Received: 2 March 2020 | Revised: 4 May 2020 | Accepted: 17 May 2020
DOI: 10.1002/er.5649

REVIEW PAPER

INTERNATIONAL JOURNAL OF ENERGY RESEARCH WILEY

Recent trends in power management strategies for optimal operation of distributed energy resources in microgrids: A comprehensive review

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Summary

The current era in sustainable development is focused on the rapid integration of renewable energy sources driven by a wide range of socio-economic objectives. Due to the inherent property of time-varying weather conditions, the intermittent sources, that is, Solar PV and Wind Energy, are considered as variable energy resources. The uncertainty and variability problem of these sources has brought many complications to distributed network operators to operate and control the complex or multi-microgrids with limited fast-ramping resources in order to maintain the power system flexibility. It led many researchers to find an alternative strategy since the conventional approaches are no longer adequate to handle the economic implications of operational decision making. At first, the brief review of various deterministic and probabilistic approaches, stochastic programming and robust optimisation strategies to address the uncertainty of variable energy resources are discussed. Furthermore, in the energy management point of view, the optimal scheduling problem of distributed sources of the microgrid is considered, and a brief review of optimisation models, advanced control strategies and demand response strategies to maximise economic benefits of microgrids are also elaborately presented. Finally, the multiagent-based distributed and decentralised control strategies for seamless integration of distributed generator units are reviewed under various configurations of the power grid along with communication network topologies.

KEYWORDS

demand side management, distributed and decentralized control, economic dispatch, microgrids, uncertainty, variability

1 | INTRODUCTION

The power system infrastructure is witnessing significant changes due to rising concerns of global warming, energy security and a need for a sustainable grid. To enhance the efficiency, reliability and eco-friendly energy production, the integration of renewable energy sources (RESs) has remained the primary objective in recent years. According to provisional data reported by the Indian government,[1] there is a substantial growth of 24.47% in a renewable generation, and a target has been set to further increase the renewable power capacity to 175GW by 2022.[2] To coordinate this massive integration of RESs effectively, and to maintain security, reliability and efficiency of the grid, restructuring of traditional power system architecture could be a viable solution. Hence the concept of Smart Grid (SG) has emerged to incorporate interactive bi-directional digital communication in all levels of the electrical system hierarchy. However, the energy management (EM) of RESs has become a crucial task for distribution system operators (DSO) in view of the fact that the modern grid infrastructure has become decentralised with the integration of non-utility generators.[3-5]

In support of the restructured power system architecture, effective integration of conventional controllable generators, RESs-based non-controllable generators, combined heat and power (CHP) based energy sources, energy storage units (ESUs) and a cluster of controllable loads are done to create microgrids (MGs). In this scenario, the distributed energy sources (DERs) especially the RESs, CHP-based sources and ESUs, have transformed the passive distribution networks to active distribution networks (ADN) by giving scope for bi-directional power flow between DERs and the main grid. Henceforth, MGs have been proposed to solve several interconnection issues within the individual DERs with an intelligent EM system.[6-8] The general schematic of a microgrid network is given in Figure 1 with an illustration of component, control and management layers of the microgrid. The communication between various MGs to the external grid is coordinated through a dedicated communication infrastructure like Wide Area Network. Within each MG, the coordination and control among various controllable loads and DERs are usually accomplished with Neighborhood Area Network as well as Home Area Network whereas, it is convenient to acquire and analyse the smart meter data.

In general, MGs can operate in both grid-connected and islanded (stand-alone or isolated) modes and can also provide ancillary services to the main grid. In the case of grid-connected mode, the MGs are either completely or partially interconnected with the main grid by enabling the power exchange and gets isolated or operated in stand-alone mode if the main grid is subjected to disturbances.[9-12]

The MGs are usually equipped with a central controller and a sophisticated energy management system (EMS) to

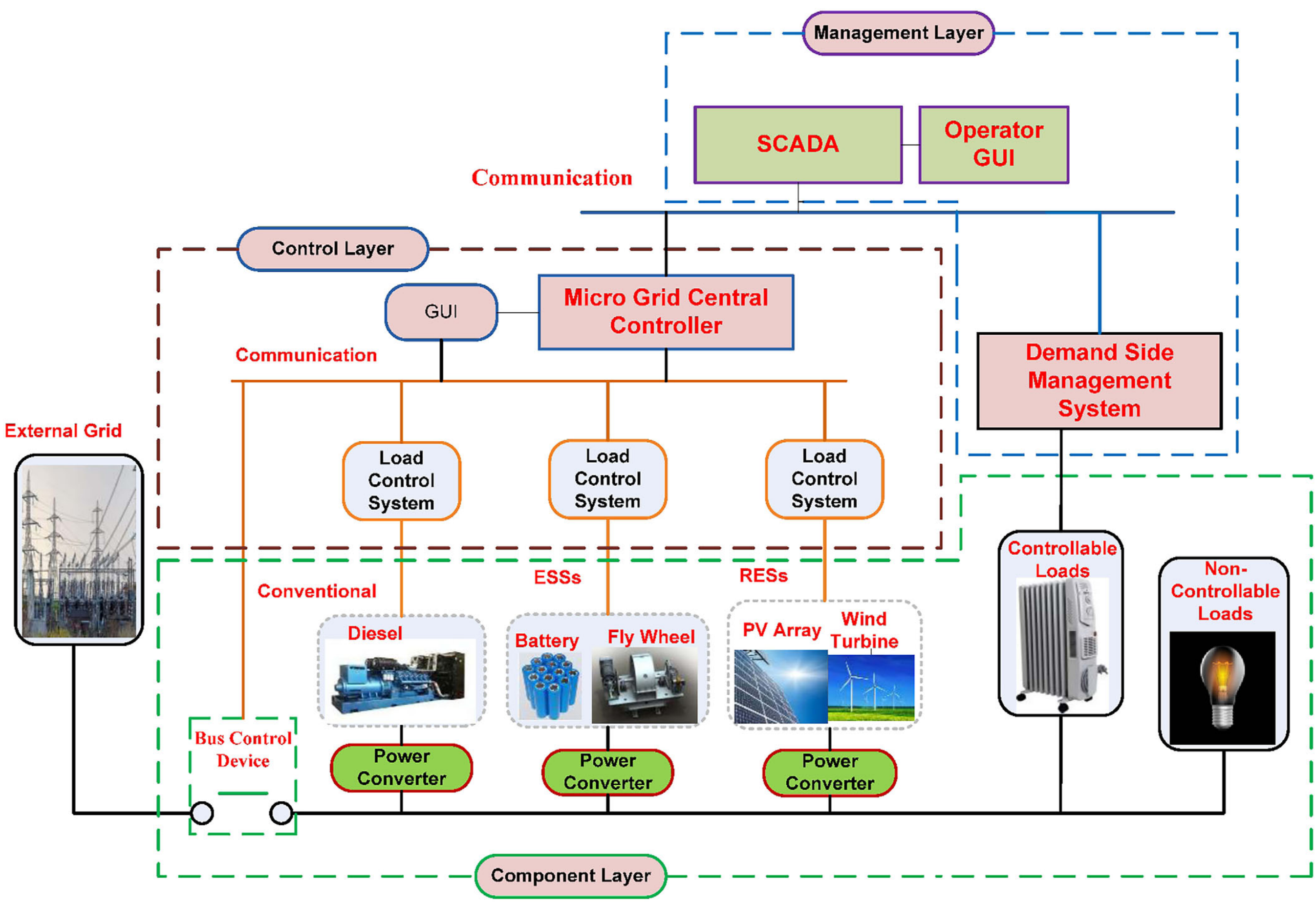

FIGURE 1 Typical microgrid architecture [Colour figure can be viewed at wileyonlinelibrary.com]

leverage the potential benefits for optimising the operation and control of MGs. Although the optimal operation of the conventional grid is widely reported in the literature, those approaches cannot be applied directly to MGs. In fact, the RESs have a maximum generation limit that varies with respect to time and that limit is uncertain and unpredictable. The presence of these intermittent sources not only incurs power balancing issues between supply and demand due to the inherent property of time-varying weather conditions, but also brings complications for the network operators as MGs are usually equipped with limited fast-ramping resources to maintain power system flexibility. The economic dispatch (ED) problem in response to these uncertainties and variations in both loads and RESs is analysed by adopting robust optimisation techniques, probabilistic-based approaches, and stochastic planning in the literature.

In recent years, some literature surveys have been published to address various objectives related to the planning, control and operation of MGs. The potential stochastic modelling and optimisation tools like the stochastic game, stochastic inventory theory were reviewed in Reference 13. The brief formulation of stochastic programming and the mathematical modelling of its variants for various objective functions are discussed in Reference 14. The authors in Reference 15 summarised the control objectives and developments in MG supervisory control based on hierarchical control. A deep insight was provided on EMS secondary control to achieve economic benefits from MGs in Reference 16. An overview of several modelling aspects and control of smart power grids to analyse optimal power flow is presented in Reference 17. In Reference 18, various short-term forecasting algorithms for power generation as well as load demand are reviewed to build an intelligent dispatch strategy for MGs. Apart from MGs, several DER scheduling strategies employed by the virtual power plant framework is reviewed in Reference 19. Yet, there are many undeveloped research objectives related to the spatial correlation of RES to be addressed. Concerning numerous viewpoints, methodologies and objectives reported in the recent literature, there is a need to review and assess the detailed problem formulation, adopted methodology and concerned objectives within the domains of MGs.

