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Energy Management in Power Distribution Systems: Review, Classification, Limitations and Challenges

MD SHAHIN ALAM, (Student Member, IEEE), AND SEYED ALI AREFIFAR, (Senior Member, IEEE)
Department of Electrical and Computer Engineering, Oakland University, Rochester, MI 48309, USA
Corresponding author: Seyed Ali Arefifar (arefifar@ieee.org)

ABSTRACT Energy management in distribution systems has gained attention in recent years. Coordination of electricity generation and consumption is crucial to save energy, reduce energy prices and achieve global emission targets. Due to the importance of the subject, this paper provides a literature review on recent research on energy management systems and classifies the works based on several factors including energy management goals, the approaches taken for performing energy management and solution algorithms. Furthermore, the paper reviews some of the most proficient techniques and methodologies adopted or developed to address energy management problem and provides a table to compare such techniques. The current challenges and limitations of energy management systems are explained and some future research directions have been provided at the end of the paper.

INDEX TERMS Energy management, load management, power distribution, data analysis, smart grids, energy storage, wind energy, solar energy, energy storage, electric vehicles.

NOMENCLATURE

ABC	Ant bee colony
ACO	Ant colony optimization
AIS	Artificial immune system
AML	Algebraic modeling language
CESs	Conventional energy sources
CET	Carbon emission trading
DERs	Distributed energy resources
DG	Distribution generation
DR	Demand response
EDS	Electrical distribution system
EM	Energy management
EMS	Energy management system
ESS	Energy storage system
EVs	Electric vehicles
FC	Fuel cell
GHG	Greenhouse gas
GPT	Grey predictor technique
GT	Geo thermal
HA	Heuristic algorithm
HSA	Harmony search algorithm
MG	Microgrid
MICP	Mixed integer comic programming
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MPC	Model predictive control
MPCC	Mathematical program with complementarity constraint
MPPT	Maximum power point tracking
MRC-GA	Matrix real coded genetic algorithm
PDE	Pareto frontier differential evolution
PHEVs	Plug-in hybrid electric vehicles
PSO	Particle swarm optimization
RESs	Renewable energy sources
SCADA	Supervisory control and data acquisition
TEMS	Transactive energy management system
TS	Tabu search
UC	Unit commitment
IOT	Internet of things

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I. INTRODUCTION

Most of the world's electric energy is generated in power plants from burning fossil fuels, which are limited in availability and have adverse environmental impacts [1].

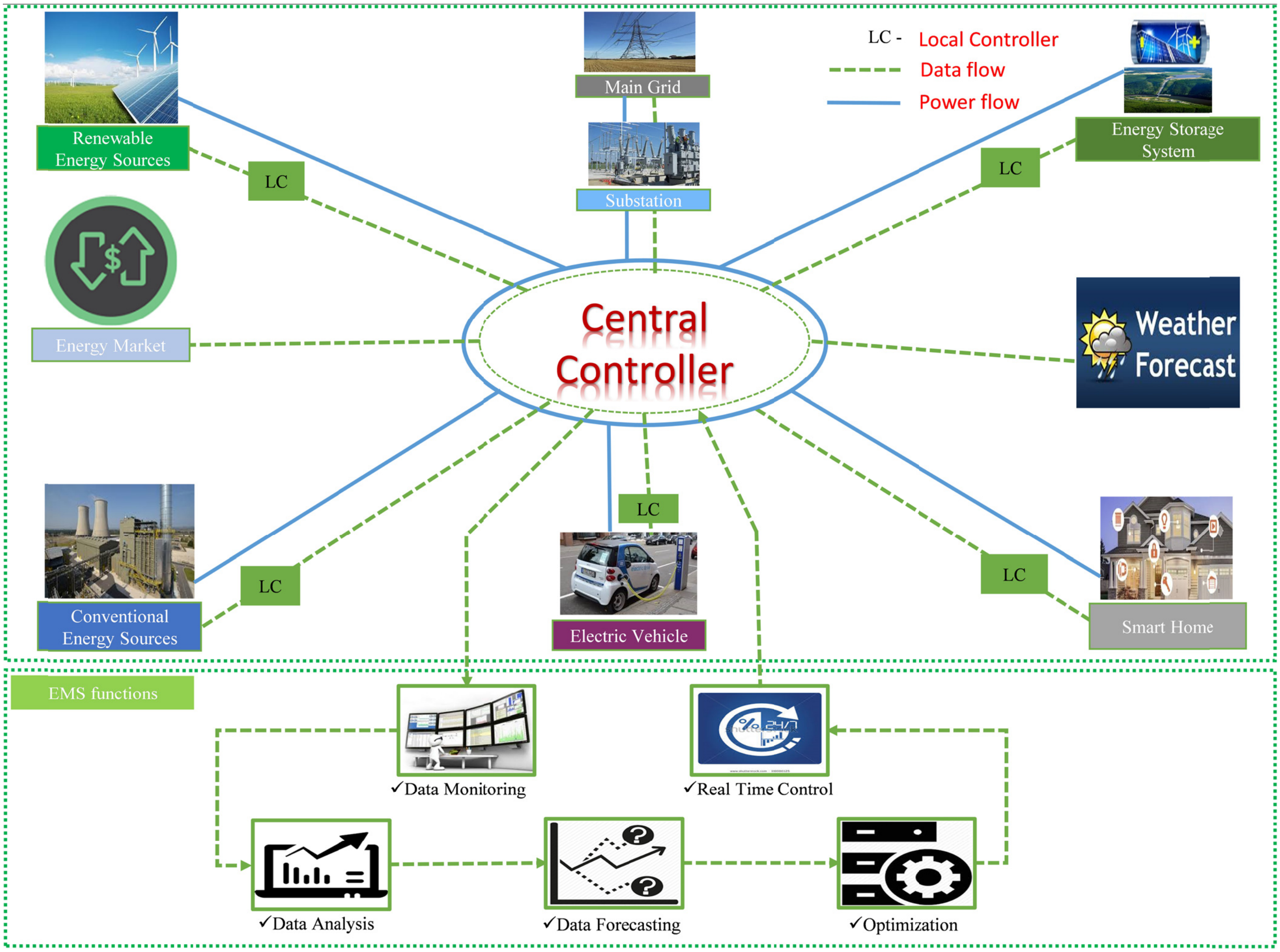

FIGURE 1. **Energy management system architecture and operation.**

Recent research shows that if the consumption rate stays constant, the world reserve for fossil fuels will last for only 50-60 years [2]. Furthermore, the United Nations Sustainable Development and Paris Climate Agreement have set goals to reduce the emissions to the environment [3], [4]. Additionally, the energy consumers nowadays demand more reliable and cost effective energy, which is not possible to achieve using manual system control options [5].

In this scenario, the need for a more efficient and effective way for generation and consumption of electrical energy is highly manifested. Balancing energy generation and consumption, so-called energy management, can have significant impacts on the journey of electric energy from generation to consumption. Energy management in power distribution systems takes into account different conventional energy sources, renewable energy sources, energy storage systems, responsive and critical loads along with EMS functions/operations shown in Fig. 1. In this scheme, the balance between generation and load is achieved by using different data such as weather forecast and energy market data, through the advanced communication and control infrastructure. Energy management can be performed in a small scale isolated MG or in a grid connected power distribution system [6]–[10]. It has been an interesting research area in the past decades, to the extent that several papers have been published on different energy management options in distribution systems. The researchers have interest on the energy management subject due to several reasons, which include: a) loss minimization in the transmission/distribution systems by the transmission/utility companies to lower the operational costs that indirectly helps the consumers pay fewer electricity bills; b) cost minimization by directly controlling and monitoring the energy resources or the controllable loads, which will result in adjusting the time of generation and consumption by different units and consequently reduce the generation costs; c) reducing GHG emissions that impacts the society by utility companies. Energy management in distribution systems plays a significant role in system operation and control and makes the power system operation more efficient by monitoring, controlling, and conserving energy. It also helps to provide power to the customers of critical load in the event of an outage in the power lines, in the primary substation or during scheduled interruptions [5].

