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Quantifying the Methods of Monitoring Timers in Electric Water Heater for Grid Balancing on Demand Side Management: A Systematic Mapping Review

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***Abstract*—**Electric water heater (EWH) is a powerful appliance that uses electricity in residential, commercial, and industrial settings, and the ability to control them properly will result in cost savings and the prevention of blackouts on the national grid. This article discusses the usage of timers in EWH control strategies for demand-side management (DSM). To the authors' knowledge, there is no systematic mapping review focusing on the utilization of EWH control strategies in DSM has yet been conducted. Consequently, the purpose of this research is to identify and examine main papers exploring EWH procedures in DSM by quantifying and categorizing information with regard to publication year and source, kind of methods, and source of data for monitoring control techniques. In order to answer the research questions, a total of 31 publications published between 1999 and 2023 were selected depending on specific inclusion and exclusion criteria. The data indicate that direct load control (DLC) has been somewhat more prevalent than indirect load control (ILC). Additionally, the mix method is much lower than the other techniques, and the proportion of real-time data (RTD) to non-real-time data (NRTD) is about equal.

***Keywords*—**Demand side management, direct load control, electric water heater, indirect load control, non-real-time data, real time data.

I. Introduction

INCREASING urbanization, regional competition, urbanization, and the Fourth Industrial Revolution need an intelligent, cost-effective, and reliable electric grid. Stability of the electrical grid needs grid balancing. DSM for grid balancing is becoming more popular among governments and electricity corporations throughout the globe. DSM minimizes peak demand electricity use by monitoring and automating activity centres, such as residential and commercial buildings, in close proximity to the DS. This research maps the strategies for monitoring EWH timers using DSM methodologies. It also evaluates existing research and discusses important challenges, requirements, and potential for future study. While figures are more easily grasped than words, it may assist researchers in enhancing DSM methodologies and identifying missing methods.

When it comes to DSM, the most popular method for achieving generation/load parity has been via the use of EWH control techniques. To the best of the authors' knowledge, no previous study has performed a systematic mapping review (SMR) of the use of EWH approaches for regulating DSM. The primary purpose of an SMR is not to extract exact information, but rather to quantify and categorize the chosen studies. But so far, it may set the stage for a systematic review, which will examine the key studies on a particular research issue, explain their methods, and report their findings in more detail [1]. This study and map compile the empirical data from 31 papers (chosen from publication channels such as IEEE, Science Direct, and Google Scholar) that examine the use of EWH management strategies in DSM and are scheduled for publication up to 2023. Mapping the EWH control in DSM based on the methodology and data collecting raises research problems that must be solved. As a result of the categorization, research gaps may be found and the scientific maturity of a topic can be estimated based on the frequency with which its articles appear in reputable journals.

The outline of this paper looks like: The associated work is described in Section II. The study's methodology is outlined in Section III. Section IV contains the results and Section V provides discussion. Section VI provides a conclusion and recommended future work.

II. Literature Review

The residential EWH is a commonly available thermal energy storage appliance that resides in millions of homes throughout the globe and provides significant prospects for interventions towards sustainability objectives and grid capacity optimization [3]. It is one of the biggest home loads at 3-5 kW and accounts for roughly 33-50% of total household energy consumption [2].

With EWH being the most common domestic end-use in the UK, residential electricity management is a cheaper option to investing in distribution network infrastructure modifications to solve these negative impacts [9]. The references emphasized the significance of energy saving strategies and the implementation procedures. The reduction of the electric storage tank water heater's (ESTWH) thermostat temperature is one of the least costly and simplest practises to undertake. This solution simply needed a one-time operation in which the thermostat setting is adjusted to a lower level to decrease standby energy losses [10], [8]. The shielding of hot water conduits leading to hot water consumption sites and the hot water storage tank to boost thermal resistance was a more expensive and time-consuming method [5], [6]. The third option needs personal discipline in a person's regular usage of hot water. In order to reduce the load

