

Applications of Rough Set Theory in Demand Side Management of Electrical Power Industry: A Review

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Abstract—The global demand for electricity is at its peak right now due to exponential advancement of technology. While electricity demand around the world is increasing, the potential scarcity of fossil fuel is roadblocking the supply side to meet this increasing demand. The most feasible solution to this problem is demand response (DR) strategies in demand side management (DSM). A crucial issue towards demand response implementation is dealing with the heterogenic and inconsistent characteristics of customer consumption patterns in power industry, less customer engagement to manage the demand side. This kind of data can be analyzed with more accuracy using rough set theory (RST). It is a powerful mathematical tool that has the strength to deal with vague, inconsistent, and incomplete data. When it comes to demand side management of electrical power industry, rough set theory has a potential to be implemented as a powerful and accurate tool for customer data analysis. This paper aims to project the currents trends of rough set theory application to implement demand response strategies in demand side management of electrical power industry by conducting a comprehensive review on the existing literature. Applications of rough set theory in terms of demand/price forecasting, fault detection, decision rule generation in electrical power industry are mapped out to provide a clear vision for the overall RST implementations and advantages. Recommendations and suggestions are provided for more appropriate and efficient future application and research.

Keywords—*rough set theory, demand forecasting, price forecasting, energy management, electrical power industry, demand side management*

I. INTRODUCTION

As the world's energy consumption rises, it is crucial to optimize demand in order to balance supply and demand, cut energy waste, and ensure the steady operation of power networks. The use of rough set theory is one new and promising strategy to handle the demands of demand side management (DSM). Rough set theory was first introduced by Zdzislaw Pawlak in the early 1980s [1]. It provides a cutting-edge paradigm for dealing with uncertainties and imprecisions in data processing. This mathematical technique was

originally anchored in computer science and data mining [2], but it has since found a variety of usage in electrical power industry from hypothesizing distance protective relay operation characteristics [3] to electricity demand/price forecasting [4]. The basic concept of rough set theory is derived from the simple information model and separated into two sections. Demand side management is essential for balancing electricity supply and demand, lowering peak loads, and encouraging energy efficiency. Rough set theory offers a potent method to simulate and optimize the actions of energy consumers and their interactions with the power system due to its capacity to deal with ambiguous and incomplete information [5]. Rough set theory enables utilities and policymakers to make informed decisions and create successful demand response strategies by gleaning useful patterns and information from large-scale data sets [6]. A thorough examination of recent developments of rough set theory application in demand side management has been provided in this review. This paper examines how rough set theory handles the issues posed by demand-price forecasting, load clustering, fault or theft detection, fault diagnosis, feature or attribute selection, reduction, and energy efficiency programmes.

II. APPLICATIONS OF ROUGH SET THEORY IN ELECTRICAL POWER INDUSTRY

The demand for efficient and reliable energy management is rising as a result of the electrical power industry's intricate network of generating (supply side), transmission (utility side), and distribution (demand side) systems [7]. This study explores the rough set theory applications in demand side management, and for this investigation purpose applications of RST in demand side management has been divided into three main groups, as follows:

- Demand Side (Distribution)
 - Electricity Price
 - Electricity Load/ Demand/ Energy Consumption

A. Demand Side (Distribution)

The market segment that represents electricity consumers or users is referred to as the demand side of an electrical market. It covers all organizations that buy energy for consumption, including householders, businesses, and industries.

