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Data compression and reconstruction of smart grid customers based on compressed sensing theory

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ABSTRACT

In order to improve collection and transmission efficiency of smart electricity information collection system with huge number of data, a compressive sensing model for low-voltage customers was proposed in this paper. This model includes data compression method and reconstruction algorithm. First, we proved that electricity power data satisfy the sparsity condition of compressive sensing in a specific domain. Then, an improved iterative threshold algorithm was adopted to reconstruct the compressed power data, and detail processes of data reconstruction were proposed in succession. Experimental results show that the power data of multiple customers can be accurately reconstructed. Interrelation between reconstruction performance with customer number and compression rate was also analyzed.

Introduction

Communication network for power consumption data is a pivotal part of smart grid. Future smart grid communication will require the capacity of the last mile communication network to support millions of smart meter, which is significantly more than the number in current networks. Wireless communication technology such as wireless sensor network has been widely used to facilitate uplink transmission from the smart meters to the base station [1]. However, existing approaches are not ideal for a large number of smart meters due to the number of collisions, leading to large delays.

Compressed sensing coding at the base station is an efficient way to address these problems. Compared with traditional data compression algorithm, compressed sensing algorithms facilitate the accurate recovery of a sparse data vector when the number of observations of the transmitted data vector is significantly less than the dimension of the data vector. Compressed sensing has been applied to some applications of power system. In power quality disturbance identification, [2] used compressed sensing to reduce transmitted data and storage space by compressing power quality signals. In fault detection, [3] showed the applications of compressed sensing in several state estimation events, such as short circuit breaking, lightning strike, harmonic distortion and power thefts, based on the sparse representation. In wireless data communication technologies, [4] has designed a wireless network medium access control (MAC) protocol with compressed sensing to reduce transmitted electricity data and minimize the reporting delay. A data acquisition scheme for home area network based on compressed sensing was proposed in [5], to reduce the energy consumption of network by transmitting compressed electricity data. Louie et al. [6] proposed a distributed multiple-access method for smart grid home area networks based on compressed sensing with multiple antennas, in order to optimal the high transmission delay caused by the large number of smart meters. In information security, a joint encryption scheme using compressed sensing in smart grid data transmission was presented in [7], the encryption is proven to possess a high security.

Most of existing researchers focused on the application of compressed sensing in different fields of smart grid, and supposed that the compressed data is sparse and can be accurately reconstructed. However different data requires different conditions to get ideal performance. For example, compressed method of power quality signal is not suitable for data encryption due to different data characters. Thus, compressed sensing modeling for smart electricity data is proposed in this paper considering the characteristic of power consumption data of low-voltage customers.

In this model, we first analyze the data feature and sparsity as the prerequisite of compressed sensing. Then processes of data compression and reconstitution are proposed with Gaussian measurement matrix and iterative convergence threshold algorithm to realize accurately reconstruction. Different databases are used to prove the efficiency of this model and show the relationship between compression rate and reconstruction error.

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System model and compressed sensing theory

Electricity information collection system

Fig. 1 is the network topology of electricity information collection system. This system consists of three parties: smart meters, access points (APs), and a control center. The smart meters collect the power readings labeled with the meter IDs and send them to the APs. These readings are stacked up and then sent together to the control center of utility by APs. In this model, the APs play an intermediary role and need to deal with huge amounts of data, when numerous smart meters are installed. Considering the huge number of low-voltage residential customers, the data compression and reconstruction modeling of low-voltage customers are focused in this paper.

We assume that each customer is equipped with a smart meter that reports power consumption data, and each smart meter must send a message include customer information to APs in each sampling interval. The message format is shown in Fig. 2.

$$F = \begin{bmatrix} f_{11} & f_{12}\cdots & f_{1T} \\ f_{21} & f_{22}\cdots & f_{2T} \\ \vdots & \vdots & \vdots \\ f_{N1} & f_{N2}\cdots & f_{NT} \end{bmatrix} \tag{1}$$

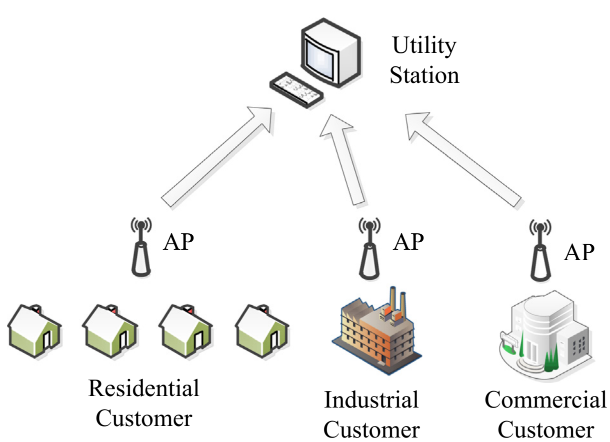

Fig. 1. Electricity information collection system model.

