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A Taxonomy of Load Signatures for Single-Phase Electric Appliances

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Abstract:

Load signature analysis is an emerging research topic highly relevant to electric utility companies. The knowledge of the nature and taxonomy of electric loads would provide invaluable information for power industry to understand how their low-voltage power sources (ac mains) are used. In this project, a new methodology in load signature analysis is reported. Using input current waveforms and 2-dimensional voltage-current trajectories, a framework for taxonomy of electric loads based on over 120 single-phase office and domestic electric appliances is proposed. This research study indicates that the front-end power electronic circuits and the mechanical characteristics of some electromechanical loads play critical roles in both load signature and taxonomy of electric loads.

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1. Introduction:

New and developing technologies provide a better understanding of the usage of electric power, and promise to strengthen the link between electric utility companies and their customers. The future may include “smart meters” that can analyze electrical load signatures to monitor usage and relay this information to the utility. Knowledge of electric load signatures is the foundation of practical technologies for load monitoring, load diagnostics, power quality control and power circuit design. Such knowledge can provide benefits to utilities, customers, regulators, appliance manufacturers and others. A utility can improve planning and operations and develop new products and services, such as enhanced building audits, optimized operation and other energy services. Customers benefit from reduced costs and improvements in power quality and reliability. Regulators can improve the precision and relevance of policies and rules. Manufacturers of appliances and equipment can improve quality and compliance, while anticipating market demands and providing more effective and efficient products.

Previously, different application-specific methods have been used to understand different aspects of loads: power quality and efficiency, reactive power compensation, system planning, load shedding, etc. At the core of these approaches is the need to understand the load characteristic - load signatures - of electrical appliances and equipment. Some understanding of load signatures has emerged from work in non-intrusive load monitoring (NILM) [1-6], echo-resonance load monitoring [7], and other methods. Recent research [8] suggests the creation of a methodology to measure and represent load characteristics, eventually aimed at the creation and use of a library of load signature information. Such knowledge is essential to most load monitoring/identification approaches as well as appliance design and deployment. A typical taxonomy of load types groups the appliances by the characteristics of their load signatures, rather than by their use (e.g., HVAC equipment, kitchen appliances, consumer electronics, etc.). These groupings and subgroupings of load signatures correspond to the underlying power circuitry of related appliances. Initiated by the CLP Research Institute, this joint research team has carried out a study on the methodology of load signature characterization based on over 120 office and domestic single-phase electronic equipment and electric appliances. An approach to load signature classification is proposed. It is found that load signatures depend primarily on (i) the front-end power electronic stage and/or (ii) the operational behavior of loads. The main factors that affect load characterization are discussed and illustrated with examples.

2. Influence of Power Electronics on Load Signatures

In buildings, power is used by a wide range of electronic equipment and electric appliances. Increasing use of nonlinear electronic and electric loads has led to various power quality issues such as harmonics and reactive power. The requirements for meeting various power quality standards such as EN-61000 have forced many electronic designers to incorporate active and/or passive means to improve the power quality of the loads. Various types of power factor correction (PFC) circuits have been developed to improve the input current of electric loads. Such development has made great impact on load signatures. When a PFC circuit achieves near-unity power factor, the entire load behaves almost like an equivalent resistance – thus masking the nature of the load;it becomes a challenge to differentiate a pure resistive load (e.g., an electric heater) from an air-conditioner with a front-end PFC circuit. For electromechanical loads such as a refrigerator, the input current of a load depends not only on the electric circuit but also mechanical load characteristics. Therefore, knowledge of the nature of electric loads would help the power industry to understand how their low-voltage power sources (ac mains) are used in buildings. The way an electronic load or electric appliance uses the ac power supply is defined here as load signature. Based on over 120 types of office and domestic electronic/electric loads, this study indicates that the front-end power electronic circuits and the operational behavior (such as mechanical characteristics of some electromechanical loads) play critical roles in the way electronic/electric loads drawn power (particularly current) from the ac power supplies.

3: Methodology and Practical Evaluation

A. Main Factors for Load Signature Characterization

In this study. the input current of each load provides load signature information . The 50Hz voltage and current waveforms were captured at a high sampling rate of 50 kHz per channel which allows us to analyze appliances through raw waveforms in addition to the traditional electrical measurements. The voltage of the ac mains is not purely sinusoidal; in this study it has a (maximum) THD of 2.83% and a maximum voltage amplitude deviation of ~8.1V, limiting the maximum error to 3.68%.

The following factors of the load current are important to characterize each type of electronic/electric loads commonly used for office and domestic applications: Current is measured during start-up transient and steady state; this waveform and its envelope are analyzed, as is the voltage-current trajectory under start-up and steady-state conditions

1. Start-up current and its envelope
2. Steady-state current waveform
3. Transient current
4. The voltage-current trajectory under start-up and steady-state conditions

B. Practical Evaluation: (Table 1)

The complexity of the classification cannot be fully explained in a digest. But some brief examples of load signature classification are given here as examples.