This literature review is mainly distinguished from the previously conducted surveys in the aspects as mentioned earlier. At first, a brief problem formulation on optimal dispatch of Solar PV, Wind, ESUs and MG is presented. Then, the research methodologies to obtain the solution for optimal scheduling of RES, EVs, Battery Storage and MGs are covered. Finally, the distributed and decentralised approaches are reviewed in detail. However, the electricity market-based dispatch models with the market price, retail price and other parameters are not in the scope of this survey. The referred research works are extracted from the following sources:

- IEEE Transactions on Power Systems;
- IEEE Transactions on Smart Grid;
- IEEE Transactions on Sustainable Energy;
- IET Renewable Power Generation;
- IEE Proceedings on Generation, Transmission and Distribution;
- International Journal of Electrical Power and Energy Systems.

This article aims to emphasise on numerous strategies for optimal scheduling of distributed energy resources (DERs) in the SG environment. The rest of the article is organised as follows. Section 2 gives an insight into the generalised ED problem formulation of Solar PV, Wind Energy and Battery Storage system in terms of operating, reserve and penalty costs. The optimal dispatch of renewable sources considering uncertainty and variability is covered in section 3. Section 4 presents an overview of the hierarchical control and optimisation strategies of the microgrid. In section 5, the review of distributed optimisation algorithms and decentralised control schemes for ED of DERs in SGs. Finally, this article ends with a perspective of future research and conclusions.

2 | PROBLEM FORMULATION

This section deals with a detailed description of various objective functions related to the ED problem in a PV system, Wind Energy System, Energy Storage System. The mathematical model may be formulated as a stochastic, deterministic, probabilistic or robust optimisation problem. Various methodologies and objectives were chosen in the literature to solve the problem as mentioned earlier formulations are briefly discussed in Table 1. In general, the optimal dispatch problem of RES can be formulated as follows.

The objective function for the optimisation of PV generation cost can be formulated with n PV generators and m loads, and it is expressed as follows[7]:

$$\text{Minimize } \mathrm{C}_{pv} = \sum_{t=1}^{k}\left[\sum_{i=1}^{Ns} P_{pvi}^{t}\, C_{pvi} + p_s^t c_s^t\right] \tag{1}$$

$$\text{Subjected to } \; P_{pvi\min}^{t} \le \mathrm{P}_{pvi}^{*,t} \le P_{pvi\max}^{t} \tag{2}$$

where C_{pv} is the PV generation cost; P_{pvi}^{t} is the power output of ith PV system at t time period; c_{pvi} is the operating

TABLE 1 Survey of optimal scheduling objectives considering the formulation type and adopted approaches

References	Formulation type	Approach	Objectives
[3]	Real-time dispatch	Participation factor	Real-time optimal scheduling of non-schedulable solar and wind energy sources by considering variable and uncertainty costs.
[4]	Real-time dispatch	Basepoint and participation factor	To obtain optimal generation adjustments with fluctuating load and RES.
[5]	Stochastic look ahead dispatch	Stochastic programming	Formulation of Stochastic Look-Ahead Dispatch to manage the near real-time operational uncertainties.
[20]	Robust optimisation	Fuzzy theory	Development of a two-stage energy and reserve co-optimization model under a fixed uncertainty set of RES
[6]	Day-ahead dispatch	Dynamic programming	Design of microgrid central energy management system for solving the UC problem with a multi-objective function.
[8]	Day-ahead dispatch	Mixed integer linear optimisation	To develop a control strategy for solving the optimal dispatch of PV system integrated with energy storage.
[11]	Bi-level optimisation	Non-dominated sorting genetic algorithm	Establishing a bi-level optimisation model to reduce generation costs and emissions in the upper-level, while lower-level integrates the generation and demand-side to influence regulation-based demand response.
[20]	Stochastic dynamic dispatch	Robust optimisation	Development of micro-EMS controller to deal with uncertainties in the presence of limited controllable resources for secure power system operations.
[21]	Stochastic dispatch	Probabilistic model	Efficient representation of wind power uncertainty and reduction of the computational cost of a stochastic economic dispatch.
[22]	Chance constrained stochastic programming	Uncertainty quantification model	Modelling of stochastic economic dispatch problem for minimising RES operational costs subjected to power flow constraints.
[23]	Risk limiting dispatch	—	To propose an improved multi-period risk-limiting dispatch to satisfy the fundamental requirements of the system operators in the power industry and to analyse the economic benefits of wind power integration.
[24]	Hybrid robust stochastic dispatch	Probabilistic planning	Minimising the potential cost of dispatching the power resources and offsetting net load variability and uncertainty.

TABLE 1 (Continued)

References	Formulation type	Approach	Objectives
25	Security constrained real-time economic dispatch	Flexible energy scheduling tool	Analysis of operating reserve strategy to mitigate variability and uncertainty of variable generation.
26	Real-time economic dispatch	Monte Carlo simulation	Analysis and design of reliable and efficient ramp capability products to manage uncertainties and load variations.
27	Robust economic dispatch	—	To propose a multi-time-scale robust economic dispatch strategy for reducing the impact of solar, wind and load forecast uncertainty.
28	Stochastic dynamic programming	Probabilistic constrained approach	Incorporation of battery cost model along with uncertain RES and load demands for solving UC and ED.
29	Stochastic optimisation	Mixed integer linear programming	Addressing the challenges associated with the real-time operation of energy storage and improving the overall operational scheme in the viewpoint of the system operator.
30	Robust dynamic dispatch	Bacterial colony chemotaxis algorithm	To address the combined uncertainties of wind energy and EV charging load in a day-ahead dynamic dispatch.
31	Robust optimization	Bender's decomposition; cutting plane algorithm	Establishing a multi-scale coordinated robust scheduling framework for solving the operational problem of an isolated power system in the presence of RES.
32	Probabilistic dispatch	Probability distribution function	Proposing a probabilistic power dispatching strategy to address the uncertainty in PV generation.
33	Robust optimisation	Column and constraint generation method	Coordinated scheduling of the tie-line flow and power dispatch by considering wind power uncertainty.
34	Stochastic dynamic dispatch	Stochastic linear programming	Developing a two-stage stochastic model for solving dispatch problem considering wind uncertainty.
35	Stochastic dynamic dispatch	Stochastic mixed integer linear programming	Analysing the impacts of stochastic wind power and distribution system reconfiguration on economic dispatch.
36	Probabilistic dispatch	Scenario-based probability distribution	Building a steady-state energy storage unit model for solving economic dispatch of a large-scale storage system interconnected with a wind farm.
37	Security constrained stochastic dispatch	Progressive hedging algorithm	Modelling a two-stage multi-timescale framework for flexible energy scheduling of variable generation and stochastic loads.

(Continues)

TABLE 1 (Continued)

References	Formulation type	Approach	Objectives
38	Day-ahead dispatch	Chance constrained Stochastic non-linear programming	Proposing a three-stage solution framework for dynamic dispatch model for wind power integrated with optimal reserve scheduling.
39	Probabilistic forecasting model	Varying variance relevance vector machine	Formulating a methodology to incorporate wind power uncertainty incremental and dispatch costs.
40	Probabilistic analytical model	Enhanced particle swarm optimisation; Stochastic linear programming	Developing an optimisation strategy for solving coordinated economic dispatch with the wind-hydro-thermal integrated power system.
41	Robust dispatch	Scenario-decomposition approach	Optimising the power system operation state while sustaining its transient stability with high penetration of wind
42	Security constrained dispatch	Linear programming	Proposing a preventive dispatch model for addressing the intra-interval security risks and intra-interval variation problems of wind power.
43	The two-level model predictive control framework	Mixed integer non-linear programming	Developing a two-stage model predictive control strategy for real-time control of microgrids.
44	Real-time dispatch	Model predictive control	Optimal load sharing of a hybrid energy storage system comprising of fuel cells, batteries and ultracapacitor in the real-time scenario.
45	Real-time dispatch	Genetic algorithm	Minimising the operational costs of DC Microgrid in the context of demand response based on real-time pricing.
46	Mixed integer second order cone programming	Benders decomposition	Optimal energy management of ADN while preserving operational privacy between MGCC and DSO.
47	Dynamic dispatch	Augmented Lagrangian-based approach	Improving the dynamic performance of economic dispatch for islanded microgrids during transients.
48	Multi-objective economic dispatch	PSO; Fuzzy min-max technique	Optimising economic and environmental costs of AC-DC Hybrid Microgrids.
49	Multi-objective economic dispatch	Quantum genetic algorithm	Minimising the economic and environmental costs of microgrids by considering a hybrid energy storage system.
50	Two-layer coordinated energy dispatch	Distributed model predictive control	Proposing a coordinated energy management scheme for optimal scheduling of energy exchange between microgrids and distribution network operators.
51	Two-time scale coordination model	Droop control strategy	To manage the impacts of uncertainty and variability for MVDC systems.