Considering controllable DGs in distribution systems, several research articles have been published in energy management for minimizing the system losses and system operational costs. For example, the authors in [11] present a model that optimally controls and reschedules the diesel generators and battery storage units to minimize the system operational costs. Reference [12] presents a multi-agent transactive energy management system to control supply in the presence of high levels of RESs and EVs. Solanki *et al.* [13] present a model to study the optimal dispatch of MG DG units to make the system sustainable. Reference [14] presents a model to control a remote MG featuring a diesel generator, ESS, and PV panels to reduce the system operational costs and ensure the supply to the critical loads. Reference [15] presents a model to control the distributed generators and ESS to minimize the system costs by maximizing the use of RESs. In [16], a modified ABC method is used for economical dispatch considering generation, storage, and load. Reference [17] presents a model to adjust the generation output according to the realistic scenario of the network. A model is discussed in [18] that takes into consideration discrete size and maximum allowable DG size in distribution systems. A model has been presented in [19] to find the real-time optimum energy management solution for a stand-alone hybrid wind turbine using PSO search method. The same PSO-based search method was used by Li and Jiang [20] for the optimal economical dispatch of wind turbines for the short-term operation. In addition, several papers addressed the control of DGs for different aspects of energy management. Tabu Search optimization technique is applied for energy management in multi MG [21], the MINLP technique is applied in a rural distribution system in [22], two-stage optimization technique is applied in MG with different penetration levels of PHEVs in [23], and the modified big bang-big crunch method is applied in unbalanced distribution systems in [24]. The EMS determines the optimal dispatch and schedules of the DERs in MG and hence is responsible for their economic and reliable operation [13]. References [25]–[42] also addressed different control strategies of DGs.

Furthermore, as an energy management option, many papers have been published in literature to address the minimization of costs and losses in the distribution systems using system reconfiguration techniques [43]–[52]. For instance, Falaghi *et al.* [53] present a model that relocates the existing switches in the presence of distributed generators during post-fault service restoration to improve the reliability of the system with consideration of economic aspects. A mixed-integer linear programming technique for the optimal sectionalizing switch position has been proposed in [54], while considering the reliability, capital investment, and annual operation and maintenance costs of the system. A specialized greedy randomized adaptive search procedure algorithm finds out the optimal switching devices to achieve optimal reconfiguration of electrical distribution systems and the optimal service restoration of EDS [55]. Ba *et al.* [56] discuss a methodology using less switching operation for system loss minimization. In [43], the authors present a method for computing the sensitivities of the state variables with respect to switching operations. In addition, references [57]–[62] also discuss the switch reconfiguration schedule for solving the same optimization problem. The authors in [27], [49], [63], and [64] discuss different aspects of capacitor control in a distribution system.

The burning of fossil fuels for energy generation adds emissions to the environment. Many research articles have been published in energy management for minimizing the environment pollution. For instance, Taha *et al.* [11] present a model considering hybrid energy sources, including wind and solar as renewable sources, as well as controllable loads, while using a diesel generator and ESS for minimizing emissions to the environment. A day ahead operational planning for the minimization of CO_2 emissions and fuel consumption of an urban MG is discussed in [26]. The authors in [13] discuss the CO_2 emission models for fossil fuel based distributed generators considering their individual emission characteristics and fuel consumption. In [19], the authors present a model for maximizing the turbine operational efficiency and reducing environmental emissions. In addition, the authors in [25] and [65] discuss how energy management helps to reduce the pollution for the environment.

Searching the literature reveals that several research papers are published in the area of energy management in distribution systems. Since the energy crisis is becoming more important, it is time to summarize and categorize all the great work that has been done on this subject so far, thus creating a clear overview of the accomplished goals and insight for future research paths. Some papers have been published recently reviewing some aspects of energy management. For instance, the authors in [66] discuss some control features of MGs, and prediction techniques for load and generation in MGs. In [67], Haytham *et al.* present literature related to developing and controlling building energy management techniques. Reference [68] gives an overview on demand side management for performing EMS operations. The authors in [69] discuss an EMS to motivate the energy users for their behavior change using monitoring, sensing, and social network friends. Although some review papers have been published on energy management subject so far, the literature still lacks a comprehensive review on energy management in distribution systems which provides insight to the subject from different aspects. To address the gap, this paper's aim is to prepare an inclusive literature review of the published research on energy management in distribution systems. The goal is to summarize the work in terms of several factors including objective functions, energy management approaches, solution algorithms, and to identify the limitations of such researches. Also, some current challenges of the energy management process are introduced and some potential future research paths are proposed.

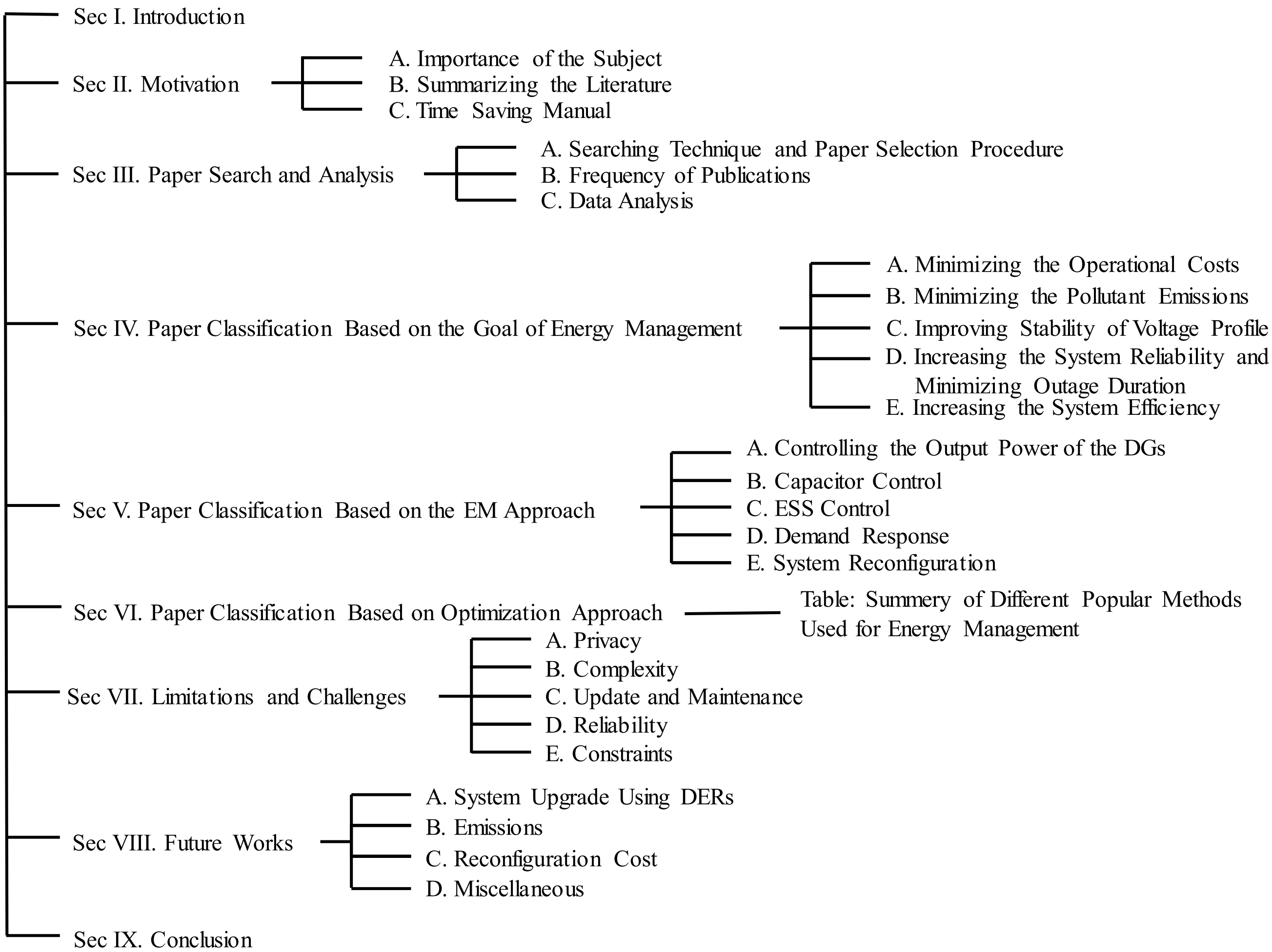

FIGURE 2. **The structure of the paper.**

The main contributions of this paper are as follows:

- Conducting a comprehensive and up to date literature review on energy management in power distribution systems.
- Summarizing the work and categorizing it based on several important factors including objective functions, the energy management approaches, and solution algorithms.
- Organizing and discussing some of the most proficient techniques and methodologies adopted or developed to address implementation of energy management.
- Analyzing the papers published on energy management subject and introducing the challenges and limitations in this area, as well as discussing open questions for future research directions.