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on the electrical system, the electricity provider distributed additional instructional materials across the country's broadcasting network emphasizing the significance of turning off ESTWHs during peak energy use hours [7]. This leads in a more even distribution of the nation's energy consumption profile and offers no energy-saving benefits [11]. However, this results in cost reductions in residential areas where time-based pricing was imposed. DSM is roughly defined as the practise of equalising the energy usage distribution of any specific demand profile. DSM actions prevent the country's energy consumption from exceeding its electricity generation [12]. If the electricity provider encountered a situation in which more energy was required than could be provided, the national power company would be compelled to shut down, which would have tremendous economic repercussions and endanger the lives of some residents [61]. The incident of the outage, sometimes known as a blackout, might take specific time to be recovered [13]. Customers' behaviour in adjusting their consumption in reaction to price changes is known as price-based (or time-based) operation of the water heater's thermal components during peak and off-peak hours while maintaining a consistent supply of hot water, when consumers do not feel like they have enough control over how the heating system is adjusted, it might cause a new high of dissatisfaction. Dynamic programming may be applied in real-time energy management systems, as shown in [23], [24]. However, more effort has been put into investigating the feasibility of developing control systems that account for dynamic pricing. The authors of [25] evaluate the viability of a plan that would adjust the optimal temperature range for water heaters based on energy prices. It demonstrates that implementing price-sensitive strategies in the residential sector requires less investments in new power infrastructure [15]. The dynamic pricing is crucial to making this a reality. Two essential characteristics must be met in the building of such systems, which presents a considerable challenge when seeking to employ water heaters for energy control [26]. First and foremost, the output water temperature should be stable and high enough to satisfy the customer's expectations for both comfort and sanitation. The second restriction is that the daily consumption maximums cannot be increased via the management process. The major objective is to create a schedule for providing power to the heating elements that maximises customer pleasure while minimizing the effect of peak periods [21]. A categorization technique for user consumption profiles might help with energy management by highlighting peak periods. However, a method of grouping based on water withdrawal profiles exists, as suggested in [27]. Home-population sizes have been used to categorize individuals in several research [28], [29]. In addition, access to this information is not always available, making it difficult to conduct quality assurance tests. Water heater power usage profiles might be clustered to help identify the greatest energy wasters among consumers [26]. Another possibility is to divide up electricity consumers into distinct groups. With that standard, a more practical suggestion for crafting a management strategy is possible [72].

The study employed an extended-energy-hub model to examine a multi-carrier energy distribution network on a chilly winter day and found that thermal storage may shift 10% of heating demand to cheaper hours [30]. Advanced water heater demand response (DR) study using fuzzy logic control (FLC) and particle swarm optimization (PSO) saved customers 56% [31]. The savings stated in the literature are enticing, but they may not be realised if a customer is linked with the lowest rates, off-peak tariff [32] or if analysis is conducted using basic peak and off-peak tariffs that do not consider real-time market circumstances [30], [32]. Tariff structure was shown by [33] using a two-phase stochastic programming model. With tariff modifications from yearly to weekly, variable load assets reduced peak energy demand by 15%. Real-time price indications may reduce costs further. A techno-economic analysis [34] evaluated the daily household energy cost using this approach. Prioritizing loads' energy demands cut energy costs 38%. Due to insufficient storage capacity and modest regulated loads, boosting energy use under low real-time pricing was not beneficial (water heating was extremely small at only 90 W).

A better thermodynamic model that allows for stratification has the potential to enhance savings academically. However, the examination of thermal forecasting revealed certain limitations. it is difficult to anticipate extreme pricing like negative real-time prices, therefore real-time rule-based control is best for taking advantage of such scenarios [35]. Aggregated control of electric storage water heaters may reduce peak consumption by 830 MW (3% network drop) and save consumers 21.6% [36]. Water heater efficiency decreases, reducing thermal supply, ensure thermal supply with midnight heating and daytime demand management [32]. Linear programming and thermal/power flow restrictions provided 48% of water heating. Night-time heating limits DR capability.