TABLE 1 (Continued)

References	Formulation type	Approach	Objectives
52	Distributed energy management system	Neighborhood-watch based algorithm	Proposing a distributed energy management algorithm to address the effect of malicious cyber-attacks on the economic dispatch of the power system.
53	Probabilistic dispatch	Energy management tool	Managing the active power dispatch of remote AC/DC Hybrid Microgrids
54	Multiperiod dispatch	Artificial bee colony	Minimising production costs and market clearing price based on responsive load demand characteristics.
55	Robust optimisation	Mixed integer programming	A two-stage optimisation approach for minimising long-term average operating costs of a microgrid subjected to quality-of-service requirements.
56	Day-ahead dispatch	Affine arithmetic-based approach	Proposing a novel EMS scheme based on the Affine Arithmetic method to provide dispatch solution for isolated microgrids.

Abbreviations: ADNs, active distribution networks; DSO, distribution system operators; MGCC, micro-grid central controllers; MVDC, medium-voltage DC; RESs, renewable energy sources; UC, unit commitment.

cost of ith PV system; p_s^t, c_s^t are distribution network power and operation cost at time period t respectively and $P^t_{pvi\,\min}, P^t_{pvi\,\max}$ are the upper and lower power output limits of ith PV system, respectively.

$$\text{Minimize } C_w = \sum_{t=1}^{k}\left[\sum_{m=1}^{Nw} C_{dm} p_m^{sc} + p_s^t c_s^t\right] \tag{3}$$

$$\text{Subjected to } P_m^{\min} \le \mathrm{P}_m \le P_m^{\max} \tag{4}$$

where C_{dm} is the direct cost of mth out of N_w wind turbines; P_m^{sc} is the scheduled power of the mth turbine; $P_m^{\min}, P_m^{\max}$ are the minimum and maximum limits of the power output of mth wind turbine.

As opposed to a conventional power unit, a battery does not consume any fuel to operate. However, the input electricity cost and power consumption cost fed to a load is considered for charging/discharging a battery via an electrochemical process.[28] The explicit battery operation cost model during charging and discharging is be defined in (5) and (6).

$$C_{\text{charging}} = C_{\text{bat}}^{\text{kwh}} + C_{\text{bat}}^{\text{avail}} \tag{5}$$

$$C_{\text{discharging}} = \mathrm{P}_{\text{bat}}^{d} + \mathrm{P}_{\text{bat}}^{ld} \tag{6}$$

in which $C_{\text{bat}}^{\text{kwh}}, C_{\text{bat}}^{\text{avail}}$ are the cost of fuel used to charge the battery and the availability cost of battery capacity respectively; $P_{\text{bat}}^{d}, P_{\text{bat}}^{ld}$ are the battery output power and the battery power loss during discharge.

The objective function for minimising the overall operation cost accounting for uncertainty and variability of the renewable power generation is presented below. These models are formulated in a real-time scenario with intra-hour dispatch intervals by considering operational and security constraints.[3]

Minimise

$$\sum_{t=1}^{\text{Nsub}}\sum_{i=1}^{Ng} C_{Gi}(P_{Gi}) + \sum_{t=1}^{\text{Nsub}}\sum_{j=1}^{Nw} RC_j + PC_j + \sum_{t=1}^{\text{Nsub}}\sum_{k=1}^{Ns} RC_k + PC_k + \sum_{t=1}^{\text{Nsub}}\sum_{l=1}^{Nl} RC_l + PC_l \tag{7}$$

Subjected to

$$\max\left[P_{Gi}^{\min}, P_{Gi}^{T-1} - R_{Gi}^{\text{down}}\right] \le P_{Gi} \le \min\left[P_{Gi}^{\max}, P_{Gi}^{T-1} + R_{Gi}^{\text{down}}\right] \tag{8}$$

$$V_{DK}^{\min} \le V_{DK} \le V_{DK}^{\max} \tag{9}$$

The terms RC and PC in (7) represents the reserve cost and penalty cost of wind power, solar PV power and load demand. Here, the reserve cost is based on the overestimation, whereas the penalty cost is based on the underestimation of available units.

As the future estimation of solar PV power, wind power and system load are uncertain at any given time, most of the works in the literature have considered their uncertainty models based on probability distribution functions. These uncertainty models (10)-(12) are explained in Reference 3.

$$f_p(p) = \frac{khv_i}{p_r c}\left[\frac{1+\frac{hp}{p_r}\nu_i}{c}\right]^{(k-1)} \text{x}\exp\left[-\left(\frac{1+\frac{hp}{pr}\nu_i}{c}\right)^k\right] \tag{10}$$

$$fp_s(p_s) = \frac{1}{2\sqrt{\frac{P_{Sr}\,P_s}{G_{std}\,R_c}}} X\left[fG\left(\sqrt{\frac{P_s\,G_{std}\,R_c}{P_{Sr}}}\right) + fG\left(-\sqrt{\frac{P_s\,G_{std}\,R_c}{P_{Sr}}}\right)\right] \tag{11}$$

$$f_l(l) = \frac{1}{\sigma\sqrt{2\Pi}} X\exp\left[\left(\frac{(1-\mu)^2}{2\sigma^2}\right)\right] \tag{12}$$

Finally, the objective function for the ED of the MGs is presented in (13). It includes minimisation of total generated power cost from various DGs, purchased and sold power costs as per market pricing and the operation and maintenance costs of MGs.

$$F_s = \sum_i \text{Cost}_{gen,si} + \left(c\,\text{x}\,\text{P}_{buy,sm} - d\,\text{x}\,\text{P}_{sell,sm}\right) + \text{Cost}_{O\&M,s} \tag{13}$$

The main objective of this review article is to minimise the total generation power cost, along with the operation of a power system in a sustainable manner. Optimisation is an essential tool for solving the problem of finding the optimal global solution among the set of all feasible solutions. Depends upon the type of problem optimisation technique consists of three steps:

- Constructing a model
- Determining the problem type
- Selecting software

An essential step in the optimisation process is classifying the optimisation model because algorithms are used to solve optimisation problems that are customised to a specific type of problem. Here, in Figure 2, illustrate a different type of optimisation problems are solved by using different approaches is addressed in Table 1.

3 | OPTIMAL POWER DISPATCH OF RENEWABLE SOURCES

Demand forecast, net scheduled interchange and forecast of intermittent sources are the critical enablers for the ED problem for the RES. Traditionally, the reserve margins are used to deal with the inaccuracies in load forecasting techniques implicitly.[20] These operating reserves ensure the real-time power balance and provide sufficient online system capacity whenever required. A brief analysis of flexibility ramping services[25] and ramp capability

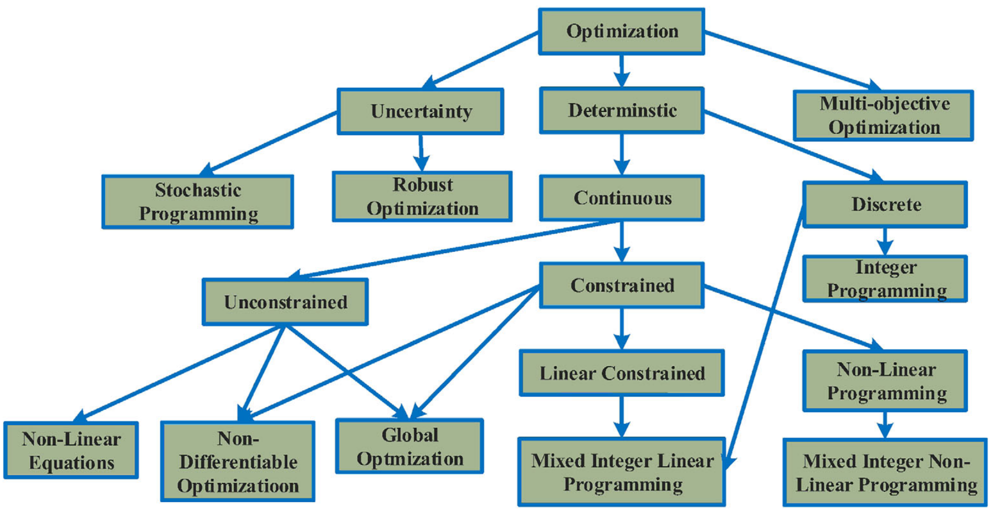

FIGURE 2 Optimisation taxonomy [Colour figure can be viewed at wileyonlinelibrary.com]

products[26] is conducted to evaluate the economic and reliability implications for efficient integration of RES. The proposed flexibility reserve techniques in Reference 25 help in reducing scarcity pricing events in the system that occurs due to insufficient ramping capacity but increases production costs. In Reference 26, a cost-efficient ramp capability product is designed to secure the ramp capabilities and manage the uncertainties in both net load and intermittent generation. Nevertheless, these operating reserves often fail to satisfy the ramping dynamics and to offset the unpredictable swings in the system. Hence, stochastic ED models have been introduced as an alternative approach to deal with the inaccuracies explicitly.[21,24]