1) Electricity Price/Tariff

a) Feature Selection/Reduction

In [8], authors suggested combining the Genetic Algorithm (GA) optimization technique with Least Square Support Vector Machine (LSSVM) to estimate daily electricity costs in Ontario. It was demonstrated that the choice of input information and parameters from LSSVM used by GA increased the overall prediction efficiency and accuracy. By building a suitable information system, rough set is utilized to select data.

b) Forecasting

In [9], rough set and support vector machines-based prediction model was introduced to increase the accuracy of price forecasting, which integrates the benefits of each model. The experimental findings demonstrate that this RS-SVM method has a greater potential than the other conventional method for improving prediction accuracy. With RS, the weaknesses of SVM can be fixed. In order to increase the accuracy of short-term power load forecasting a SVM short-term power load forecasting method based on grey relational (GR) analysis and K-means clustering was proposed. In [10], grey correlation analysis is used to choose the most useful parameters for the electricity price forecasting problem. After that, a dimension reduction procedure using RST is used to identify the key aspects of the incoming data while discarding the rest. To forecast the day ahead electricity tariff, the preliminary structure artificial neural network (ANN) was used. In [11], a novel rough set and improved SVM based model was developed for forecasting short-term electricity prices (SVM).

Table I shows the selected research works on RST application for Demand Side (Electricity Price) of electrical power industry.

Fig.1. illustrates the overall process of electricity price forecasting where RST has been implemented mainly for feature selection and reduction. Implementation of RST along with Support Vector Machine, Deep N1 Neural Network for classification has proven to provide more accurate results with future potentials for further exploration.

2) Load/Demand/Energy Consumption

a) Feature Selection/Reduction

In [13], rough set fuzzy clustering-based method to analyze electricity consumption behavior in smart grids was proposed. In order to preserve data information on the characteristics, the clustering result was expressed as lower approximation set and upper approximation set. The strategy was effective in increasing accuracy rate of clusters and providing a detailed analysis of the target customers for demand response, as demonstrated by a case study. Researchers used intuitionistic fuzzy rough set theory to imitate the method of wind power segment compensation in [14].

TABLE I. SELECTED RESEARCH WORKS ON RST APPLICATION IN ELECTRICITY PRICE

Area	RST Application Category	Ref	Method	RST Application
Electricity Price	Forecasting	[10]	Grey correlation analysis with deep NN with RST and ANN	Set approximations to convert NN to rough NN.
		[12]	SVM based GR analysis and K-means clustering	RST to derive approximation rough sets of similar days.
		[11]	RST and improved SVM	RST to reduce information table without informatio loss
		[9]	RST and SVM	RST to build decision table
	Feature Selection	[8]	GA optimization technique with LSSVM and	RST to build suitable information system

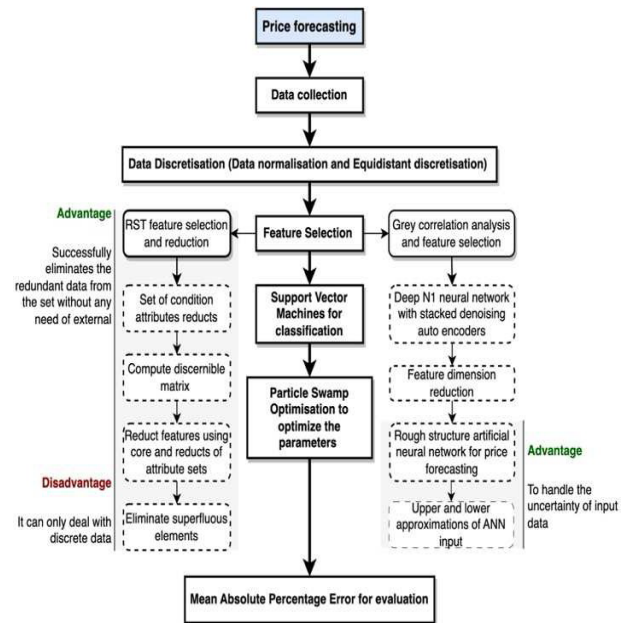


Fig. 1. Electricity price forecasting methods combined with RST according to reviewed literature.

b) Forecasting

The authors of this study [15] concentrated on load forecasting, and introduced an enhanced rough set for medium-long term load forecasting. Numerous cutting-edge machine learning (ML) methods, including support vector machines (SVM), logistic regression (LR), naive bayes (NB), K-nearest neighbor (KNN), decision tree classifier (DTC), and neural networks (NNs), were implemented along with RST in [16] in order to analyze their performances. The purpose of the research proposed in [17] was to examine the applicability of a RST based model to calculate the

consumption of thermal energy by buildings undergoing energy rehabilitation. In [18], researchers used RST and deep NN to anticipate building energy usage over the short and mid-terms. The outcomes demonstrate that the deep neural network and integrated rough set provided the most accurate results. A novel method merging rough sets theory and an artificial neural network (ANN) based on data-fusion technique is provided in [19] to forecast an air-conditioning load,. By using data mining tools, a novel load forecasting strategy was developed in [20] this study.

