalability issue. Design trade-offs between the demand of showing details and the information loss brought by aggregation should be taken into consideration. Second, automatic frequent pattern mining approaches should be further supported to enhance the efficiency.

10 Conclusions and Future Work

In this paper, we introduce a novel visual representation targeted at the application domain of simulation based stability analysis in the electric industry. We propose an effective visualization system for correlation analysis of multi-variate simulation time series, aimed at helping analyze the stability of power grid. We collaborate closely with domain experts and extract a series of analytical tasks and requirements to guide the system design. Case studies and the feedback from experts have verified the effectiveness and practicability of our system. To the best of our knowledge, this is the first attempt to apply a systematic visual representation in the stability analysis of power grid. We believe that the presented work is promising to inspire future analysis for power grid.

There are several directions for future work. First, as the WaveLines has been deployed in the CEPRI, it becomes possible to study its long-term performance. Advanced learning approaches like deep learning could be applied to automatically generate and gather reports, realizing an intelligent investigation. Second, the WaveLines needs to be extended to large-scale datasets with a more sophisticated solution. Third, the design should adapt to the level-of-details principal, allowing explorations of different levels of granularity. Fourth, automatic frequent pattern mining methods need to be introduced to accelerate the tedious process of manually pattern mining. Finally, automatic algorithms can be used to detect and suggest possible insights to further enhance the efficiency of the discovery process.

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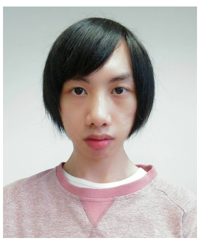

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