As shown in Fig. 2, the rest of the paper is organized as follows: Section II describes the motivation behind the work for this paper. Section III discusses the paper searching technique, paper selection procedure, frequency of publications, and data analysis of the reviewed papers. The classification based on the goal of energy management that categorizes all the reviewed papers in terms of their optimization objective functions is discussed in Section IV. The EMS approaches of the studied papers is presented in Section V. Classification based on optimization approaches is discussed in Section VI. The challenges and limitations of the current research is presented in Section VII and future work recommendations are discussed in Section VIII. Finally, the conclusion of the paper is discussed in Section IX.

II. MOTIVATION

Several factors motivated the authors to carry out the summary or literature survey on the energy management subject in this paper and they are described in the subsections below:

A. IMPORTANCE OF THE SUBJECT

Energy management has been and still is an ongoing research in distribution systems due to several factors. To meet the increased energy demand, reduce the environmental pollution, and reach the socio-economic benefit for sustainable development, extensive research and innovation is still needed in this area. Thus, it is of great importance to investigate this subject more in depth.

B. SUMMERIZING THE LITERATURE

Even though there are a couple of partial review papers on energy management in different perspectives, per our knowledge, no existing paper is available in this area that aggregates the current work, operating methods, optimization objective functions, solution algorithms, challenges, and the limitation of current research on energy management systems.

Also, this paper summarizes most of the proficient techniques used in this area that provide the information for the audience to make the right decision for performing energy management in a distribution system. The researcher can get ideas about the strengths and limitations of the presented techniques, helping them to work in a more confident way.

C. TIME SAVING MANUAL

This article is a literature review paper that works as community service intended to help researchers, potentially saving their time and making their lives more manageable. This paper will be an ideal guideline for those who are entering this area in the beginning stage and can get knowledge and information about the related research topics. Furthermore, categorization of the related papers in the easiest way will let the researchers know about the state of the recent research on energy management and the related existing/challenging research topics.

III. PAPER SEARCH AND ANALYSIS

This section describes the paper searching technique, paper selection procedure and presents some data analysis. The primary searching strategy for the energy management articles was by searching for certain keywords. Through this strategy, papers were filtered according to their title, abstract, full-text reading and quality assessments. Relevant information is collected from the studied papers which are analyzed and used to classify the papers based on objective functions, EM approaches, and optimization strategies.

A. SEARCHING TECHNIQUE AND PAPER SELECTION PROCEDURE

The content of the papers on energy management subject, generated from random selection, were investigated. The first filter excluded duplicate titles from our search. Content from relevant titles and abstracts were examined, and relevant articles were read. Reviewing the articles further reduced unrelated articles. The final selection for the review papers got to the last stage by screening at a couple of selective stages as well as reading the whole paper, as shown in Fig. 3.

B. FREQUENCY OF PUBLICATIONS

Fig. 4 shows the number of published papers per year on energy management. As energy management has been flourishing since 2010, this graph presents the number of papers from 2010 to 2019. It is observable that each year after 2010,

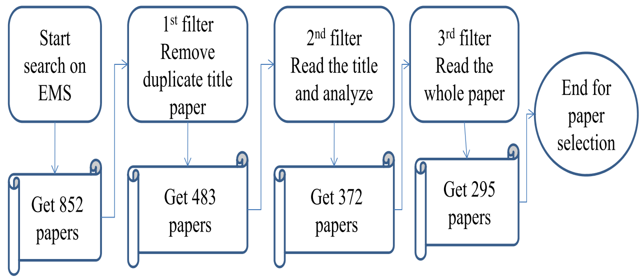

FIGURE 3. Paper selection procedure.

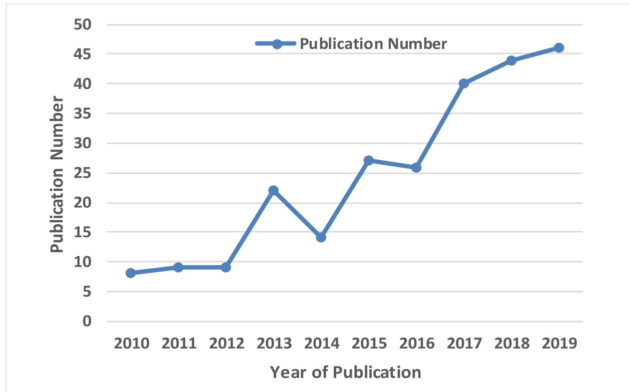

FIGURE 4. Number of publication per year.

the EMS papers increased and the maximum amounts of papers were published in 2019 compared to other years. The average number of papers per year is around 25 and has increased in recent years as shown clearly in Fig. 4.

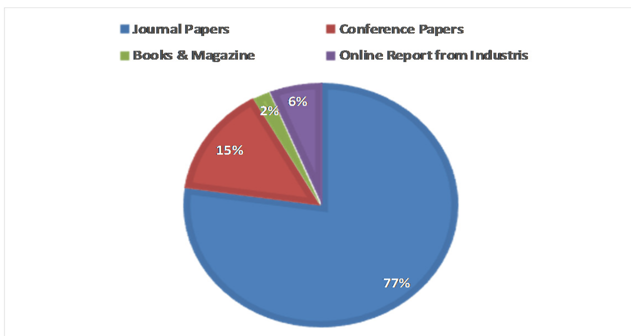

FIGURE 5. Publication by journals, conferences, books & magazines, and online reports from industries.

Fig. 5 shows the ratio of journals, conferences, books and magazines, and online reports from industries on energy management subject in the literature.

C. DATA ANALYSIS

The selected research papers were investigated for further relevant information. Research on energy management began in early 1998-1999 [70]. With the emerging sector of energy management, this has drawn the attention of many researchers around the world. Fig. 6. shows the frequency of

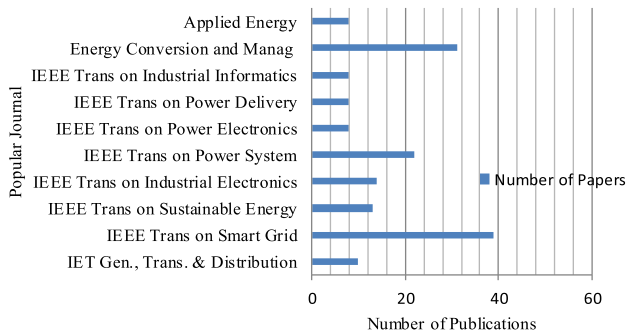

FIGURE 6. Number of publication by popular journal.

the published papers in different reputable journals. Among them, the highest number of publications are in IEEE transactions on smart grid and energy conversion and management. There are also a significant number of papers published in IEEE transactions on power delivery and power systems, and IEEE transactions on industrial electronics.

IV. PAPER CLASSIFICATION BASED ON THE GOAL OF ENERGY MANAGEMENT

Energy management is usually performed by defining a goal or objective function and optimizing it. In this section, the studied papers are classified in terms of the goal of energy management. Different approaches are applied to find the best global solution for the same objective function.