Table II shows the selected research works on RST application for Demand Side (Electricity Price) of electrical power industry.

Fig.2 illustrates the overall process of Demand/ Load/ Energy Consumption Forecasting where RST has been implemented mainly for feature selection and reduction. Implementation of RST along with Grey theory model, Artificial neural network, Deep belief neural network, K-nearest neighbors and Naïve bayes techniques for classification has proven to provide more accurate results with future potentials for further exploration.

3) Energy Management

a) Feature Selection/Reduction

In this [21] study, authors established an evaluation system with three rule levels: economic, environmental and social; and adopts rough set theory to determine the weights of each index. The study used energy conservation and outflow decrease of construction waste slurry treatment as its background. In [22], a mapping relationship between customer visual sensitivity and hybrid electric vehicle (HEV)

TABLE II. SELECTED RESEARCH WORKS ON RST APPLICATION IN ELECTRICITY LOAD/DEMAND/ENERGY CONSUMPTION

Area	RST Application Category	Ref	Method	RST Application
Electricity Load/ Demand/ Energy Consumption	Feature Selection/ Reduction	[13]	Rough set fuzzy clustering	Introduce lower and upper approximation set, calculating clustering center to retain behavior characteristics
		[14]	Intuitionistic fuzzy rough set theory	Convert fuzzy sets to more accurate data sets
	Forecasting	[20]	RST and genetic algorithm	RST and GA for feature selection
		[18]	RST and Deep NN	RST for attribute reduction
			LR, SVM, NB, DTC, KNN, and ANNs with RST	RST for attribute reduction
		[19]	RST and ANN	RST to reduce historical data and relevant factors
		[17]	RST	RST to eliminate redundant features from the decision table and generate decision rules
		[15]	Enhanced Rough set	RST to eliminate redundant data using core and reduct sets of conditional attributes.