In the security-constrained ED problems, the operating risk is reduced by considering a more extensive uncertainty set, but the scheduling costs get increased. Although the deterministic look-ahead dispatch strategies require less computational efforts while dealing with complex models, they often fail to produce optimal results when the level of uncertainty increases. On the other hand, the stochastic approaches can better handle the higher level of uncertainties, but they require additional computational resources. Hence a novel concept of uncertainty response is proposed in Reference 5 that maps the operational uncertainties and economic risks. Figure 3 illustrates the trade-off solution between the stochastic and deterministic approaches based on numerical experiments of a real 5889-bus system. An alternate concept is proposed in Reference 20 based on fuzzy theory and robust optimisation to give a better trade-off solution between system operating risks and economic scheduling costs. It is reported that the soft boundaries of uncertainty sets can be ideally modelled by using fuzzy theory rather than using probabilistic terms.

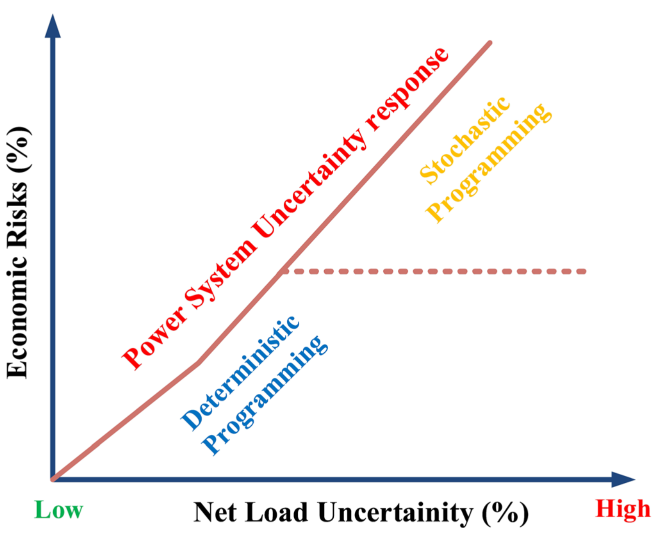

FIGURE 3 Illustration of uncertainty response[5] [Colour figure can be viewed at wileyonlinelibrary.com]

Several approaches related to stochastic optimisation have been adopted to explicitly model the uncertainty in RES that deals explicitly with the forecast errors. The need for accurate uncertainty models and computational costs for large datasets has led researchers to find an alternative to conventional techniques like Monte Carlo sampling. Hence, advanced modelling and sampling techniques based on polynomial chaos expansions (PCE), Karhunen-Lo'eve expansions (KLE) and compressive sensing have been adopted in References 21 and 22 for accurate propagation of randomness in a stochastic ED problem. The authors in Reference 21 have implemented PCE on a wind farm for quantifying the number of samples and KLE for an efficient reduction in the dimensionality of the ED problem formulation. In Reference 22, the dimensionality is reduced with compressive sensing method, which represents the deterministic sampling instead of random sampling. In support of the industrial requirement and risk assessment of RES integration, the basic risk-limiting dispatch (BRLD) has been chosen in Reference 23 to address the uncertainty. The author has extended the BRLD as multistage dispatch problem by incorporating various risk metrics along with unit ramping constraint and transmission network thermal limit constraint. The locational marginal price analysis is performed to study the impact of RES integration, and it is found that limited transmission capacity and forecast errors are the crucial factors that reduce the economic benefits of integrating RES into the grid. The main drawback with the scenario-based stochastic planning is the curse of dimensionality as far as the computational requirements are concerned. In addition to this, this approach is limited to inter-hourly schedule but not effective on sub-hourly or intra-hourly schedule. Hence, robust planning[27] and hybrid robust stochastic approaches[20,24] have been proposed as an alternative to stochastic planning. A robust optimisation strategy is proposed in Reference 27 for multi-timescale dispatch based on the variable confidence level. The deterministic constraints of day-ahead, intra-day and real-time scale scheduling are modified as robust constraints to increase the confidence level and to achieve the power balance effectively under uncertainties.

In Reference 24, the authors proposed a hybrid robust-stochastic approach based on probabilistic planning to reduce the scenarios which, in return, help to overcome the curse of dimensionality. The power system flexibility for dispatchable sources is characterised by offsetting both net load variabilities and uncertainty dynamics on an intra-hourly basis. A novel approach based on robust power system security is proposed in Reference 20 to treat uncertainties with continuous evaluation of generation schedule (GS). A micro energy management controller (EMS) is developed to have high feasibility of dispatch with the help of RES prediction data available online. The authors have optimised the proposed EMS controller based on improved time-sequence dynamic feasible algorithm in two distinct stages. The previous stage refines the GS against prediction errors for day-ahead operation, and later stage carries out the real-time schedule along with charging/discharging of battery systems for every 5 minutes. The uncertainty problem which is discussed earlier is a major concern, especially in long-term power system planning. However, in real-time operation, the range of uncertainty not poses a severe threat, as the forecast data is accurate for shorter timeframes. Figure 4 illustrates the effect of forecast data accuracy for different dispatch time horizons considered in this article. Moreover, the conventional real-time economic dispatch (RTED) is a deterministic approach that optimises the generation costs over single dispatch interval, and the limited ramp capabilities may not be effectively utilised to maintain the grid security. Hence, a dynamic RTED with coordinated decision making over multiple intervals is essential to manage the ramping capability of dispatchable energy sources.[3,5] Furthermore, these ramp capabilities would be secured five to 20 minutes in advance to maintain the grid security.[20,26] This particular concern has been addressed in References 3 and 4 to obtain optimal results in a real-time scenario.

The earlier optimisation approaches for RTED makes use of participation factors (PFs) evaluated at basepoint generations to restore the power imbalance between the load and intermittent energy sources.[3,4] According to authors in Reference 3, these approaches have neglected the variable generation cost between two consecutive scheduling intervals, and it may not be beneficial in an economic point of view. Hence a novel approach of 'best-fit' PFs is proposed for real-time dispatch by accommodating both variability and uncertainty costs in discrete time intervals. This approach has been applied for sequential and dynamic variants of RTED subjected to the availability of power forecast data of RES. The similar objective is focused in Reference 4 to adjust the GS in real-time for handling a wide range of fluctuations caused by the load as well as RES. This method incorporates the data of load deviations at each load bus and the deviations in RES into a normalised vector. The resultant generation adjustment factors have shown a significant improvement in terms of accuracy when compared to the participation factor method.

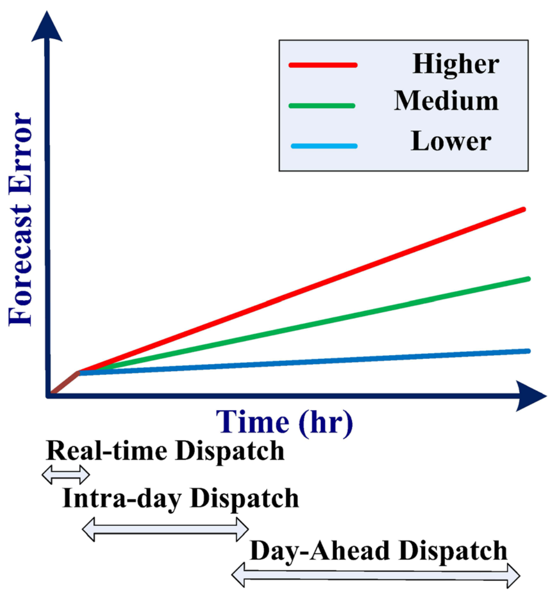

FIGURE 4 Effect of forecast data accuracy on the dispatch time interval [Colour figure can be viewed at wileyonlinelibrary.com]

3.1 | ED problems associated with solar PV

It is worth mentioning that the solar PV system is more variable and less uncertain compared to the other RES. Hence, various studies are reported to deal with the variability as well as uncertainty. An optimal allocation model is established in Reference 7 based on the load forecast data and reliability index of the PV system to solve the ED problem in the ADN. The proposed model uses a fuzzy-based probability sampling approach which determines the supply and load equilibrium and multi-objective particle swarm optimisation to get the scheduling solution for distributed networks. In Reference 6, the authors designed a Microgrid Central Energy Management System to anticipate day-ahead operational planning. This study mainly focuses on optimising operational costs, startup and shutdown penalties along with the reduction of emissions in urban MGs. The uncertainties in forecasting models are adjusted to calculate global power reference that balances active and reactive power in MGs. The proposed system is implemented in supervisory control and data acquisition to validate the economic and environmental benefits in real-time scenarios.