The domestic EWHs' frequency response reserves are connected to consumers' performance expectations using a Monte Carlo simulation. At a temperature of 1.1 °C in EWH temperature reduction [37], frequency response reserve increased 24%, preserved thermal performance and found that basic EWH management will increase network frequency reserves by 5.7% by integrating hourly and 10-ms time-series analysis [38], frequency responses (cutting electricity consumption), although water heaters may raise and reduce frequency reserves, saving money all on [37]-[39]. All water heaters were collapsed into an isothermal body of water to facilitate [40], [41] and [30] note that this oversimplification is common in the literature [40], [42] may lead to erroneous exergy and thermal energy calculations. However, power flexibility and energy rebound were linked, emphasizing the need of proportional heating reactivation following frequency regulation [40].

The water heater may be handled in line with the frequency regulation on the grid, which makes it possible for the water to be heated to the proper temperature [19].

III. Research Methodology

Building upon the suggestions by [43] and [14], the systematic map explains that the objective of a systematic map is to identify and classify the selected studies creating a framework for a systematic review to examine in detail the important studies associated to a given research area and analyse their methodology and conclusions [1]. Although their objectives are diverse, mapping studies and review studies employ a comparable research methodology [44]. A systematic map and review involve key stages like: preparation, execution, and documentation [1]. Fig. 1 [1] depicts the steps involved in each of these three phases. Knowledge maps [45], web site quality evaluation [46], and knowledge sharing difficulties and practises in global software development are just a few instances of the research that applied this technique to perform a systematic review [47]. Although [48] guidelines are often used, there are other techniques for doing a systematic review, for example, [49] and [50], utilized the criterion in [51].

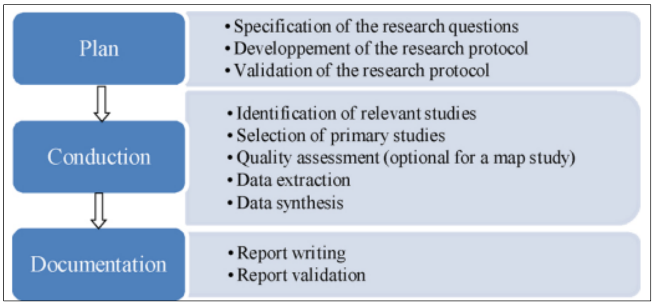

Fig. 1 Research methodology process [14]

Since, to the best of the authors knowledge, no attempt has been made to publish a SMR of this topic, the goal of this study is to identify, quantify, and summarize timers' control in EWH-related papers regarding the application of timer control methods that are connected to LFC for grid, with no restrictions on the start date. Table I shows the specified inclusion and exclusion criteria.

Search Terms

The search string is largely determined by the keywords that were selected for this particular matter. The following combination of terms was approved by the supervisory team, and it was as follows: "control" OR "monitor" OR "manage" AND "Electric water heater" OR "EWH" AND "Load frequency control" OR "LFC" OR "load frequency" OR "demand side management" OR "DSM", in order to find the primary papers. A search was conducted using this search keyword in the following list of digital libraries: IEEE Xplore, Science Direct, and Google Scholar. These digital libraries include lots of power system engineering-related articles that are accessible for interested individuals and organizations at any time.

Inclusion and Exclusion Criteria

The selection procedure aims to find research that may assist to answer the RQs provided in the introduction by defining inclusion and exclusion criteria [52]. Two of the study's original authors used the inclusion/exclusion criteria indicated in Table I to independently assess each article found by the search. When both the inclusion criterion (IC) and the exclusion criterion (EC) are present, the Boolean operator OR is used to join the two sets of criteria (EC). A paper is approved if it satisfies at least one IC but none of the EC, and it is rejected if it satisfies any EC. This verdict was arrived upon after reading the abstract, keywords, and title, and the whole material if more study was needed. After the study's conclusion, the supervisors consulted to share their results. In the case of a disagreement, the paper is discussed at length to reach a compromise. There were many areas of agreement; just 36 points of disagreement were found, and after extensive research, 31 of the contested articles were selected for further study.

