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A novel approach for load profiling in smart power grids using smart meter data

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ABSTRACT

Increasing penetration of distributed energy resources, varying load demands and big data of smart meters require new load models to support power system studies. The big data of smart meters and non-linearities in the load demand require the smart meter data to be represented in an alternative way to use in stochastic simulations to enhance processing. This paper proposes a novel method for stochastic load modelling of smart meter data. The approach turns smart meter data to a manageable level by linearizing energy consumption patterns producing energy classifications. A case study, using real world smart meter data, simulated scenarios to prove the robustness and accuracy of the method. The accuracy of results validates the stability and robustness of the approach and model validation provided substantiation for application in probabilistic studies.

1. Introduction

Load models are widely used in power system applications including; constant power, constant current, constant impedance models, depending on the time constants used in the applications. Integration of new smart technologies such as heat pumps, electric vehicles, RES, etc. add additional uncertainties to existing uncertainties in a power system, particularly with intermittent natures of RES and stochastic nature of smart loads. The uncertainty in a smart power system for applications such as risk modelling and security and reliability assessments, needs to be modelled probabilistically [1]. Therefore, a paradigm shift from deterministic load modelling to stochastic load modelling particularly, of smart meter energy consumption data with reduced complexity and computational burden is highly desirable in a smart grid.

Deterministic models study only pre-determined conditions whereas probabilistic models incorporate pre-determined probability density functions [2]. The component based load modelling approach involves development of a composite model, which exacerbates the modelling intensity by modelling the individual loads to develop a system load model [3]. The modelling intensity can be reduced by using data aggregation in measurement based modelling approach. In the past the measurement based load modelling was often limited to load measurements at substation level but the smart grid advanced metering infrastructure provides load measurements from each individual consumer at time resolution from 15 min to an hour. This provides the opportunity of developing more accurate load models and utilizing actual data from the system under study provides opportunity to track seasonal variations in load as well as energy consumption behavior of consumers thus capturing the uncertainty in energy demand.

Historically the load demand data, often referred as load duration curve, was used for power system expansion planning and load forecasting purposes [4]. However, with the advent of smart meters, the power system applications that utilize detailed load data of smart meter increased in numbers and they include load profiling for demand side management [5,6], optimal renewable energy sources (RES) utilization at individual consumer and higher levels [7], energy forecast at consumer/grid level [8] and many more particularly probabilistic studies. In the era of smart grids, the planning horizon has become narrow and deployment of new technologies require more data to ensure accuracy but much quick decision with faster computation and less time for processing.

Some of the previous works have incorporated smart meter data for load modelling; however, the large-scale application of such models using big data still faces many challenges. For example Li and Wolfs [9] used hierarchical clustering to produce a residential load model that can be used for Monte Carlo simulations applications, however, the processing time of hierarchical clustering and data conversion to and from frequency domain make it computationally expensive. Similarly, Ref. [2] introduced a novel probabilistic load modelling approach, however, the proposed power mismatch index produces a very large number of clusters in a distribution network study scenario, thus rendering the clustering process ineffectual. Authors of Ref. [10]

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developed a residential electric load model using Markov models however the intensity of modelling makes the model unfavorable.

Further, some previous studies have used linear approximation of the load curves such that non-linear problems can be solved using linear techniques such as mixed integer linear programming (MILP). Ref. [11] used step function to approximate the load curve such that they can be used in both stochastic and ordinary linear program to determine the impact of uncertainty in demand forecast. Similarly, authors of Ref. [12] argue that for forecasting of electricity demand, improved results can be obtained by allowing data to dictate the model as well as the parameters. Load curve linearization in a multiple energy system was achieved using Douglas–Peucker algorithm for use in expansion planning by Ref. [13]. Often the linearization if carried out by selecting typical days instead of full year [14,15] or by using stepwise approximation of load duration curve [16]. However, authors of Ref. [17] argue that although stepwise approximation of the curves should be carried out as close to the original curves as possible, however they recommend to select typical days due to computation burden thus avoiding the linearization of year long curves.

Using the big data of smart meters for detailed large-scale simulation is computationally expensive. But the accuracy of system study relies on the load model being reflective of the actual network loads. Apart from the issue of big data, the highly non-linear complex load patterns also prove to be computationally expensive and difficult to handle by linear system study methods particularly for stochastic simulation applications and to the best of authors knowledge, no attempt has been made to address this issue at the level of smart meter data. This can be achieved by linearization of the smart meter data. But as discussed above, due to its complexity and high processing time, it is not carried out on large scale. On the other hand, the smart meter data provides a more detailed insight of consumer load and can yield better results if used for studies that incorporate load duration curves. Thus, the key challenges in modelling smart meter data is the determination of an appropriate representation of the load to decrease uncertainty margins with reduced complexity and computational burden. Therefore, considering the gap in the research, this paper proposes a novel approach to model the big data of smart meters for different system studies by linearizing with less computational burden and approximation close to the original load curves.