Type 1: **Passive and Active resistive loads**: These loads behave like resistors. Examples of passive resistive loads are heating equipment such as hair dryers, kettles and heaters. Examples of active resistive loads are systems with front-end PFC circuits that operate at near-unity power factors. In general, the steady-state V-I trajectory (Table 2) of passive resistive load is a straight line, whilst that of an active resistive load is a "zig-zag" curve along a straight line. The "zig-zag" is due to the switching ripple of the PFC.

Type 2: **Rectifier Loads**: This group of loads usually draws current pulses in steady state. The front-end circuits are usually diode-rectifier loaded with an output capacitor or a valley-fill circuit.

Type 3: **Motor Loads**: This group of loads is commonly used in office/domestic applications. Examples are electric motor loads such as refrigerators and fans. They are inductive loads and tend to have a characteristic start-up process (due to the accelerating speed of the motors).

Type 4: **General Inductive loads**: Unlike Type 3, Type 4 loads do not necessarily have repeatable start-up behavior. Examples are magnetic ballasts for lighting devices. The igniter of the ballast consists of a bimetallic switch (S) which operates differently at different times, depending on the initial voltage and thermal conditions.

C. 2-D Voltage-Current Trajectory (Table 2)

A new approach to classifying load signatures is to use the 2-D V-I trajectory. Table 2 shows the VI trajectories of a wide range of loads. These 2D trajectories under start-up and steady-state conditions can be classified in various ways. In the full paper, we will provide the details of the taxonomy based on eigenfunction decomposition and feature-based analysis.

4. Conclusion:

Based on the analysis of input current measurements of over 120 office and domestic electronic equipment and electric appliances, we propose a framework for taxonomy of electric load signatures. The proposed taxonomy can be used to classify various types of electric loads commonly used for office and domestic use. It is envisaged that such taxonomy would evolve continuously with future changes of load characteristics and new types of loads. The framework proposed here, however, forms the basis for individual load signature identification and taxonomy study. Active research is being carried out to use signal processing means to differentiate different types of loads used simultaneously in the same ac mains.

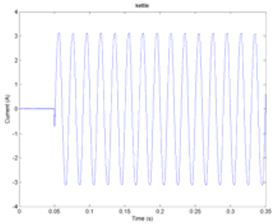
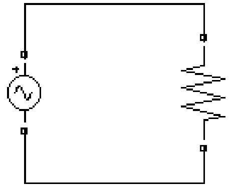
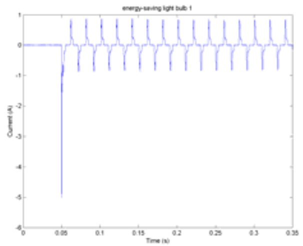
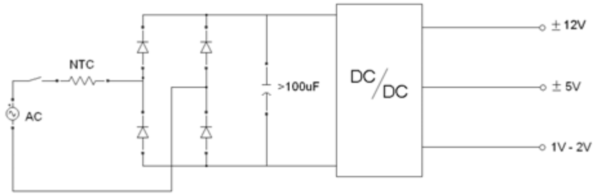
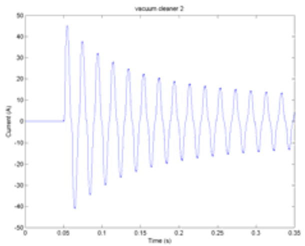
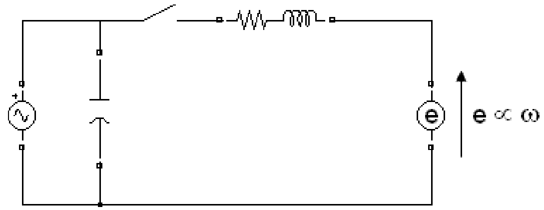
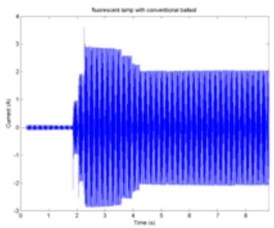
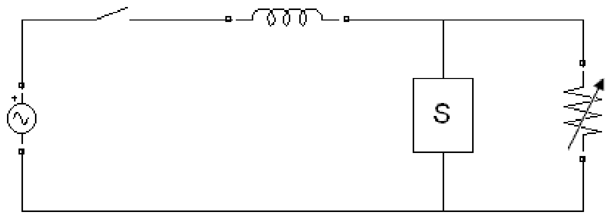
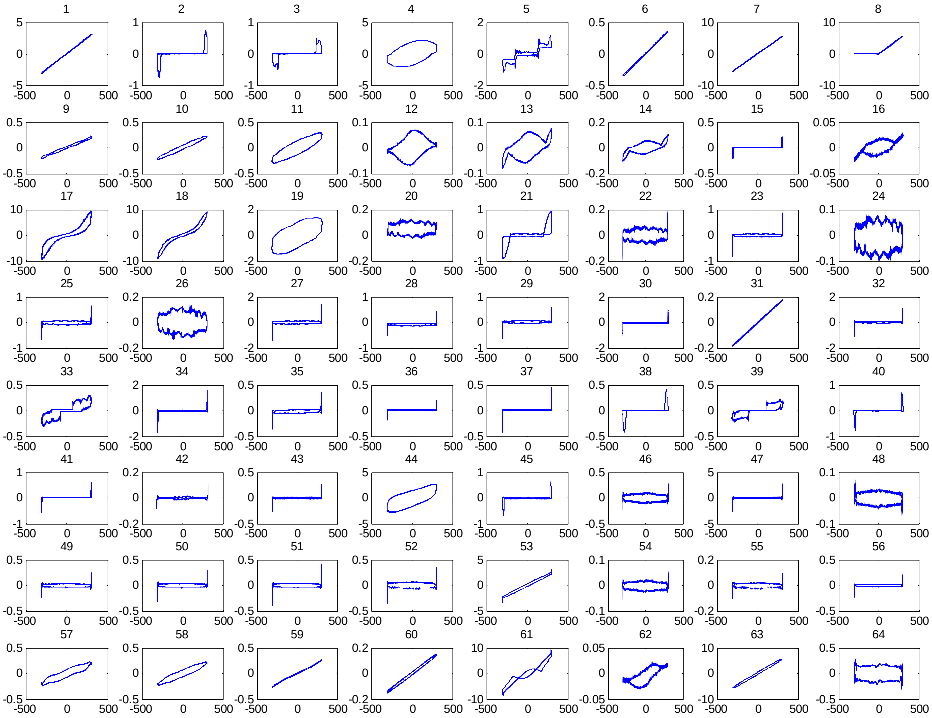
Type of load	Observations	Waveform examples	Typical equivalent circuit
1.Passive and active resistive loads Examples: kettle, hair dryer	No transient or significant transient: transient current is nearly the same as steady state current. Steady-state current: sinusoidal; little phase difference between I and V.	Kettle 	Pure resistive 
2. Rectifier loads Examples energy-saving light bulb, desktop PC	Short transient and a large peak at the beginning: the magnitude of the first peak of transient current is at least a few times (over ten times in some cases) of steady state peak current, and the current reaches steady state after a few cycles (less than 5 cycles in some cases). Steady-state current: pulses near voltage peaks.	Desktop PC 	Desktop PC 
3. Motor loads Examples: fan, vacuum cleaner, refrigerator	Slowly decay envelope: transient current gradually decreases to steady state because of the increasing back EMF (e) of motor loads, a function of motor speed (ω).	Vacuum cleaner 	Motor with back EMF 
4. General inductive loads Examples: fluorescent lamp with conventional ballast	Non-repeatable: transient current envelope is different every time. Steady-state current: sinuoidal, out-of-phase with voltage.	Fluorescent lamp with conventional ballast 	Fluorescent lamp with conventional ballast 