TABLE I
INCLUSION AND EXCLUSION CRITERIA

Inclusion	Exclusion
1. Paper in English	1. Paper in foreign language
2. Grid based approach	2. Topic is not related to grid
3. Timers/thermostat to control EWH	3. Thermostat inside EWH
4. Control methods and techniques	4. Review paper without proposed technique

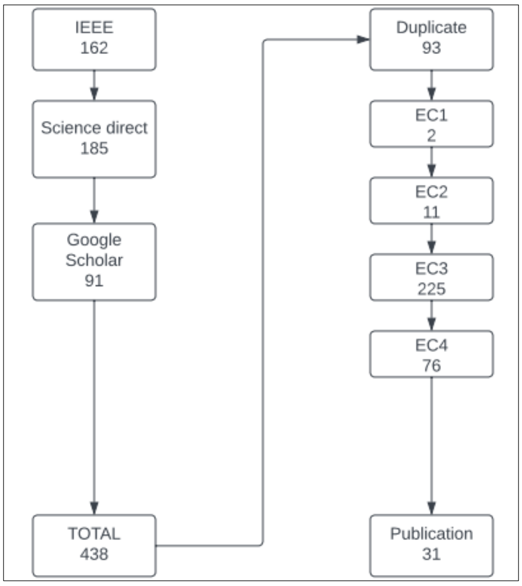

Fig. 2 Selection process based on EC and IC

IV. RESULTS

The selected publications have been analysed with regard to a variety of characteristics, including publication year and origin, control technique, method classification in connection to load control, and data source that was employed to execute control method.

In order to put together this extensive review, 438 primary research publications were retrieved from the databases Science Direct, IEEE Xplore, and Google Scholar. Throughout the selection process, the Rayyan App serves as an automated system that provides assistance.

The end result was 31 studies being selected. The vast majority of these studies investigated various load management strategies for EWH with the goal of balancing the grid in DSM. A piece of writing is selected for usage with the Rayyan App if it satisfies the grid application criterion as well as at least one other inclusion condition, and if it does not satisfy any exclusion criteria.

Just nine of the 31 research that were chosen for further examination were published in journals, compared to 22 studies that were presented at conferences (70.96%). The number of articles that were published in each year is shown in Fig. 3. From the beginning of the last decades, there has been a discernible increase in the amount of focus placed on the incorporation of EWH approaches into grid balancing. In point of fact, it only detected two published articles prior to 2010, which is equivalent to 6.45% of the total, while 93.55% of the total number of chosen papers were published after 2010. In addition, the number of published articles in a given year has climbed to the highest level as of 2018 for the papers that were chosen. Moreover, the first article to be published in a journal appeared in 1999, and it is important to point out that no paper was published in a journal between 2000 and 2011, in addition to 2023 from the selected studies.

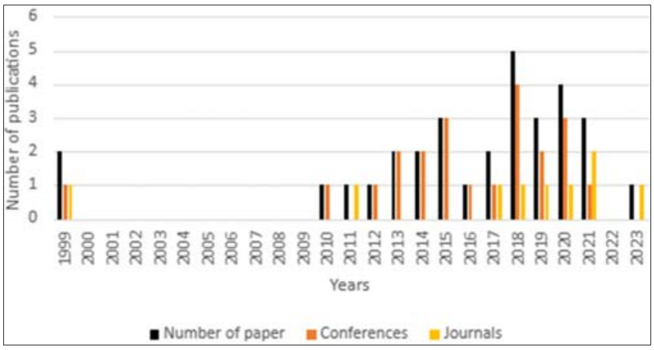

Fig. 3 Source of publication

The application of EWH strategies to the problem of maintaining grid balance was the aspect [18] research that received the greatest attention. This study provides the foundation upon which the classification of the methodologies is based. In point of fact, 16 of the selected papers (51.6% of the total) dealt with DLC, whilst only 13 of the study (41.9% of the total) studied ILC. The remaining two published papers from the selected study each deal with both methods, bringing up 6.5% of the overall contribution from the publications. On the other hand, each of the selected papers was analysed in order to discover the method that it used in order to control EWH, and this process was carried out in accordance with whether or not the primary goal was to guarantee the satisfaction of the consumer. Fig. 4 provides a visual representation of the classification bar charts.

RTD sources that collect grid status information for control methods in EWHs can provide immediate feedback on changes in the grid frequency, which allows for quick and accurate adjustments to be made. As shown in Fig. 5, 20 of the selected studies have RTD sources, which accounts for 64.5% of the total. Some examples of these data sources include smart grid sensors, SCADA systems (which stand for supervisory control and data acquisition), substation monitoring systems, and smart metres. Historical data for the same site are one of the NRTD sources that are used for gathering grid status information for control techniques in EWHs. This accounts for 35.5% of the total number of studies included in the selected papers.