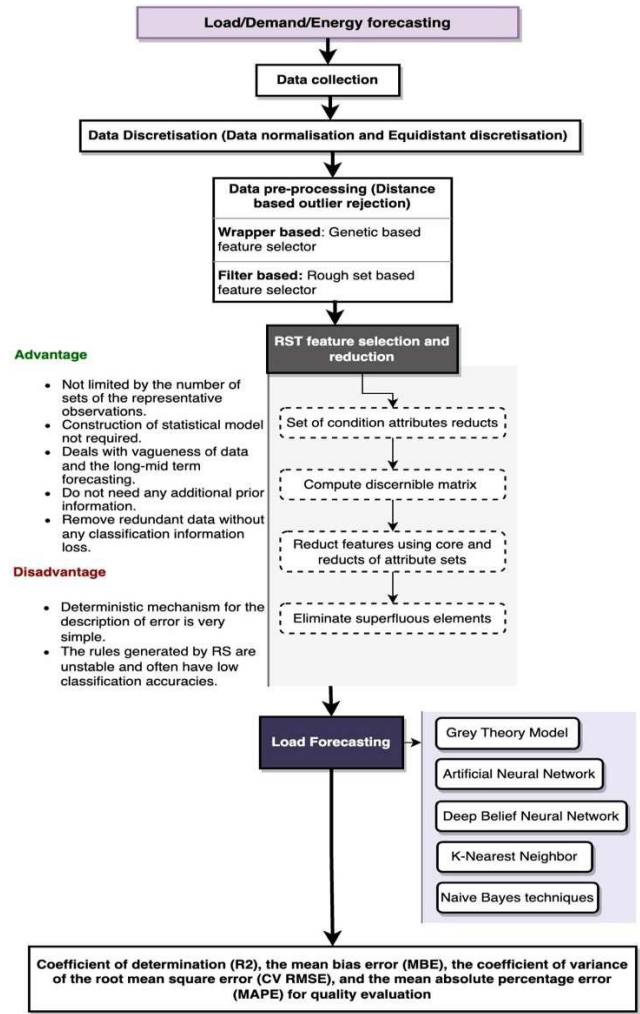


Fig. 2. Electricity demand/ load/ energy consumption forecasting methods combined with RST according to reviewed literature.

form design based on Kansei engineering was explored. In [23], A multi-grid linked microgrids (MGs)-based active distribution system was suggested by authors as a novel dynamic energy management technique with the cooperative interaction of an energy system. To choose an appropriate answer, RST is used in this case. In [24], authors recommended an artificial intelligence-based energy management model (AI-EMM) in green buildings. The rough set theory was used in this research to reduce the number of factors impacting energy usage of the buildings.

b) Decision Rule Generation

A smart city SC was modelled in [25], which lowered the amount of power used, using a modified version of the traditional cooling and heating system. Part of a central energy management system (CEMS) model for regulating, observing, and controlling thermal energy flow is the scheduling of heat to satisfy the urgent needs for thermal energy.

c) Forecasting

In [26], the authors set out to evaluate the viability of RST-based model that enables the analysis of vague, generic, and ambiguous data. The authors adopted a different strategy, namely a technique based on thermal characteristics of buildings, to collect input information in quantitative form for the RST model.

Table III shows the selected research works on RST application for Demand Side (Electricity Price) of electrical power industry.

Fig.3 illustrates the overall process of Demand/ Load/ Energy Consumption Forecasting where RST has been implemented mainly for building information system and decision rule generation. Steps of the processes marked in blue shades.

III. ADVANTAGES AND DISADVANTAGES OF RST APPLICATIONS IN POWER INDUSTRY

A. A. Advantages of RST Applications

Rough Set Theory offers several advantages when applied to forecasting and energy management in electrical power industry. These advantages can significantly improve data analysis, decision-making, and system performance. Here are some of the overall benefits:

- RST can manage high dimensional data successfully by selecting the most significant features, minimizing data complexity, and enhancing the efficiency of subsequent analysis [27].
- It assists in the simplification of complex data structures by removing superfluous or redundant elements to it decreases noise in the data [27]–[30].
- RST is well-suited to dealing with ambiguity and partial data by allowing the building of rough bounds, which aids in the identification of relevant features and decision-making based on existing information [31]–[35].

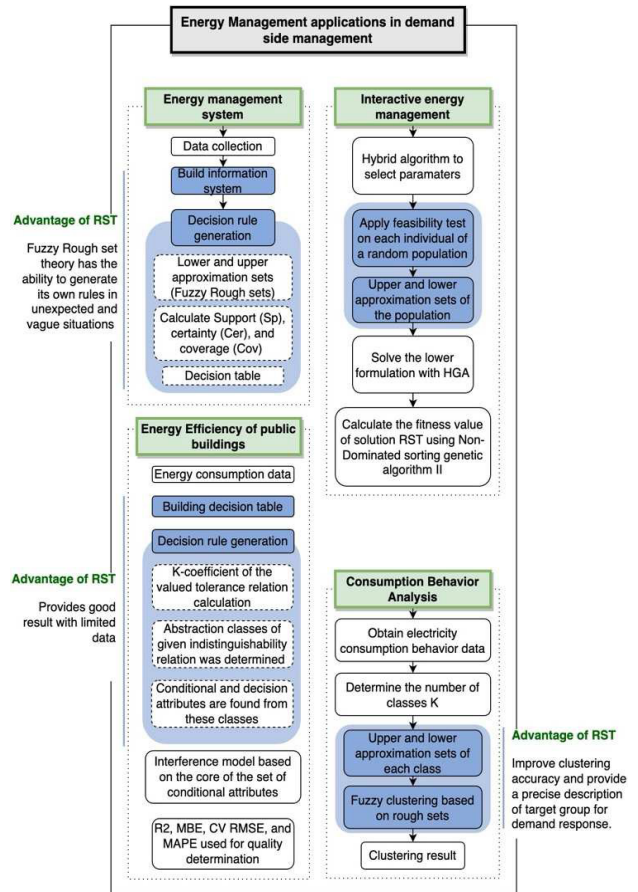


Fig. 3. Energy management methods combined with RST according to the reviewed literature.