Main contributions of this paper include development of novel and uniform method to model the big data extracted from smart meters. An innovative clustering algorithm is developed that produces more compact clusters, is computationally efficient than divisive hierarchical clustering and good at outlier detection. An innovative approach is introduced that simplifies the complexity of data while keeping the resolution close to the original and minimizing the number of linear patterns as compared to conventional linear approximation techniques. Key benefits of the approach include reduction in processing time of stochastic simulation and reduced complexity of interaction of load profiles with other uncertainties. Moreover, for non-linear optimization problems with big data simulation, the approach will reduce the likelihood of converging to local optima.

The rest of this paper is structured as follows. Section 2 delineates the methodology of load profiling and linearization process. Section 3 outlines a case study and detailed discussion of the results and their analyses is given in Section 4. Section 5 concludes findings.

2. Methodology

Stochastic modelling of smart meter data in a big data scenario is a multistage process. The method adopted in this paper consists of four main stages which include data clustering, curve smoothing and linearization of curves, optimizing the linear curves and finally energy classification for stochastic load modelling. Fig. 1 shows the flowchart of the process stipulating steps involved at each stage.

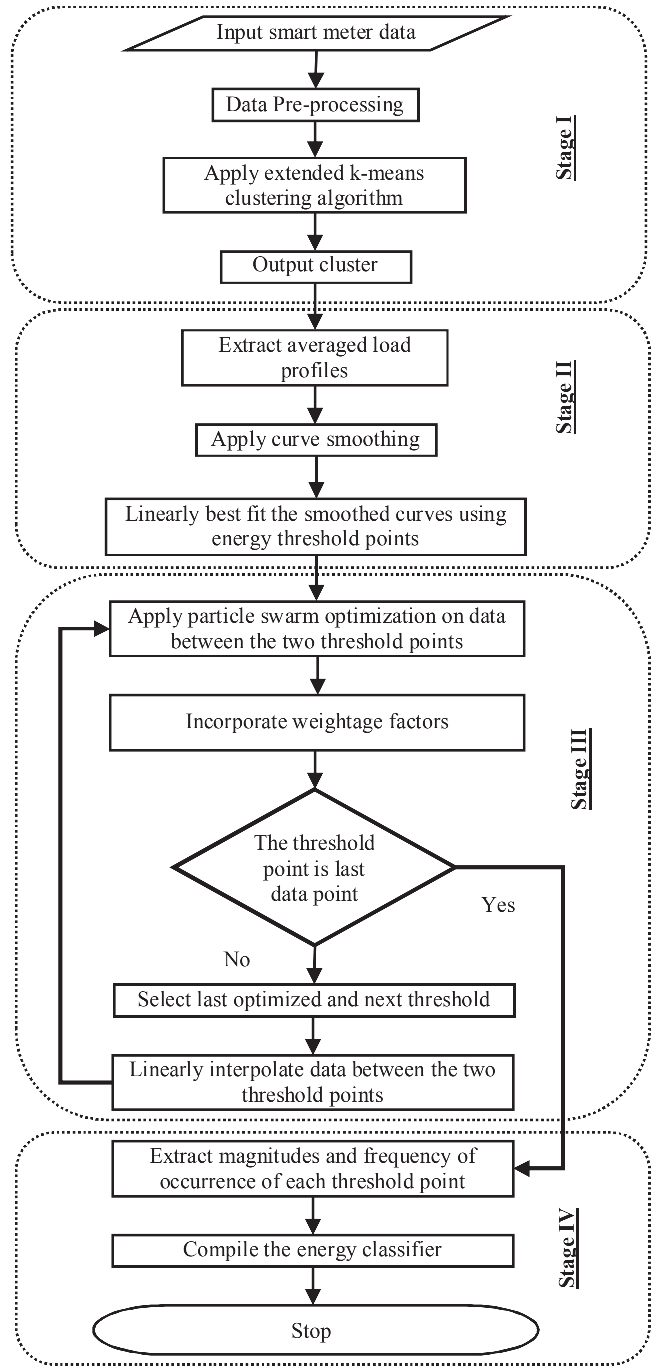

Fig. 1. Flow chart of proposed methodology.

2.1. Data pre-processing

Data pre-processing is required for data sorting and removal of erroneous values. Any data sample with missing values or zero values was removed from the dataset. In the published literature, before applying the k-means clustering on the data, the data is normalized between 0 and 1.0. The rationale for normalization is to minimize the effect of magnitude on the clustering process as cluster formation can be biased by the magnitude. A key disadvantage of normalizing is losing the magnitude and having variations in energy consumption only. The process of normalization can result in losing the data features which are more apparent without normalization. Depending on the type of normalization used, the sensitivity of the clustering algorithm varies and it affects the process. Consequently, data feature may be lost with higher