A mixed-integer linear optimisation algorithm is developed in Reference 8 for the optimal dispatch of energy storage integrated with the PV system. The objective of the algorithm is to maximise the power production of the integrated system based on the day-ahead PV forecasting data. Advanced functionality is modelled to estimate storage round-trip efficiency by incorporating the battery state of charge dynamics, which is one the primary requisites for the effective integration of commercial storage systems. The proposed approach is validated with an existing Distributed Management System installed in an LV microgrid test site to study the applicability and effectiveness of storage system integration. A Probabilistic optimal power dispatch strategy is proposed in Reference 32 to study the impact of PV uncertainty on power system performance. Unlike the deterministic power flow algorithms, the probabilistic power flow (PPF) determines the power flow solution in terms of probabilistic values. It optimises the generation costs by satisfying the line overload probability constraint. It is reported that the consideration of conventional generation dispatch significantly affects the PPF solution for the reason that the high ramp rate conventional resources compensate the variations of PV generation and achieves the active power balance. A generalised procedure for optimal dispatch methodology of RESs considering various operational constraints along with weather related and load related forecast data is shown in Figure 5.

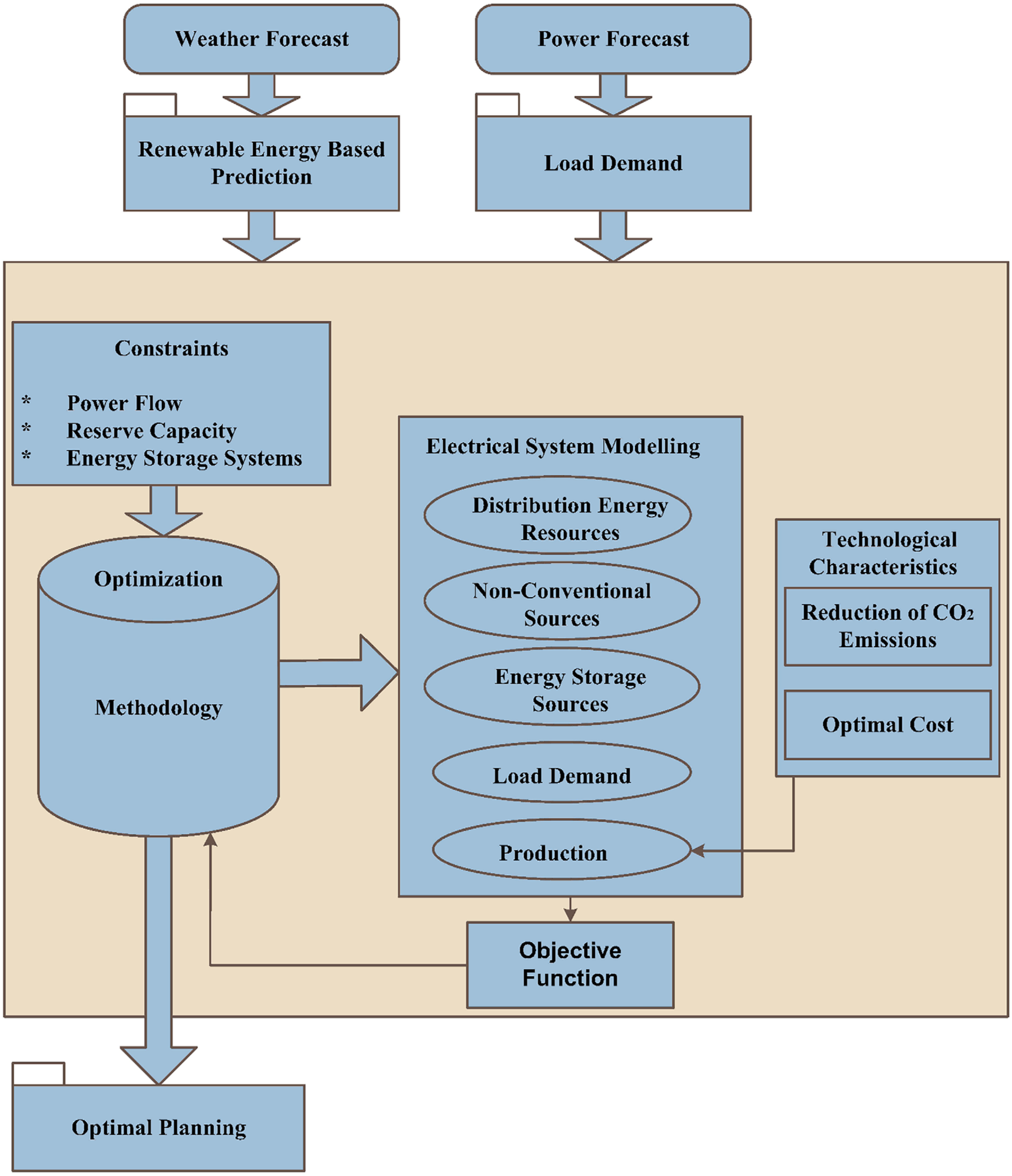

FIGURE 5 Optimal dispatch of renewable energy sources [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | ED problems associated with wind energy system

In recent years, the wind power generation is increased drastically due to the reduction of carbon emissions and pollution-free power generation. It is required to find alternatives to thermal energy power generation, and one of the primary renewable sources that are currently inspecting additional widespread usage is Wind Energy. One among the foremost benefit is after the initial land and capital costs concerned with in the production of power from wind energy conversion system (WECS). Moreover, the generation cost of wind can be decreased by providing power from the wind without curtailment such that the system should be operated sustainably by providing ancillary services and system reserves. The large scale of wind power generation is very complicated due to uncertainty nature, and it may lead to the power curtailment at the time of valley load periods. Additionally, the impact of WECS on Environment is to be low and environmentally friendlier than the Conventional thermal generators.

A cost-risk model is proposed in Reference 57 to deal with increased uncertainty a probabilistic model is established to evaluate the uncertainty of wind power and load. The risk index is included in this model to assess the losses of load and spilling associated with the wind energy to find out unpredictable deviations between generation and load. A novel day-ahead ED model is developed in Reference 38 based on the stochastic model generation of wind power is integrated into the grid along with optimal reserve planning by using chance-constrained non-linear programming. Integration of intermittent energy sources by pushing the grid to prepare more reserves to meet the supply and load balance. In Reference 58 focused on optimal reserve scheduling considering with reserves available in the generators. Economic emission and dispatch (EED) with DR not only reduce the cost and emissions it can provide communication to the distributed network operator (DNO) and flexibly handle the system, due to the essence of volatility, and it is challenging to get the constant energy from the source. A two-stage stochastic programming problem model is developed in Reference 34 to evaluate forecast errors with an efficient solving algorithm as Robust optimisation to minimise the forecast errors and uncertainty on dynamic economic dispatch (DED).

A finite-state Markov chain model had implemented for the forecasting of wind generation and also extracted the statistics of wind farm generation from the real-time with different epochs during the time interval. The joint optimisation approach has optimised the cost of operating reserves, and it levels the forecasting errors. A stochastic mixed-integer linear programming is adopted in Reference 35 to analyse the operational performance of EDS to meet the power generation and load balance. In case of wind power generation, non-linear uncertainties are subjected to the wind power forecasting, to balance these forecasting uncertainties an additional cost can be incurred to the power system and requires accurate quantification for an increase in generation costs. Another joint stochastic based optimisation of ED, along with interruptible load management was discussed in Reference 59. A probabilistic forecasting wind methodology is introduced in Reference 39 to determine the induced costs, and it can be defined as wind power uncertainty incremental cost and wind power uncertainty dispatch costs. A tie line adjustment strategy is implemented in Reference 60 to reduce the deep cycling occurring in the ED model. The strategy is developed based on operational characteristics of interconnected wind coal intensive power systems. The stochastic model-based offline strategy is proposed in Reference 61 to give a stochastic reserve margin against the wind power uncertainty and generation. Forecasting of the load has been facing a challenging task along with daily peak load is also one of the significant issues that have been considered at the time of power dispatch. An optimised, integrated tool is implemented in Reference 37 to solve various stochastic configurations and deterministic submodels such as low, medium and high wind penetrations integrated to the power system. The progressive hedging algorithm is implemented to resolve the stochastic issues to maintain computational tractability.

A method was implemented to convert the stochastic model into the deterministic quadratic problem in Reference 62 through linearising by considering the constraints are branch flow, transmission interface flow to solve with the help of sensitivity analysis method. Price elastic load is a demand response (DR) source, and it provides an alternative option to address the challenges that are facing in wind power fluctuation. A new persistence model was implemented in Reference 4 with the help of error feedback concept to find the wind forecasting. The error feedback mechanism is to evaluate the wind data and the relationship between the error and original forecast values. A new constraint is considered in Reference 42 for short-term load forecasting, which is essential to make the system as secure. The uncertainty and randomness characteristics exhibit by the wind such that short-term variations of wind power to bring the system into the unsecured operating region and it leads to intra-inter security (IIS) problem and to ensure the security during the time-period. A case study of high wind energy penetration system (IIVs) to encounter the sizeable IIS problems.