A. MINIMIZING THE OPERATIONAL COSTS

Energy management greatly helps to reduce the system's operational costs. It can optimize the share of energy generation for the generators and avoid the expensive energy sources based on the demand requirements, especially during peak hours. Also, network reconfiguration and reconfiguration scheduling in a distribution system helps to reduce the system losses and eventually, the operational costs. Some research has been published for minimizing the system operational costs with different approaches in the following literature: [11], [12], [14]–[17], [19], [21], [25]–[27], [30]–[33], [35]–[41], [51], [53], [54], [56], [58], [62], [15], [71]–[130], [132], [132]–[161].

Moreover, utility companies are affected by line losses due to the load, which is far away from the generating station due to economical, environmental, and geographical issues. Many developing countries transfer electrical energy from the neighboring counties over high voltage transmission lines. Regarding this issue, occasionally, DGs are integrated for grid reinforcement and reducing power losses, where new challenges will be introduced to the operation of the power distribution systems. Such challenges are addressed in the following published research: [11], [22]–[24], [33], [34], [43]–[50], [52], [55]–[64], [79], [106], [121], [154], [155], [162]–[174].

B. MINIMIZING THE POLLUTANT EMISSIONS

Global warming is one of the major concerns for the present world, which contributes to the rise of the average temperature of the earth's climate system. Several factors are responsible for global warming including the use of factories, gas consuming vehicles, and other emissions from fossil fuels. Although fossil fuels cause emissions in the environment, still a higher proportion of the world's energy is produced by fossil fuels. The reason for using fossil fuel-based energy generation is their reliability and low prices compared to renewable energy sources. The energy management system has a significant role in minimizing the greenhouse gas effects by properly managing and controlling energy sources in distribution systems while concentrating on system's reliability and efficiency. The following papers contribute to minimizing the power generation related emissions to the environment: [11]–[13], [19], [25], [26], [37], [83], [84], [90], [91], [105], [108], [121], [128], [130], [135], [160], [175]–[178].

C. IMPROVING STABILITY OF VOLTAGE PROFILE

Voltage stability is a concern in distribution systems which could happen due to the fluctuation of loads or generator outage. When the loads change or generators go out of order due to sudden disturbances, the voltage levels also change. The voltage stability problem may be alleviated by using reactive sources in the system. If the reactive power cannot provide enough support to keep the voltage within tolerable limits, the bus voltages further fluctuate and cause a cascading effect in the neighboring region. In a modern distribution system, the demand response program gives the opportunity to the utility to take the load in an optimized way. If the utility company has a clear idea about load consumption, they can manage reactive sources accordingly and avoid such causalities. The system then needs energy management to optimally control the load, generation and reactive sources. Research has been done to address this issue with different approaches in the following literature: [28], [34], [45], [49], [58], [60], [106], [155], [163], [164], [172], [175], [179]–[184].

D. INCREASING THE SYSTEM RELIABILITY AND MINIMIZING OUTAGE DURATION

EMS reviews the data for all the devices connected to the power network by data center utilizations, and identifies the zones with peak capacity or under-performing capacity. This data is essential to future capacity planning, load supplies, and balancing the load and generation. The utility energy suppliers need nearly 100% uptime to the loads, specifically for the critical loads during the extreme events. The system reliability could be improved by optimally managing the ESS, DR, EV using EMS in a distribution system. This subject is supported by the following research: [14], [29], [36], [44], [53], [54], [80], [15], [90], [94], [97], [98], [100], [101], [110], [131], [133], [152], [158], [165], [173], [175], [178], [181], [185]–[208].

Energy outages are a common scenario for the developing world. Research is focused on EMS based on economic optimization, where the combination of energy production and energy storage are able to meet the load demand in a power system. When the energy storage units fail to meet the load demand during peak time, the system will suffer from some outage. Several approaches have been taken to reduce the outage duration. For instance, sectionalizing switches helps to reduce the restoration time if the fault occurs in the distribution system. After a fault occurs, it is located and the faulted part is isolated using sectionalizing switches. Then, the load is restored from the main or alternative sources. The effectiveness of this process strongly depends on the number and locations of sectionalizing switches. This summary of effective approaches has the potential to predict the risk and potential time of occurrence for such an outage and to eliminate or minimize the outage duration. The following research have been conducted for managing energy to minimize the outage duration: [15], [43], [44], [209], [210].

E. INCREASING THE SYSTEM EFFICIENCY

Energy management helps the utility companies to monitor the energy distribution in an optimized way. With the development of technology (IOT sensors), the consumer can get updated energy usage data from the system and optimize the energy saving by re-scheduling the energy consuming devices, or in some cases upgrade the energy inefficient devices. Energy management with smart decisions help the utility and consumers to reduce the energy consumption while ensuring the effectiveness of the power network. In addition, energy management can monitor and control the energy resources located at the consumer side, help to reduce the transmission line stress, and reduces the system loss, which ultimately increases the system efficiency. The following papers contribute to increasing the system efficiency: [19], [36], [117], [118], [134], [165], [177], [15], [193], [211]–[227].

In addition to the papers discussed in previous sections, several reviewed papers that address different aspects of energy management are listed in the following. Reference [228] coordinates the energy sharing to achieve maximum profit and [229] improves the life cycle of batteries. The objectives of maximizing MG and consumer profits individually is discussed in [230], maintaining the privacy concern for both generators and consumers is proposed in [208], and maximizing the total revenue for the PV/battery system is presented in [231]. Reference [232] maximizes the accounting profit in energy trading with the main-grid. A decentralized energy management system is reviewed in [233], miniaturization for autonomous wireless sensor nodes is described in [234], modified Dolphin Echolocation Optimization is reviewed in [235], and advanced metering infrastructure (AMI) analysis is presented in [236]. Reference [237] proposes an online and offline EMS for economy and ecology framework of the system. The authors in [238] describe the differences between distributed energy sources and conventional energy sources and control and dispatch strategies of DGs on MGs. A day-ahead market of wind turbine, photovoltaic, micro-turbine, and fuel cell energy systems considered as one virtual generator in terms of aggregated capacity is discussed in [239]. Wang and Nehrir [240] propose an ac-linked hybrid system to manage power flows among the different energy sources and the storage unit. Chen *et al.* [241] propose an energy management system for economic operation of the distribution system. Ren *et al.* [242] propose an energy management system in MG to ensure its stable operation using PV, storage battery, and fuel cells, and reference [243] discusses and compares different models for performing EMS on SG. Lee *et al.* [244] improve the resiliency of the MGs, and Jafari *et al.* [245] improve operational performance of MGs. Khan *et al.* [246] propose a comprehensive communication framework to increase the privacy and security of the network.

V. PAPER CLASSIFICATION BASED ON THE EM APPROACH

In order to perform energy management or balance the generation and consumption in distribution systems, some actions must be taken. Depending on the availability, such actions will be different for different systems. This section briefly describes the different approaches that are used in literature as tools to perform energy management in distribution systems.

A. CONTROLLING THE OUTPUT POWER OF THE DGS

Distributed generation is strategically placed in the power system network for grid reinforcement, reduction of power losses, on-peak operating costs, improvement of voltage profiles and load factors. In addition, DG helps for deferring or eliminating system upgrades, and improving system integrity, reliability, and efficiency. Also, the transmission loss due to the long distance transmission lines creates high interest in distributed power generation located near the consumption center. The loss minimization, system upgrade option, risk minimization, and the confirmation of using the maximum amount of DGs in the distribution system depends on how the DGs are organized and controlled. In addition, conventional distributed systems have been constructed without the consideration of DG connection. As a result, some problems will occur for DG penetration. The problem will be devastating if the large portions of the DGs are renewable. In that case, voltage deviation and fluctuation according to output fluctuation of the DGs become a major problem which might not be easily solved. As a countermeasure, the management and control of DGs is necessary and by performing energy management, the appropriate scheduling of DGs can solve the voltage deviations and fluctuations. Depending on the operation schedule of DGs, the system performance could be optimized.