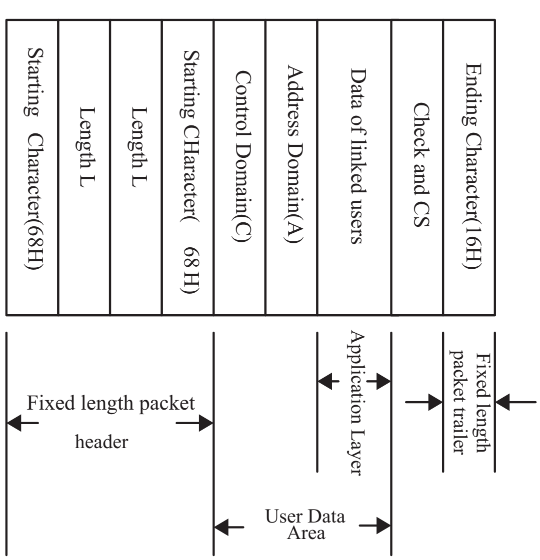

Fig. 2. Message form in electricity information collection system.

Without loss of generality, for an AP with N smart meters, data construction in a period of time T is $F \in \mathbb{R}^{N\times T}$, shown in (1). Each row means the data from one customer, and each column means the data at a sampling time. There are two possible data compression method for $\boldsymbol{F}$, row compression or column compression. However, row compression will cause accumulation of data in different sampling times and pressure of data storage and processing in APs. As most data applications of smart grid have high requirement for delay, the compression method studied in this paper will send compressed data to the station at every sampling time to reduce delay.

$$f = [f_{1t}, f_{2t}, \cdots, f_{Nt}]^T \tag{2}$$

$$f' = [f_{1t}, f_{2t}, \cdots, f_{Mt}]^T \tag{3}$$

f' is the compressed data of f from N smart meters at any sampling time t only if $M < N$, and $\rho = N/M$ is the compression rate. Compressed sensing is an efficient method to compress data at APs and reconstruct it at utility station when meeting the special conditions.

Compressed sensing theory and sparsity

In this paper, we refer to the data from one sampling time (one column of **F**) as one data block. From the compressed sensing theory, we can compress the data if they possess sparsity properties in a certain domain. Specifically, we can express the data vector $\boldsymbol{f}$ as

$$f = \Psi x \tag{4}$$

where $\Psi \in \mathbb{R}^{N\times N}$ denote the sparse basis in space dimensions. x is the equivalent representation of f which only has K non-zero elements ($K < N$), and it is referred to K sparse representation of f.

We denote $\Phi \in \mathbb{R}^{M\times N}$ as the observation matrix where entries in the matrix are independent and identically distributed uniform random numbers where $M < N$. specifically, we can employ Φ to sample the power consumption data, from which we obtain the following observation vector

$$y = \Phi f \tag{5}$$

From compressed sensing theory, we can reliably reconstruct the data vector f by using the observation vector y if M is appropriately chosen. Before we describe the data construction method, suitable sparse matrix has to be chosen to satisfy the sparsity of compressed data f.

Fourier transform and wavelet transform are widely used to map signals to frequency domain or wavelet domain. As the compressed data in this paper is not time continuous series, Fourier transform is inappropriate to process data. Wavelet transform was used to identify different loads of power system in [8], but no studies detailed prove that it is also useful in data compression of electricity information collection system.

The concept of wavelet transform was proposed by Morlet and Grossman, i.e.,

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}} g\left(\frac{t-b}{a}\right) \tag{6}$$

where $\psi_{a,b}(t)$ is called the daughter wavelet, g(t-b/a) is the mother wavelet, a is the scale factor, and b is the shift factor. Wavelet transform can be classified into continuous wavelet transform (CWT), discrete wavelet transform (DWT), stationary wavelet transform, and wavelet packet transform. CWT is defined as

$$\omega_{a,b} = \int_{-\infty}^{\infty} \psi_{a,b}(t) f(t) dt \tag{7}$$

where $f(t)$ is the original signal. As the compressed data in this study is discrete, DWT will be used to make it sparse. In order to