3.3 | ED problems associated with batteries and EV

For effective integration and management of the intermittent RES, several studies have been conducted on incorporating ESU in the viewpoint of system stability. Among all existing ESUs, there is a substantial interest in battery storage systems due to its fast ramping capabilities.[20-23,28] A flexible operation strategy with a two-step modelling framework is developed in Reference 29 to evaluate the potential benefits of batteries with RES. In the first step, the stochastic unit commitment model is formulated with day-ahead scheduling. In the second step, stochastic simulation is performed on the hourly-dispatch model to examine the uncertainty in renewable generation. It is reported that the proposed flexible operation strategy is more effective in real-time dispatch compared to a fixed schedule, no-schedule, look-ahead schedule dispatch methods. A robust multi-stage scheduling framework is proposed in Reference 31 to solve the operational problems in an isolated power system. Unlike the traditional two-stage optimisation that implemented in Reference 29, this multi-stage framework is more flexible and adaptive due to inter-stage coordination among the pre-dispatch, re-dispatch and real-time dispatch stages. The robustness of the proposed scheduling framework is tested by employing fast response hydraulic units which maintain the system security against fluctuations in RES.

A scenario-based deterministic optimisation model is proposed in Reference 30 to solve the dynamic ED and ensure the solution feasibility for all 'worst-case' scenarios in the uncertainty set. The author considered wind power and electric vehicles (EVs) penetration and formulated a 'bad-scenario' model to address the uncertainties. Since the usage of battery switching stations (BSS) is a convenient way to charge EVs, a BSS model is developed by the authors, and the obtained parameters are solved by using bacterial colony chemotaxis algorithm. To increase the solution feasibility and robustness of the proposed algorithm, the authors adopted multi-agent systems to handle a large number of constraints. In Reference 28, a battery operation cost model is proposed for better coordination of ESUs and solving the ED problem in MGs. This model helps the operator to consider battery as an equivalent generator unit without adding battery dynamics as additional parameters in the objective function, unlike the approach considered in Reference 21. Additionally, a probabilistic constrained approach is chosen in this work while addressing the uncertainties in load demand and RES forecast without considering the substantial number of scenarios which may increase the computational burden. With the rapid integration of EVs and their charging facilities, the DSOs must face new challenges for planning and operation to facilitate the highly uncertain level of EV penetration. The random nature of EV charging significantly changes the shape of the net demand profile, and thus, several works have been reported for optimal scheduling of EVs. For example, an online optimal charging strategy is developed in Reference 63 for coordinating multiple EV charging stations and optimising their charging costs. In Reference 64, an optimal dispatch strategy is proposed to analyse the impact of peak shaving and valley filling on fuel cost and emission of EVs. A probabilistic multi-objective optimisation method[65] is proposed for EED of conventional generation to study the impact of stochastic charging demand in the presence of EVs.

As most of the battery storage systems suffer from degradation effect, it is important to study the impact of operational scheduling on their depth-of-discharge (DOD) for each cycle. As stated in Reference 28, out of several ESUs, vanadium redox batteries have negligible degradation effect compared to lead-acid or lithium-ion batteries which are commercially installed at the utility level. A cost-benefit analysis conducted in Reference 29 indicates lower benefits for large scale test systems with less fuel cost and conversely, higher cost benefits for specific short-scale test systems with high fuel cost. More specifically, as the renewable penetration level exceeds more than 15%, the usage of battery storage results in greater cost savings. In this analysis, the authors emphasised that the lifetime of the battery is sensitive to DOD for overall equivalent discharging-cycles. Still, it has a negligible effect on DOD of each discharging cycle. On the other hand, maintaining low state-of-charge (SOC) is suggested to enhance the battery lifetime. For example, the results of a synthetic case study conducted in Reference 66 recommend that charging the battery at a small window of SOC periodically just before the load consumption can prolong the lifetime by limiting the effects from ageing. However, it has remained an open research question to decide the optimal value of SOC in several applications.

4 | OPTIMAL POWER DISPATCH OF MICROGRIDS

The fossil-fuel based energy generation is the most significant contributor to produce Greenhouse gases emissions, and the energy sector ensures that the infrastructure of the system should be resilient to the contingencies. Incorporation of DERs to the system increases the efficiency of the system and reduces demand from the distributed system. The operation and control of the system become complicated because of penetration of DERs are in the system from this scenario micro-grid concept was introduced. A micro-grid consists of various DGs, energy storage devices and controllable loads which can be operated in islanded mode or grid-connected mode. MGs control and management is a multi-objective mission which comprises distinct technical areas, time scales and physical levels. A hierarchical control scheme is shown in Figure 6 to provide a standardised solution for adequate MGs Management. It consists of three levels

1. Primary level control deals with the local power, voltage and current.
2. Secondary level control deals with power quality.
3. Tertiary level controls deals with the management of power flow between MG and external grid.

These three hierarchical control levels are usually associated with micro-grid central controllers (MGCC) in the control layer. Notably, at the tertiary control level, MGs receive forecasting data and dispatch signals from network operators. A micro-grid is an ADN associated with conventional and RESs are integrated into the network to provide bi-directional power flow information takes place in the power system. Microgrid provides a promising solution for the integration of RESs, energy

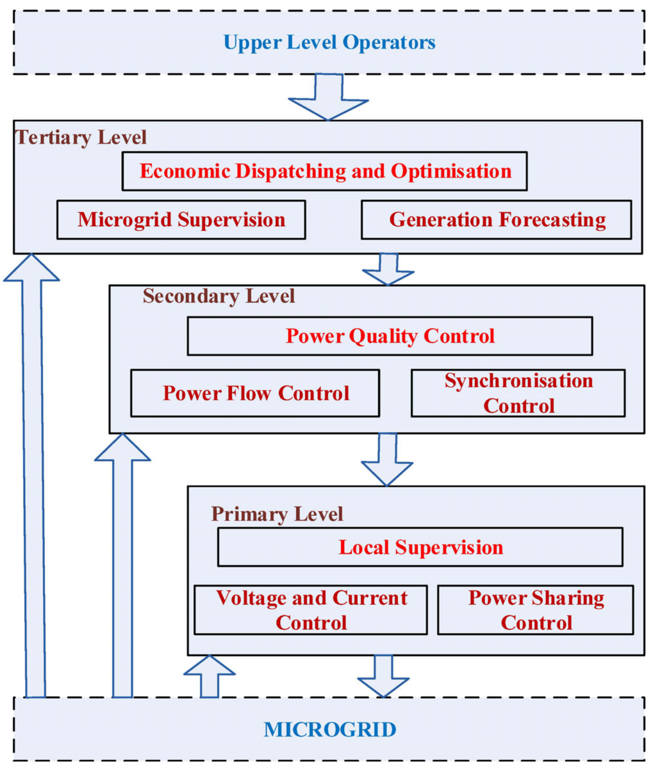

FIGURE 6 Microgrid hierarchical control [Colour figure can be viewed at wileyonlinelibrary.com]

storage devices and interconnected loads are coordinated with distribution network. A mixed-integer second-order cone programming is introduced in Reference 46 providing decentralised ED approach for an ADN when DSO associated with MGCC residing in a set of interconnected MGs for improving the ADN energy management. Case studies have been carried out on IEEE-33 bus distribution system and evaluated the computational performance, accuracy, robustness, with great potential in EM of an ADN. The optimal dispatch of a micro-grid is a challenging problem in both aspects of social and economical. To ensure the MG should be operated in an economical, flexible, environmental manner, a hybrid energy storage model-based ED strategy was established in Reference 48 a grid-connected mode by using improved quantum genetic algorithm. The usage of EV's, when compared to the battery, is described, and it plays a crucial role in peak-load and valley load in MG to improving the system performance and environmental protection.

Operation and planning of future distribution grid have become a challenging problem. Future distribution grid consists of MGs can be regarded as small-scale energy zones with more uncertainties in load and generation. A stochastically and probabilistic modeling of both small-scale energy resource (SSER) and load demand at each MG analysis has done in Reference 12 using particle swarm optimisation algorithm along with coordination of SSER balance between the total power generation of each MG and the load demand. The planning of CHP based micro-grid, and its DERs capacity is selected and deployed that it becomes economically self-sufficient to provide all the loads of the system without utility participation. A CHP-based system is considered in Reference 67, which are independent of size and DERs types. To track the demand, economically among the micro-turbines and diesel generators of various sizes satisfied different heat demands by considering a 4-DER 14 bus micro-grid using PSO technique. A new constraint was considered in Reference 9 to ensure the stable operation of a micro-grid and power-sharing principle regarding distribution generators by considering 15 units test system to observe the variations of parameters. A bi-level optimisation model was developed in Reference 12 to solve the dispatch problem based on the interaction between power generation and demand sides. The proposed energy dispatched model extracts ED of scheduling thermal units and control of flexible loads for energy-saving dispatch in the electricity grid. The same scenario is considered in Reference 50 by using coordinated energy dispatch based distributed model predictive control optimisation technique caters to optimal scheduling for exchanging energy between DNO and MG.