This section summarized the papers that discussed DGs control in EMS in the literature: [11]–[15], [17], [21]–[26], [29]–[42], [73], [81]–[85], [88]–[90], [93], [94], [96], [97], [99], [104], [103], [108], [109], [111], [113], [115], [129],

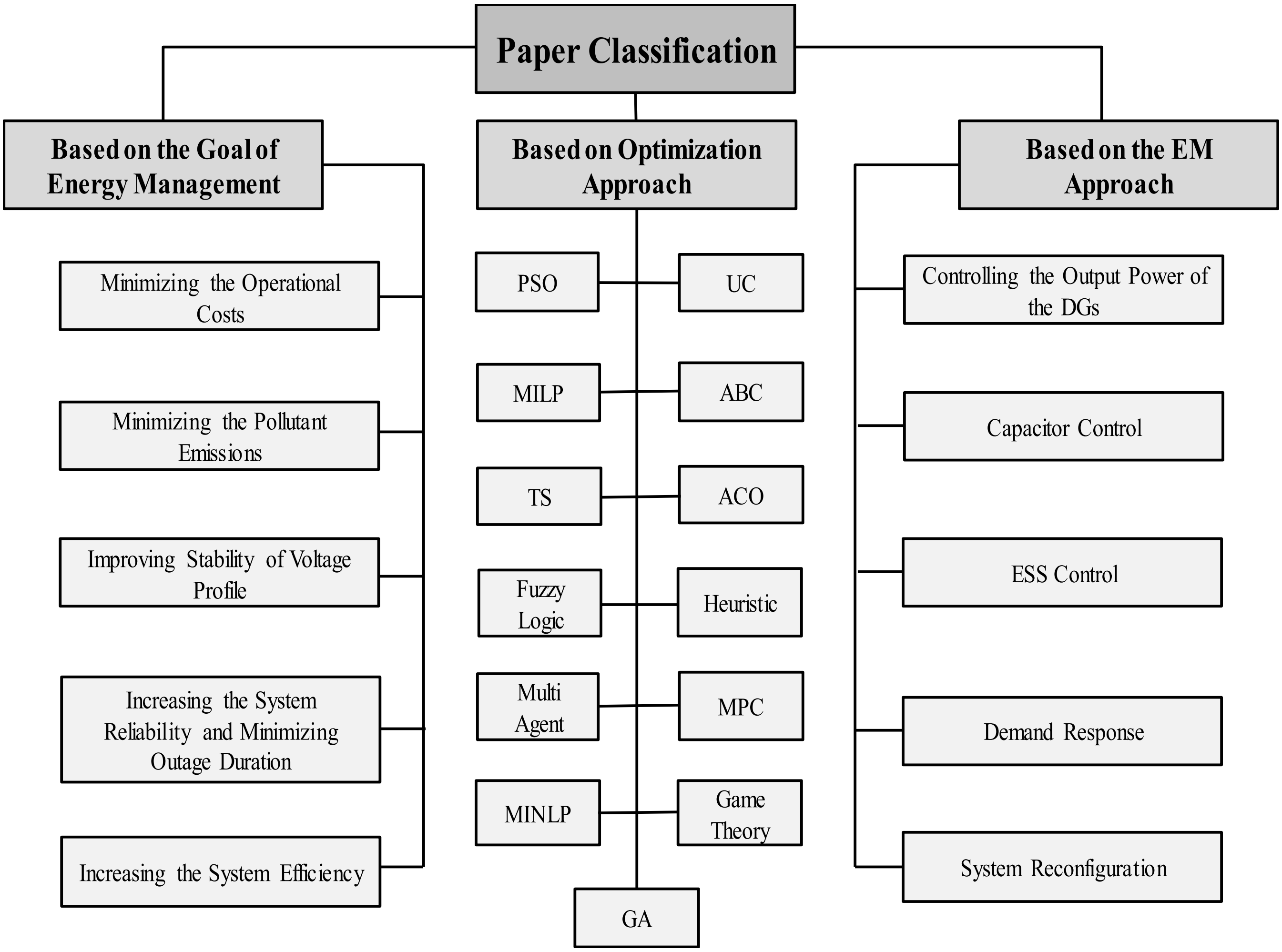

FIGURE 7. EMS article classification.

[130], [133], [136], [151], [157], [163], [166], [167], [172], [175], [176], [185], [189], [190], [192], [194], [196], [200], [201], [209], [212], [213], [216], [218], [219], [221], [222], [247]–[259].

B. CAPACITOR CONTROL

The main purpose of using a capacitor bank is to provide reactive power in the system, which is typically used to correct power factor or phase shift inherent in AC power supplies. It is also used in DC power supplies to increase storage energy and improve the ripple current capacity of the power supply. Capacitor banks are widely used due to their efficiency in reactive compensation. The installation of capacitor banks in optimal places and control over them can help to significantly reduce the system loss, maintain the voltage regulation, and returns a financial benefit for the distribution companies. The authors in [49], [63], [64], [192], [252] discuss capacitor control applied in EMS.

C. ESS CONTROL

In modern distribution systems, renewable energy sources have become popular as clean and cheap energy. The problem of renewable sources is uncertainty, such as the output of PV depends on the outside temperature; winds output depend on the speed of the air. The EMS technology using ESS has led to increased popularity of clean energy. ESS can store extra power during off-peak times for later use and helps to increase the system efficiency and reliability. For energy management operation, the ESS can include battery storage units, flywheels, and EVs. Specifically, EVs could be used as both the load and generation (V2G program) at different times of a 24 hour period. There are many relevant works to the ESS system in the literature: [11], [14], [21], [32], [41], [78], [102], [103], [105], [106], [110], [112]–[114], [153], [160], [167], [171], [174], [175], [181], [183], [184], [195], [196], [198], [202], [208], [229], [247], [260]–[263].

D. DEMAND RESPONSE

The control of timebased consumption from the production side is known as demand response. Demand response helps to decrease the customer's consumption during the system's energy shortage period and meet the ever-increasing demand for energy. Energy management allows the system to take advantage of the demand response program.

Demand response shifts the load requirement from peak time to off peak time and reduces the system operational costs and emissions. Energy management papers that have demand response contributions can be listed as: [12], [13], [25], [91], [103], [103], [107], [114], [127], [141], [147], [264].

E. SYSTEM RECONFIGURATION

System reconfiguration is one of the approaches to perform successful energy management. System reconfiguration is commonly used in power systems for minimizing the transmission line losses. The system reconfiguration for radial distribution network adds complexities for protective relay coordination and demands combinatorial optimization approaches. Sectionalizing switches help to reduce restoration time if the fault occurs in distribution systems. They could disconnect the faulted area and the other loads can still be energized or restored from the main or alternative sources. The effectiveness of this process strongly depends on the number and location of sectionalizing switches. There are many papers published in the literature that address system reconfiguration and its scheduling approaches: [42], [43], [43]–[48], [50]–[55], [57]–[62], [154], [210], [265]. In addition, reconfiguration using switch allocation will produce change in the voltage at which power is being delivered. Thus, it is required to bring the voltage back within its operational limit. Tap changer reconfiguration helps to bring that voltage within the operational limits [44].