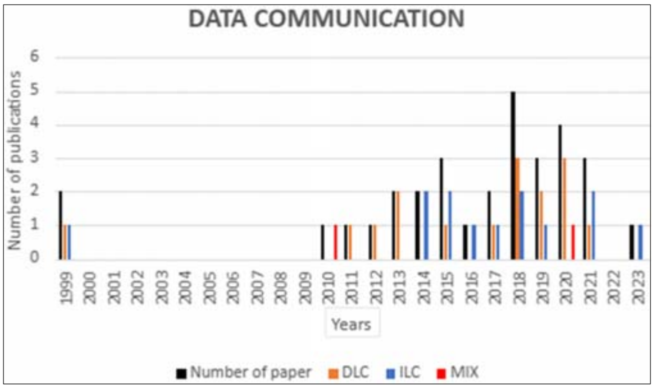

Fig. 4 Control approaches based on DLC, ILC and MIX

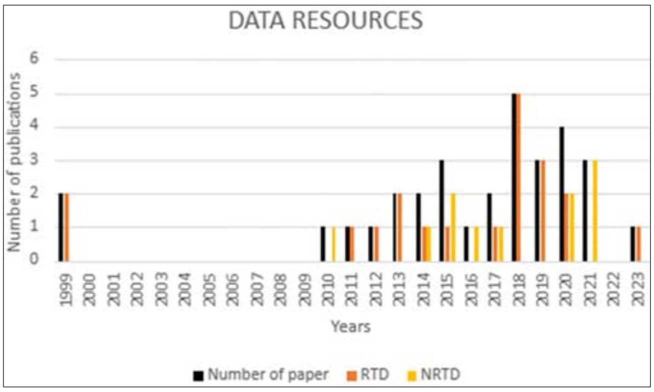

Fig. 5 Data sources for the grid status

VII. Discussion

Quantifying and analysing the findings of research that were conducted on the use of EWH control approaches in DSM was the purpose of this systematic map and review. As a result, out of a total of 438 investigations, only 31 publications were chosen to be reviewed and analysed. In this part, it conducts analysis and discussion of the findings that were acquired for the research questions that were established.

Fig. 3 illustrates the limited scope of the publications used (2 different sources for 31 papers). As a result, it is able to draw the argument that there is a publishing channel that is specifically devoted to the implementation of EWH control strategies in DSM, the prevalence of selected studies published in conference proceedings within publication channels specializing in the power and smart grid industries exceeded those disseminated through journals, this difference may be explained by the fact that the research in this subject is still in its early stages and has not yet achieved a high degree of development and maturity. However, the overall number of research that was published in reputable sources was rather high. Based on Fig. 3, it can be seen that the number of publications by 1999 was rather low. This is because 1999 was the start of the involvement in EWH control for DSM approaches in grid, in particular for applications involving smart grids. Since 2010, the DSM has seemed to gain greater attention, as seen by the rising average number of articles produced each year. In addition, over 93.5% of the research that were chosen were first published after 2010. Thus, researchers are strongly urged to carry out further studies in this area. On the other hand, as a result of the procedure, there were fewer publications published in 2021-2023, this might be the exclusion criteria caused some research to be disqualified from publication.