For the grid performance improvement, an integral-based, PID-control based algorithm was implemented in Reference 47 to improve the dynamic performance of the grid. The PID performance is compared with the conventional integral based control ED in the grid. Decentralised energy generation has obtained to increase the number of popularity within the electricity zone. Due to the steady boom in fossil fuel expenses and simultaneously, the growth of energy demand in rural areas desires for sustainable power systems are rising. To reduce the operation costs a hybrid energy supply, including RESs by using an advanced control strategy was implemented in Reference 43 for optimal operation of micro-grid by utilising a two-layer model predictive method. The first layer focused on real-time forecasting of forthcoming power profiles, and the second layer focused on adjusting the diesel generator power to improve the robustness of the control strategy. A combination of a fuel-based thermal system with integration of RES sources is considered in Reference 10 to perform the intelligent economic scheduling operation is concerning scheduling and dispatching TG, WG, PV and PHEV. A hypothetical test system is considered with 10 thermal units including PHEVs, solar, wind by using Intelligent Quantum Inspired Evolutionary Algorithm. Aforementioned in Reference 50 same optimisation approach is used in Reference 44 considering the real operational scenario is presented and validated in an existing experimental plant. A renewable energy micro-grid with hydrogen/batteries/ultra-capacitor hybrid ESS is developed and to ensure the logical states of start-up/shutdown of the fuel cell, electrolyser charge/discharge in the batteries and ultra-capacitor.

4.1 | Energy management system

The intermittent sources are non-dispatch able and having some limitations to provide a sufficient amount of demand-side delivery in MGs, and the main problem had existed in the power system. EMS ensures the system in a reliable, flexible and quality manner such that the available distributed generators (DGs) are utilised in an optimised manner. Basically, in rural micro girds the intermittent sources are incorporated to local micro-grid (locally available resources) like RES, wind, solar, along with diesel generators are associated to back-up the system as well as to meet the electrical load demand. A proposed system controller is designed and integrated to ensure the dispatch rules with hybrid optimisation of multiple energy resources software is used in Reference 68 to design an isolated MG. Affine arithmetic (AA) method is used to design an isolated MG in Reference 56 to compute the noise symbols values in affine forms, and it has obtained in a real-time dispatch with cost-effective solutions.

The smart energy management system (SMEs) optimises the operation of the power system. In SMEs, energy storage system (ESS) module is considered to find out the optimal operation strategies with multiple steps, and it evaluates the energy prices. A matrix real coded genetic algorithm is implemented in Reference 69 to evaluate load management with multiple operation policies. Figure 7 illustrates the structure of the SMEs to produce appropriate desired values for all sources along with storages in such a way that optimal dispatch is kept to obtain specific demand. A probabilistic economic tool is to examine the EM studies at remote hybrid AC/DC MGs in Reference 53. The parameters are examined related to the system by using the probabilistic model, and the EM approach builds a management system between storage devices and battery.

Moreover, the DR of customer participation in the system leads to paradigm shifts from conventional to interactive activities because of development in technology. The same scenario is considered in Reference 54 with an Artificial Bee Algorithm using Markov chain to obtain optimal dispatch. A medium-voltage DC is considered, which has both conventional and RES including schedulable and un-schedulable loads are considered. Two-time scale coordinated EMS was introduced in Reference 51 with two key factors are considered as operating point and droop coefficient. To ensure the system security droop coefficients with the help of coefficient optimisation and the controllers are responsible for the voltage profiles are maintained within the dispatch interval.

Distributed EM algorithm is implemented in Reference 52 to obtain accurate control computation at the time of load dispatch in the presence of comprising generation units. The Distributed algorithms provide robustness,

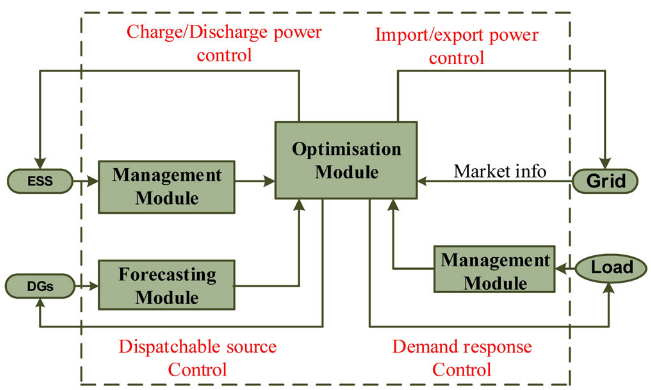

FIGURE 7 Smart energy management system [Colour figure can be viewed at wileyonlinelibrary.com]

scalability and flexibility. The system resilience is focused with the help of distributed control without disturbing the remaining generator units should reach the optimal operating point asymptotically. A robust two-stage optimisation approach has implemented in Reference 55 to schedule the power generation even under in uncertainties condition to minimise the long-term average operating cost subjected to the operational constraints. In the first stage, the scheduling of conventional generators (CGs) through a day head schedule and second stage performs the ED of CGs, ESS, and energy trading through the real-time scheduling. Technical aspects of thermoelectric power plants in different aspects of the power plant are analysed in Reference 70 with the help of computational intelligence technique. The statistical analysis had done when the engine is failed, and this phenomenon is considered as a pre-dispatch condition, and further to increase the reliability of the engine and power supply with the help of management tools to reduce the annual cost of maintenance is focused.

4.2 | Demand-side management

Demand-side management (DSM) has gained more attention in the electric power market domain to obtain economic benefits for utilities as well as consumers. Most of the DSM schemes reported in the literature mainly focuses on financial savings, system reliability and environmental aspects.[71] In general, any DSM strategy can be broadly classified into two types. The former category is customer induced DSM, where the customer participates in several DR programs. The latter is utility induced DSM where the utility can be able to initiate the load management Schemes. A brief classification of DSM is shown in Figure 8.

DR is a strategy to monitor load variations such that the grid can be operated sustainably along with the additional feature to provide impressive benefits such as price reduction and reliability of the system at the consumer end side. Figure 9 illustrates the schematic diagram of the DR architecture at the DMS level. The DR engine would receive the meter data from the meter data management system, which receives and collects the data from individual customers or the aggregator(s) through different communication means along with DR manages the interface between an aggregation of handling loads and system operator.

Due to the asset of DR, several demand response programs (DRPs) has been implemented and categorised into two types. Intelligent implementation of DRP not only reduce the price of electricity market it improves system reliability. In Reference 72, optimal incentive-based DRPs, emergency DRP (EDRP) and direct load control are implemented. Increased penetration of DRES pushes the grid for more reserve to meet the load and demand along with the efficient strategy of DR to decrease the load at peak interval. In Reference 58 focus on minimising the cost of operation of the fuel, startup cost, reduce the Greenhouse gas emissions by considering 10 traditional units includes one large scale wind farm with three different test conditions are interruptible load, direct load and load as a capacity source.

A new method was implemented in Reference 73 to describe the load shifting ability of flexible electrical loads through asymmetrical blocks. With the help of case studies, DR should be evaluated for the provision of regulating power. A new ED framework with scenario-based had implemented in Reference 74 by removing samples from a finite uncertainty set such that to improve the operating performance of ED and the results have been carried out on IEEE 3 bus, 14 bus and 118 bus systems. A real-time day head model is implemented in Reference 70 scheduling with renewable sources and reserve

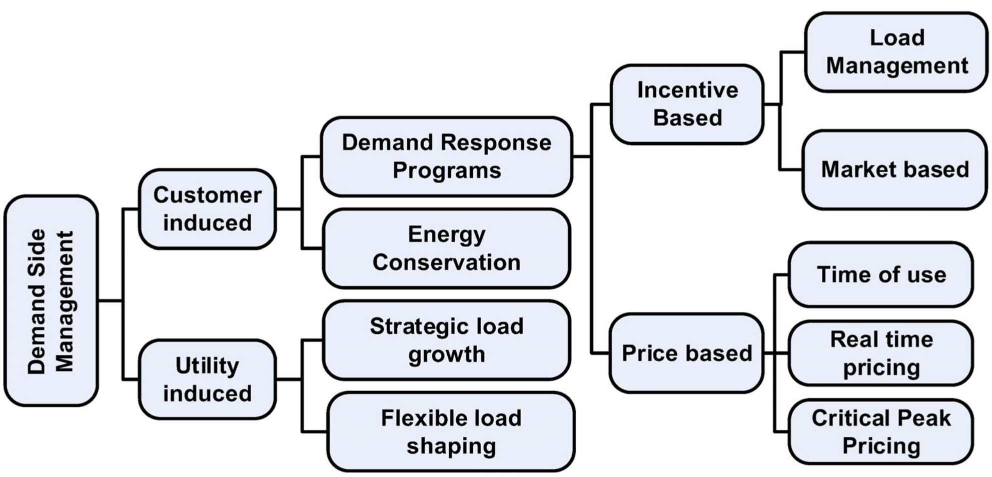

FIGURE 8 Classification of demand side management [Colour figure can be viewed at wileyonlinelibrary.com]