In addition to the papers reviewed in the previous subsections, several papers that address different aspects of energy management are: reference [65] where Taguchi's orthogonal array (OA) testing method is used to maximize the total exchange cost, while getting the minimum social benefits cost. A multi-leader, multi-follower, non-cooperative Stackelberg game in malty MG is discussed in [266]. Ref [267] reviews the district energy management system controls, the real-time energy consumption of the district, and minimizes additional real-time energy requests. A Fuzzy Prediction Interval Model in MG is discussed in [268]. The review of MG and the applications of EMS in MG are discussed in [269]. In addition, ref [270] reviews the DERs in MG. A Cuckoo search algorithm in hybrid power system is discussed in [271], ABC algorithm in hybrid power system is discussed in [272]. A multiple-battery system that avoids the use of communication cables is proposed in [98], a standalone PVS used for mobile systems is discussed in [273], and a CCHP coupled multi-energy system is proposed in [92]. In addition, an online alternating direction method of multipliers algorithm is discussed in [274]. Reference [275] studied an effectively integrated group of MGs. Wave let-fuzzy logic based energy management strategy is studied in [190], and data distribution service based EMS is proposed in [276]. The voltage and current fluctuation of the fuel cell reviewed in [205]. A poly generation MG is discussed in [277], district EMS is presented in [256] to maximize the utilization of energy, recursive algorithm based reliability model is discussed in [206] and reference [278] proposes an energy management algorithm for hybrid storage systems. Some energy companies that are currently deploying energy management system are Advantech [279], ABB [280], General Electric's [281], Schneider Electric [282], and Alstom [283]. Siemens is implementing EMS to reduce the energy consumption and emissions [284]. Integration of EMS for all organizations and companies and its guidelines are discussed in [285]. Control strategies and economic operation of MG for performing EMS is discussed in [286]. Allied market performs research to monitor and control EMS, do maintenance, and consultation and training [287]. There are some other companies that work for energy management areas. Clean Park provides an energy management to enable the integration, installation, operation, and maintenance of MGs [288], Entouch Controls provide energy intelligent software to accurately access and control energy consumption and expenditure [289], Naya Energy works for meter demand reduction [290], and Panoramic Power enables businesses to optimize the energy consumption and improve operational efficiency [291].

VI. PAPER CLASSIFICATION BASED ON OPTIMIZATION APPROACH

EMS performs operations using different methodologies and strategies which adequately help to find optimal solutions based on multiple objective functions described in the previous sections. The papers are categorized and analyzed based on the most interesting and proficient methodologies of the reviewed research works shown in Table 1. In addition, the goal of the papers, sustainable energy generation, strengths sides and weaknesses has been recorded that will help the planner to choose the suitable optimization strategy for their specific case study. It is seen that the Particle Swarm Optimization and the Fuzzy Logic Algorithm are the two mostly used and efficient techniques used for solving energy management problems.

VII. LIMITATIONS AND CHALLENGES

Even though energy management in a distribution system helps to improve the system performance, it has limitations and challenges as well. The privacy of the customer side, operations in a big system, upgrade the system in a regular manner and EMS reliability issues have not been addressed properly by researchers. Such challenges and limitations may impact EMS operations; therefore, it's necessary for the relevant researchers to formulate effective solutions to overcome such limitations in EMS.

A. PRIVACY

Energy management provides a balance between production and consumption. It decreases customer's consumption during the system's energy shortage period and helps to reduce the system operational cost, reduce the dependency of fossil fuel based energy generation and decreases the pollution level in the environment. Since the customers' energy consumption pattern should be considered for an optimal

TABLE 1. Summary of Different Popular Methods used for energy management.

Optimization Techniques	Ref. No.	Authors	Goals	Sustainable DGs	Strengths	Limitations	Year
PSO	[25]	N. Zhang et al	Minimize the system operational cost and emissions	Not defined	Achieve load and generation balance	CET raises the price of fossil fuels which need to minimize	2016
	[19]	S. A. Pourmousavi et al	Minimize the system operational cost and emissions while maximizing the system efficiency	Wind	Extremely fast convergence time	No complex multi-source systems in this research	2010
	[27]	C. D. Rodríguez - Gallegos et al	Reducing the system cost while fulfilling the load demand and maintaining the power quality	Wind	Consider the probabilistic nature of load and DGs	Need to optimize the dispatch strategy and improve the employed constraints	2018
	[20]	X. Li et al	Minimize the operational cost	Wind	Consider the uncertainty and intermittency nature of wind power	Uncertainty of wind energy may cause economic losses	2011
	[56]	W. Ba et al	Find out the fault recovery strategy to restore the power supply and reduce the power loss	Not defined	Recover more loads, less switching actions, and reduce the power loss of the system	DGs locations are not optimal which will impact fault recovery	2017
	[33]	B. Yuan et al	Minimize the system cost and emissions	Not defined	Achieve an effect with a small increase in cost and a big discount of loss	Minimizing the loss of converter may increase the operational cost	2017
	[59]	F. J. Rodríguez et al	Reduce the system loss while fulfilling the load demand	Not defined	Open shortest path first, routing protocol to accomplice the network reconfiguration	This model is not capable of sending the failure notification	2016
	[216]	Huynh Ngoc Tran et al	Increase the efficiency of fuel cell	CHP, FC	Make a reasonable schedule of CHP systems for a 24 hour period	Does not show a good convergence result in the proposed method	2018
	[90]	Seyed Arash Alavi et al	Reducing the operational cost and pollutions while increasing the reliability of the system	Wind, PV	Consider the probabilistic nature of renewable based DGs	System operational cost and conservation may increase due to extending time period	2015
	[91]	G.R. Aghajani et al	Reduced the system operational cost and pollution	Wind, PV	Consider uncertainties associated with the wind and solar energy		2015
	[95]	A. Hussain et al	Minimize the operational cost and increase the reliability of the system	PV	Form a hybrid algorithm using PSO and GWO		2018
	[113]	A.	Minimize the system	PV,	Ensure fast and efficient	There is a	2018

TABLE 1. ***(Continued.)*** **Summary of Different Popular Methods used for energy management.**

		Elgammal et al	operational cost	FC	data flow between generation units	complexity about computational time	
MILP	[11]	M. S. Taha et al	Minimize the cost and emissions	Wind, PV	Battery cycle number and minimum state of capacity have been considered so that the battery can give back up before damaging the system	Total system cost may go higher than traditional one for flat-shaped pool price	2018
	[14]	N. Anglani et al	Reduce the operating cost and supply the power to the critical load of the system	PV	Consider the state of charge, life time and cost for the ESS to evaluate the total cost	Operating times need to be carefully considered for operative planning	2017
	[83]	Nicolás Pérez-Mora et al	Find the optimal scheduling for energy generation	GT	Reduce the final cost by avoiding cooling wastes and reducing the system impossibility	Condensing requirements of the generators	2017
	[95]	A. Hussain et al	Reduce the operation cost	Not defined	Customer privacy has been increased	Large computational time for multi MG	2018
	[141]	L. Ma, N. Liu et al	Reduce the prosumer cost	PV	Promoting consumption of PV energy, leading to increase homeowner profit.	There are bounds for shiftable loads	2019
	[244]	H. Lee *et al*	Improve the resilience of the MGs	PV	Can operate in islanded mode during fault	May arise operational cost during unpredictable time	2019
	[131]	M. Ban et al	Increase the system reliability, resilience, and economics	PV	Higher resilience capabilities	Need cost allocation in the proposed cyber physical energy management system	2019
TS	[21]	S. A. Arefifar et al	Minimize the operational cost	Wind, PV	Consider the uncertainties of loads and generators in different states		2017
Fuzzy Logic	[181]	Shi-jun Wu et al	Increase the system reliability and voltage stability	Not defined	Can regulates the evaluated variations in DC load power with a minimal average error	The cost related to the ESS is ignored	2018
	[194]	Diego Arcos-Aviles et al	Minimize the fluctuation and power pick while sharing the power with grid using RESs and ESS	Wind, PV	Achieving a smooth grid power profile and a battery SOC center close to the rated battery capacity	Did not consider the voltage regulation of the MG	2017
	[102]	Juan P. Fossati et al	Minimize the operational cost	Wind	Making a day ahead scheduling for MG by controlling the output power of the ESS	To reduce the operational cost, power loss might be impacted.	2015
	[105]	A. Chaouachi et al	Minimize the operational cost and emission	Wind, PV	Fuzzy environment uncertainties can handle for MG operation	Did not consider the demand response	2013
	[229]	M. Nasr et al	Improve the life cycle of battery	Wind, PV	Maximum power point trackers are associated with PV panels and	Did not consider demand response program and may	2013