Table 1. Example of load types



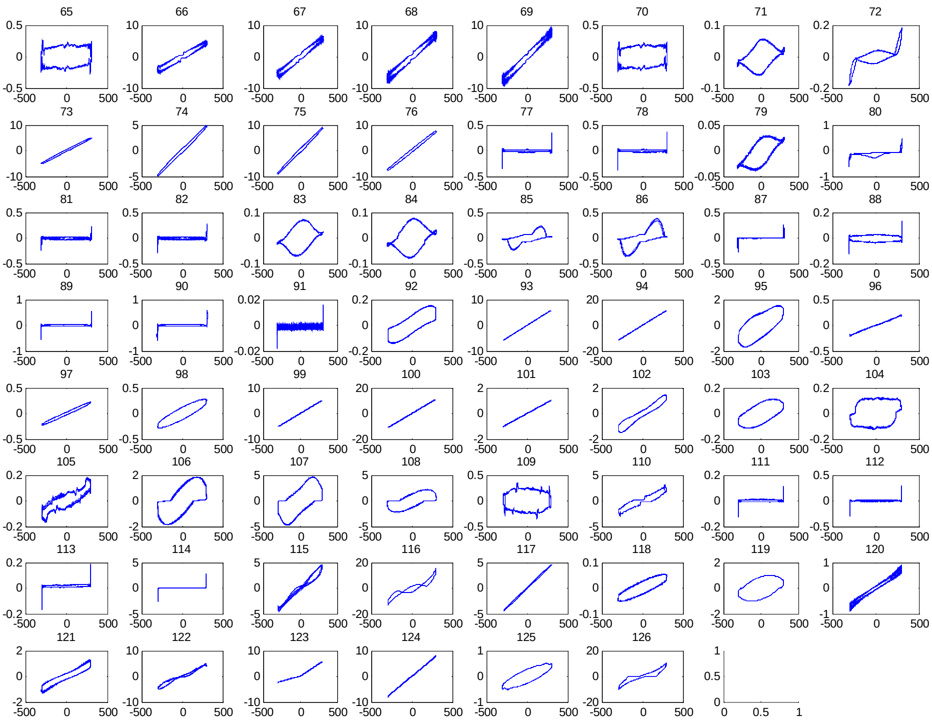


Table 2. Two-dimensional voltage-current trajectories of 126 electric loads, each with 5 periods plotted; unit are Amps vs. Volts.