TABLE III. SELECTED RESEARCH WORKS ON RST APPLICATION IN ENERGY MANAGEMENT

Area	RST Application Category	Ref.	Methods	RST Application
Energy Management	Feature Selection / Reduction / Evaluation	[22]	RST	Identify key patterns of HEV that have an impact on customer satisfaction
		[24]	RST with AI-based EMM	Reducing number of elements that influence building energy usage
		[23]	RST	RST to select a suitable solution.
		[21]	RST	To ensure the objectivity determine the weights of each index
	Decision Rule	[25]	Fuzzy-RST-based CEMS	Scheduling heating.
	Forecasting	[26]	RST	RST is used here to build a decision table based on the input data

- RST is flexible enough to handle a vast range of data, including numerical and categorical data. This adaptability makes it suitable for a wide range of power system datasets [36], [37].
- RST can handle multiple fault scenarios and identify complex fault interactions, contributing to more comprehensive fault diagnosis [31], [38]–[40].
- RST can adapt to changing data patterns, making it suited for defect detection and diagnosis systems in demand side [29], [33], [41].
- To construct hybrid defect detection and diagnostic systems, RST can be integrated with expert knowledge and domain-specific rules [1].

B. Disadvantages of RST Applications

- One of the primary challenges in RST applications in a large and continuous data containing critical information is data discretization. Selecting the appropriate approach for data discretization prior to RST implementation can make or break the deal in utilizing the tremendous potential and benefits of RST.
- In RST, the deterministic mechanism for describing mistake is relatively straightforward. As a result, RS rules are frequently unstable and have low classification accuracies [19], [42].
- Setting various parameters, such as the threshold for dependence measures or approximation accuracy, is

part of rough set theory. These options may involve subjectivity, and complexity in calculation [43].

IV. CONCLUSIONS AND FUTURE RECOMMENDATIONS

A. Conclusion

This study has offered a complete summary of rough set theory applications in demand side management. Rough set theory, as proven, provides essential tools and approaches for addressing the numerous difficulties faced by the power industry, which are characterized by uncertainty, complexity, and huge amounts of data. According to the literature, RST has been effective in dealing with uncertain and imprecise data, allowing for the construction of transparent and interpretable decision rules. Its capacity to reduce data dimensions, perform feature selection, and react to real-time data patterns has made it useful to power system operators, planners, and researchers alike. RST combined with time-series analysis, big data analytics, and multi-criteria decision-making has opened up new paths for tailored, efficient, and long-term demand-side management techniques. Recommendations for future rough set applications in demand side management are provided in this study.

B. Future Recommendations

- Future applications of RST in DSM may include incorporating time-series analysis techniques to reflect the dynamic character of energy consumption patterns. DSM techniques can be adjusted to address specific time-of-day or seasonal fluctuations by considering temporal characteristics of energy consumption.
- DSM entails making decisions based on a variety of objectives and limitations. Using multi-criteria decision-making techniques in conjunction with RST can aid in the prioritization and optimization of DSM actions by considering aspects such as cost-effectiveness, environmental impact, customer satisfaction etc.
- Microgrids enable localized energy distribution and administration. RST can be used to optimize demand response tactics within microgrids, increasing their resilience and contributing to overall grid stability.

Integrating behavioral analytics with RST can aid in improved understanding of consumer energy usage habits and preferences. This data can be used to create DSM therapies that are in line with consumer behaviors and incentives.

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