TABLE 1. *(Continued.)* **Summary of Different Popular Methods used for energy management.**

					wind turbines	cause load shading.	
	[107]	George Kyriakarakos et al	Minimize the operational cost	Wind, PV	Profit increase for less component of ploy-generation MG	Did not consider the demand response	2012
	[245]	M. Jafari et al	Improve MG operational performance	PV, FC	Can operate in islanded mode independently	Need more details about MG dynamic response	2019
Multi Agent	[92]	Shilei Lu et al	Reduce the system operational cost	PV	Effective solution to the problem of resource shortage, can be used in small-scale regional energy supply	Need to introduce energy storage system and transmission system energy consumption	2018
	[103]	Amjad Anvari-Moghaddam et al	Optimal use of energy sources and minimize the system operational cost	Wind, PV	Reduce uncertain parameters effects in the environment and guarantee the secure and optimal operation of the system	The cost related to the ESS is ignored	2017
	[114]	H. S. V. S. Kumar Nunna et al	Reducing the peak demand and minimizing the cost of electricity	Not defined	Utilize diversity in load consumption patterns of the customers and energy availability from the DERs	Leads to fast degradation of battery	2013
	[121]	C. Dou et al	Minimize the operational cost and emission and line losses in the distribution system	Not defined	Secure voltages as well as maximize economic and environmental benefits	Have complex formulation	2013
MINLP	[164]	R. Sanjay et al	Minimize power loss and better voltage profile	Not defined	Propose the optimal location of DGs while meeting the real and reactive power demand in the system		2017
	[36]	Mousa Marzband et al	Improve reliability and efficiency as well as to reduce the total cost of energy	Wind, PV	Establish the strategy for participating in MG generation with minimum information shared between micro-sources	Power losses are neglected	2013
	[18]	Y. M. Atwa et al	Minimize the system's annual energy losses	Wind, PV, Biomass	Consider a probabilistic generation-load model	Have voltage limits, the feeders' capacity, the maximum penetration limit, and the discrete size of DG units	2010
GA	[73]	C. Chen et al	Minimize the system cost	PV	Consider initial, operation and maintenance costs, load forecasting, energy price structures, and fuel prices	Concerning more relevant factors, such as the industrial and commercial profiles of a city or region	2011
	[260]	S. Leonori et al	Reduce the fluctuations of energy exchanged with the grid and maximize use of the ESS	PV	Consider both MG configuration and energy flows between each subsystem in real time	Need to consider the shiftable loads, energy balance and the presence of a controllable small	2017

TABLE 1. ***(Continued.)*** **Summary of Different Popular Methods used for energy management.**

						diesel generator	
	[106]	C. A. Sepulveda Rangel et al	Reduce the cost and loss in the system	Wind, PV	Mitigate the grids reverse power flow	Did not consider the cost related to the ESS	2017
	[108]	Moataz Elsied et al	Minimize the system operational cost and emissions	Wind, FC	Provide an economical and environmental solution for all MG power systems	There is a complexity about computational time	2016
	[120]	Santosh Chalise et al	Reduce the system operational cost and battery degradation cost	PV	Battery degradation cost is considered to increase its lifecycle	Emission was not considered.	2016
Game Theory	[163]	M. H. Moradi et al	Minimize system loss and improve the voltage regulation and voltage profile	Not defined	Make optimal operation schedule strategy of the DGs		2016
	[162]	K. Wang et al	Loss reduction, benefit increase, reduce loss allocation, feedback control, and system stability	PV	Optimizes both loss reduction for maximum DG benefit and load feedback for system stability	Potential cooperative incentives and communication requirements need to be considered	2015
	[228]	D. Newell et al	Address energy sharing management (ESM) problem in the MG while considering demand response in the consumer site.	PV	Treat the uncertainty of PV energy and load	Did not include the ESS into the system	2017
	[230]	H. M. A. Ahmed et al	Maximize MG and consumers profits individually	PV	Effectively determine the MGO's prices and improve the load characteristics of the whole MG	Emission from micro turbine was not considered	2016
	[126]	G. E. Asimakopoulou et al	Minimize the production cost and maximize the net profit	Wind, PV	Bi-level structure for integrating various distributed resources	Need to consider the ESS in the system	2013
	[144]	L. Han et al	Minimize the coalition energy cost	PV	Centralized control to minimize the energy cost	Have computational complexity	2019
	[161]	X. Yang et al	Minimize the system operational cost and increase the system resilience	Wind, PV	Maintain supply demand balance	Need to consider cyber risk, and transmission error	2019
	[71]	J. Lee *et al*	Minimize the cost of energy	PV	Can predict the energy generation and the load for the optimal operation of ESS	Optimization-based control may vary with operation environment or the electricity tariff	2018
	[34]	M. Falahi et al	Minimize the loss and improves voltage and frequency profile	Wind, PV	Can control active and reactive power in distributed generation integrated distribution systems	Model can be used as a prediction model to achieve the optimal control sequence over a	2013

TABLE 1. ***(Continued.)*** **Summary of Different Popular Methods used for energy management.**

						horizon of time	
MPC	[35]	Zhaoyu Wang et al	Minimize the operational cost	Wind, PV	Consider the uncertainty and variability of RESs DG outputs		2015
	[225]	O. Gomozov et al	Increase the system efficiency and ESS lifetime	Not defined	Increase the lifetime of the overall system	Needs to focus on the inclusion of losses	2017
	[187]	H. H. Abdeltawab et al	Achieve the maximum net profit and increase the reliability of the system	Wind	Achieve the optimal profit with the minimal sacrifices in the battery ESS life	Optimization depends on receiving the market price and wind power predictions	2015
	[217]	T. Morstyn et al	Increase the system efficiency	PV	Circulating currents are prevented and reduce lifetime degradation	Strategy might not work for large MG having higher voltage	2018
Heuristic	[164]	R. Sanjay et al	Minimize the power loss and enhance the voltage profile	Not defined	Find the optimal location while meeting the real and reactive power demand		2017
	[61]	Fei Ding et al	Reduce the system loss	PV	Needs less computational time		2015
ACO	[60]	H. Bagheri Tolabi et al	Reduce the system loss, improve the voltage profile and feeder load balancing	PV	PVs used a combination of DGs and distribution static compensators	Did not consider the probabilistic nature of the PVs	2015
	[40]	Mousa Marzband et al	Reduce the system operational cost	Wind, PV	ESS was properly used and reduced the period of undelivered power	Battery degradation cost was not considered	2016
ABC	[272]	T. Malakar et al	Maximize the profit of hybrid power system	Wind, Hydro	Less power purchase requirement, and better power management	Sensitive to both wind power prediction and prescheduled contract agreement	2014
	[117]	Mousa Marzband et al	Maximize operational efficiency and minimize operational cost	Wind, PV	Convergence speed increase	Emission cost did not considered	2017
UC	[26]	H. Kanchev et al	Reduce the operational cost and emissions of the system	PV	Carries multiple objective functions with time varying load and probabilistic DG model		2014
	[13]	B. V. Solanki et al	Measure the fuel consumption and emission	Wind, PV	Consider the uncertainties of the renewable sources and demand response	Inclusion of both operation and emission costs does not guarantee reduction of these costs with DR	2017
	[84]	Kutaiba S. El-Bidairia et al	Minimize the use of fossil fuels and reduce the emissions	PV, wind, tidal	Enhance the system performance in both the renewable energy penetration level and economic aspects	Did not take into account the intermittency of renewable generation in both	2018
						grid- connected and islanded modes of MGs	
	[183]	M. Nasr et al	To determine the system cost against the variation of PVs	PV	Consider uncertain characteristics of PV	DG have limitations to turn off	2019

generation scheduling, extensive research is still necessary to maintain the customer privacy issues [292]. Especially radio waves may reveal customers locations, and what and when customers are consuming energy [293]. Even though EMS is providing improvements to the environmental and security issues, still it is a concern for the customers to invest in this area due to having a long time to get back their investments [294]. In addition, accuracy of time-based energy price for customer consumption needs to be ensured and therefore requires more elaborative study for safe and faithful communication system for cost management.

B. COMPLEXITY

In a distribution system, energy management gives permission to override or control the system operation. Monitoring these controls is fairly simple for a handful of sites, but it becomes a real challenge with hundreds or thousands of locations that need an enriched process and communication.