TABLE II
INCLUDED PAPERS

Reference	Data stream	Method	Approach
[14]	RTD	Fuzzy logic-heater power demand profile and shift them from periods of high demand for electricity to low demand periods.	DLC
[52]	RTD	Time series analysis used, such that the dynamic conditions of both the water heater and the electrical network can be considered.	ILC
[41]	NRTD	Smart Scheduling and Control System using data-driven disturbance forecasts in a robust Model Predictive Control (MPC).	ILC
[40]	NRTD	Time scheduling for a water heater that guarantees comfort based on the consumption habits, the monitorisation of temperatures and dynamic electricity prices.	ILC
[54]	RTD	Controlling the thermostat setpoint of an EWH, its power consumption rate can be controlled.	DLC
[55]	RTD	Using an incentive-based DR programme.	ILC
[56]	RTD	Optimization-based home energy management system.	DLC
[25]	RTD	K-means for a number of clusters.	DLC
[57]	RTD	Fuzzy logic supervision of EVs and EWHs leads to an important reduction of the energy transmission cost.	DLC
[58]	NRTD	Classification of warm water usage.	ILC
[59]	RTD	Monte Carlo approach.	DLC
[60]	NRTD	Bus split (BS) aggregation and user commitment (UC) methods.	DLC
[15]	RTD	To manage pick-up demand when reactivating heating elements at the end of a load shifting period, stagger the reactivation, ensure sufficient system capacity, size elements properly, use control mechanisms, and implement monitoring systems.	DLC
[61]	RTD	Load spreading that takes grid load limits, real-time temperature measurements, water usage patterns, individual user comfort, and heater meta-data into consideration.	DLC
[13]	NRTD	Mixed-integer linear programming (MILP).	MIX
[62]	RTD	Fuzzy logic.	ILC
[63]	RTD	Optimal operation scheduling algorithm of EWHs.	ILC
[64]	RTD	A control strategy based on virtual state of charge (VSOC) priority.	DLC
[65]	RTD	Using Q-learning algorithm. Rewards are assigned for each action-state pairs proportionally to the fuzzy membership of the system in the new state.	DLC
[66]	RTD	Reinforcement learning algorithm, called fitted Q-iteration.	ICL
[67]	RTD	Two methods are proposed to mitigate the adverse effect from this rebound effect. Using battery energy storage system, using EWHs as thermal energy storage systems.	ICL
[68]	NRTD	Binary particle swarm optimization (BPSO).	DLC
[59]	RTD	An optimization function employs proportional and integral methods in optimizing the DLC switching programs to meet peak reduction targets.	DLC
[34]	RTD	MILP.	DLC
[35]	NRTD	Standard bang-bang controller operating at steady state.	DLC
[70]	NRTD	Using scheduling control to EWH s through a machine-to-machine (M2M) solution with cloud-based set point and schedule control.	ILC
[71]	RTD	Multi-objective optimization model based on a hybrid coding differential evolution algorithm.	ILC
[4]	NRTD	Mitigation strategies based on a stochastic delay enabled by individual controllers on each EWH within a population.	DLC
[72]	NRTD	By predicting the actual load profile in the presence or absence of load shed control action.	DLC
[73]	RTD	State of Charge (SOC) for EWHs as well as the development and evaluation of several load control strategies of various sophistication levels.	DLC
[74]	NRTD	BPSO to achieve realistic results.	MIX

DLC is a method that allows an aggregator or a supplier to control the amount of electricity that is consumed by EWH for the purpose of maintaining the stability of the grid. This method has garnered attention from a relatively early point in time, despite the fact that customers did not anticipate being able to take such action due to a lack of instruments which could offer real-time readings and the possibility that their power bills would be lower. The alternative strategy, known as ILC, has been implemented on the premises of improving the level of comfort experienced by customers. The combination of the two has been put into effect in order to prioritize the comfort of the customers while also preserving the integrity of the grid.

RTD sources give information that is reliable and up-to-date on the state of the grid. This information is essential for making intelligent selections regarding when EWHs should be turned on or off. It makes it possible for control methods to have short reaction times, which in turn makes it possible for control methods to act rapidly to fluctuation in the grid. There are a few negatives associated with it, such as the fact that it may be costly to install and maintain, especially for installations of a smaller size, it is possible for it to be complicated to operate and maintain, requiring specific skills. Additionally, it can generate massive amounts of data, which may make management and analysis challenging.

It is possible that the costs of the NRTD sources will be lower than those of the RTD sources, especially for installations of a smaller size. When compared to RTD sources, it could be easier to run and maintain. It is able to generate manageable volumes of data, making it simpler to handle and analyse. However, it may not provide up-to-date information on the state of the grid, potentially leading to less accurate control techniques. It may also not respond rapidly to changes in the grid, resulting in less efficient control techniques. Additionally, it may not offer RTD, which would limit its utility for monitoring and operating EWHs, especially during periods of high demand.