C. UPDATE AND MAINTENANCE

Developing the energy baseline and making it adaptable for checking the system performance on a yearly basis is important. In addition, during EMS installation, sensors are placed in optimal locations for better system performance; however, over time, as load or generation levels change and facilities are remodeled or changed, this ideal location may become more of a nuisance. Therefore, appropriate steps should be taken to perform energy management, yet in a cost effective and efficient manner. Furthermore, temporary or long-term maintenance periods might be an issue for the EMS approach.

D. RELIABILITY

Reliability in grid connected systems has been a mature research area in literature; however, for off grid operations, reliability still might be a big issue because limits are always a concern for the maximum capacity of CEs, REs along with ESS. This reliability area needs to be properly addressed to get the maximum benefit of EMS.

E. CONSTRAINTS

There are constraints involved for performing EMS in the distribution system. Limits are always a concern for the maximum capacity of CESs, REs, and ESS in order to handle system reliability and energy balance issues for the network. Reactive power support and demand response can also improve the EMS performance. Some EMS constraints are summarized in Fig. 8.

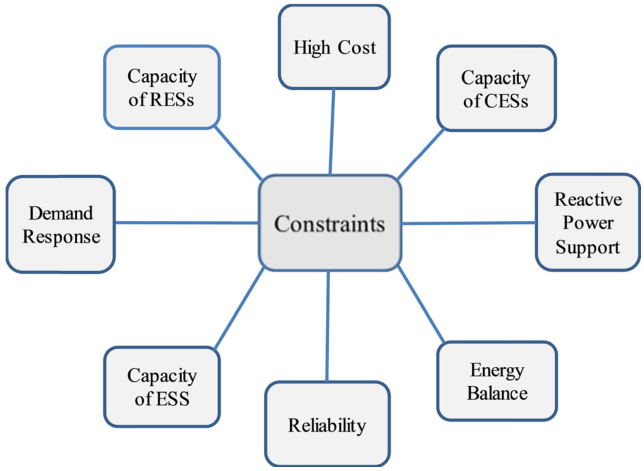

FIGURE 8. Energy management constraints.

VIII. FUTURE WORKS

This paper briefly studied ongoing research on energy management and has raised more questions than it has discussed. Many different adaptations, tests and field experiments are yet to be addressed to make energy management more manageable. Based on this review paper, there are several lines of research arising which should be pursued in future.

A. SYSTEM UPGRADE USING DERs

Energy management technologies provide access for the utility companies to upgrade the distribution system with distributed generators. This will help to reduce the system operational costs, power line losses, and environmental pollutions by using appropriate operational schemes. The DG integration step can be done in different ways considering individual DGs (e.g. adding natural gas-, diesel-, PV- and wind-based generators individually) or combined DGs in the system. Therefore, upgrading the system using individual DGs or combined DGs to improve the energy management success, that is defined based on different objective functions, can be extensive research in this area. In addition, distribution systems can be further upgraded by using reactive sources, ESS and EV's charge/discharge stations. The ESS technology discussed in the previous sections led the renewable power, as a popular source of clean energy, to be stored for later use. Reactive sources are also added in a distribution system to satisfy the reactive power requirement for the inductive loads, improve the stability of voltage profile and reduce the system losses. The reactive sources could be considered as fixed or variable capacitors/inductors or as an auxiliary service of the distributed generators. Such devices should be placed in optimal locations and operate optimally so that the system has minimum operational costs. In this scenario, the system upgrading scenario using reactive sources, ESS and EVs can be accomplished by considering energy management success as an extra objective function during the design process.

B. EMISSIONS

Much research has been conducted to minimize the CO_2 emissions that cause global warming. Besides CO_2, SO is emitted from burning fossil fuels and reacts with water and forms sulfuric acid, causing acid rain [1]. Acid rain is responsible for the deaths of fish and the planet, damage to the metal homes and buildings, and severe disruption to ecological balance. Hence, minimizing the SO and other emissions in the air in a qualitative and quantitative way should be explored in further research.

C. RECONFIGURATION COST

Applying energy management in a distribution system changes the index of energy generation. For instance, system reconfiguration by switch allocation reduces the system loss and it would be necessary to consider multiple switch operations which may cause a raise of overall system costs. As a consequence, the cost related to the multiple switch operation might be analyzed and needs extensive research for maximizing the robustness of energy management.

D. MISCELLANEOUS

Energy management helps to minimize the cost and losses in distribution systems and is a challenging task for the planners to implement in an intelligent way. Using real-time data for performing energy management can optimize the EMS performance. The data has a wide variety of sources including different sensors, meters along with utility scales. In addition, SCADA data, EV charging data analysis, and satellite can perform the systems facility at any point in real time. This helps the utility companies find the disruption point where the grid might be vulnerable for service interruption [295] and needs more research that will bring financial benefit to the utilities as well as the consumers.

In addition, energy management has the capability to operate the distribution system in a more efficient way by using advanced computational tools. High performance computing brings the maximum benefit from the system that needs proper functionality and accurate design to match the application with computing hardware. For some cases, it might need extensive research on high performance computing. In addition to HPC, the General Purpose Graphic Processing Unit (GPGPU) provides a cost effective commodity hardware solution that will provide the computational power equivalent to high performance computing servers and needs further research for maximizing the benefit for performing energy management.

IX. CONCLUSIONS

This paper provides a comprehensive review of the published research on energy management in distribution systems including applications, latest developments and ongoing research. The studied papers are a combination of conference and journal papers as well as magazines and industry reports, with the majority of papers published in renowned journals. The review papers were analyzed from different perspectives based on energy management objectives, energy management approaches and solution algorithms. Moreover, limitations and challenges of EMS in distribution systems is investigated. For instance, the literature shows that the consumers are still slightly unwilling to acknowledge the EMS benefits and invest in it due to the deficit of technological knowledge and financial issues. As a result, extensive research is still required to make the EMS usable and trustable for relevant consumers. In addition, the system reliability concerns should be studied thoroughly for off grid modes of operation and still need substantial exploration. In reviewing the studied papers, it is clear that energy management research is getting more attracted by the academics and industries, and is flourishing day by day to make the energy sector more sustainable, manageable and efficient. The paper also provides future research directions on energy management and highlights the emerging and interesting research areas that need to be extended. Thus, by providing a complete and classified overview of recent research on energy management in power distribution systems, this paper further emphasizes the importance of energy management and saves researchers' and engineers' valuable time by collecting such information.

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MD SHAHIN ALAM (S'16) received the B.Sc. degree in electrical engineering from the Rajshahi University of Engineering & Technology (RUET), Bangladesh, in 2009, and the M.S. degree in electrical engineering from McNeese State University, Lake Charles, LA, USA, in 2017. He is currently pursuing the Ph.D. degree in electrical engineering from Oakland University, Rochester, MI, USA, where he has been a Research Assistant, since 2017. His research interests include energy management in active distribution systems, smart, reliable and secure power system planning, optimizations in planning and operation of modern distribution systems, and renewable energies integration in smart grids.

SEYED ALI AREFIFAR (S'06–M'10–SM'17) was born in Isfahan, Iran. He received the B.Sc. and M.Sc. degrees (Hons.) in electrical engineering and power systems from the Isfahan University of Technology, Isfahan, Iran, in 2001 and 2004, respectively, and the Ph.D. degree in energy systems from the University of Alberta, Edmonton, AB, Canada, in 2010. He was an NSERC Visiting Fellow with CanmetENERGY, Natural Resources Canada, Varennes, QC, Canada, from 2011 to 2014. From 2014 to 2016, he was Postdoctoral Research/Teaching Fellow with the Electrical and Computer Engineering Department, The University of British Columbia, Vancouver, BC, Canada. Since 2016, he has been with the Electrical and Computer Engineering Department, Oakland University, MI, USA, as an Assistant Professor. His current research interests include renewable energies and optimizations in planning and operation of smart grids and microgrids.