Because the time span for the selected paper ranges from 1999 to 2023, the systematic mapping is displayed in Fig. 5. It can be observed that the DLC has a slightly higher potential for application compared to the ILC and significantly higher than mixed method. In addition, the methods have been applied primarily for contemporary control techniques and some machine learning algorithms.

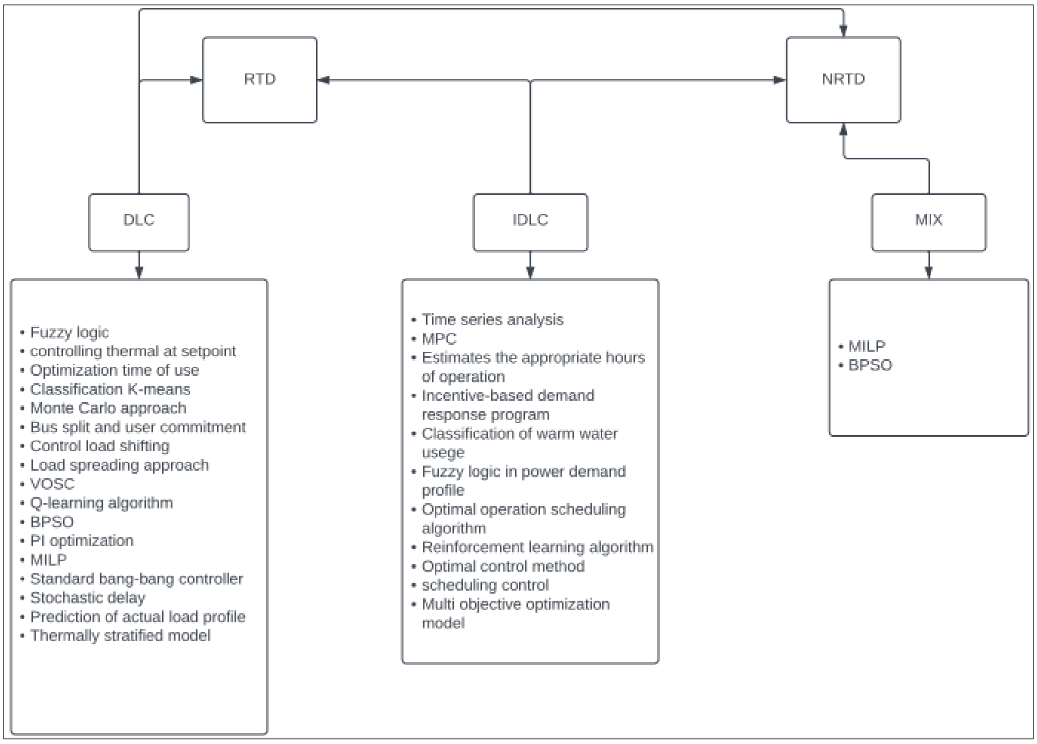

Fig. 6 Systematic mapping

VIII. Conclusion

This comprehensive map and review aim to quantify and categorize the research published in the period 1999 to 2023, since no SMR had been conducted previously to the publication of this work, and to identify the DSM methodologies and potential future recommendations. The selection procedure yielded 31 publications that were organized by year and source of publication, control technique, and data source, to offer answers to the stated research questions. Because of the fluctuating frequency response caused by the incorporation of different factors, DSM with EWH management approaches has garnered increased attention over the last decades. A variety of information criteria (IC) and estimation criteria (EC) were applied to filter the publications, which were published in a variety of journals and conferences. Fuzzy logic was found to be used repeatedly in the existing methods for controlling EWH. Furthermore, machine learning models are also examined. It is important to note that none of the DSM control methods used are prominent. Using machine learning methods to DSM requires more work, since this discipline has not yet achieved full maturity. Thus, it should include researching AI and deep learning, as well as working with both RTD and NRTD at same time, in order to enhance a plan to respond to cyber-attacks. Finally, to be able to evaluate offered models, it is strongly advised to construct a power cost impact comparison list and power stability degree to persuade both customers and suppliers.

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