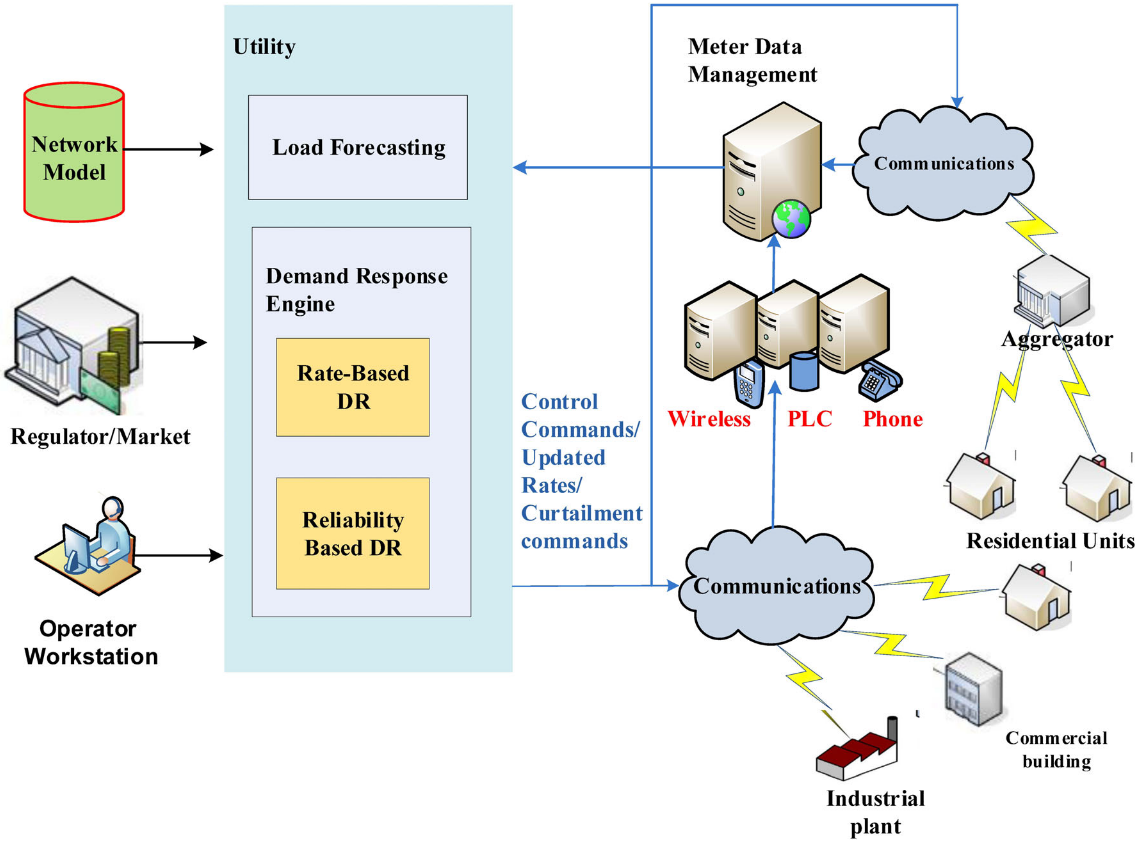

FIGURE 9 Schematic diagram of the demand response at the DMS level [Colour figure can be viewed at wileyonlinelibrary.com]

capacity. An iterative algorithm bi-level is implemented on both demand and generation side in Reference 75 to solve the uncertainty problem. Upper level minimises the emissions and improves the power generation, and the lower level minimises the cost of the expected total load to DR providers and emission cost.

5 | DISTRIBUTED AND DECENTRALISED APPROACHES

The traditional centralised optimisation techniques like lambda iteration method are sensitive to initial conditions and require the cost function to be convex.[76] This issue is addressed by several computational intelligence methods, mainly Genetic Algorithm, Particle Swarm Optimization and Differential Evolution by considering the practical ED problem with non-convex cost function.[77] With the advent of SGs, as more and more DGs being added to make the power system distributed, the research trend has shifted from a centralised approach to decentralised and distributed approaches for addressing distributed features of the SGs. The main reasons for this shift in research trends are listed below.[78]

1. The extensive implementation of SG communication infrastructure might not yield desired results with the centralised control mechanism. It leads to communication congestions and makes it difficult for the system operators to act upon the appropriate time frame and decision making under system uncertainties.
2. The multi-agent-based decentralised and distributed approaches are more reliable and adaptable to variable topologies in both communication and power infrastructures associated with the operation of various plug-and-play DGs.
3. Moreover, the application of distributed and decentralised control strategies encrypts the critical information of local participants such as DG cost function data and power consumption utilising auxiliary variables to protect the privacy of the participants as well as load equipment.[79]

This section reviews various distributed and decentralised strategies implemented in the recent literature to address the challenges confronted by centralised approaches. A typical variation between centralised and decentralised control approaches is shown in Figure 10.

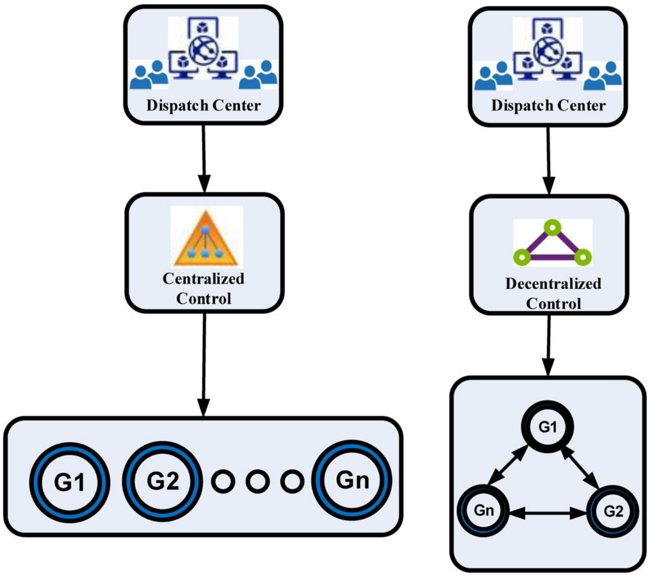

FIGURE 10 Centralised and decentralised architectures for optimal dispatch [Colour figure can be viewed at wileyonlinelibrary.com]

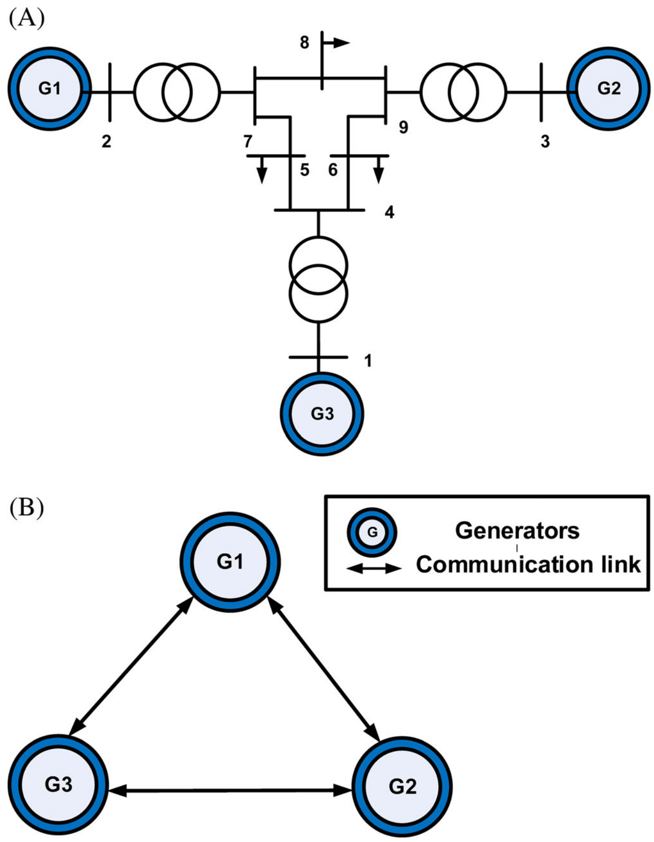

FIGURE 11 A, Typical IEEE 9-Bus system with three generator units. B, Communication topology graph of IEEE 9-Bus system [Colour figure can be viewed at wileyonlinelibrary.com]

5.1 | Applications of distributed algorithms in conventional grid

A typical distributed dynamic programming (DDP) based distributed strategy is proposed in Reference 76. This approach utilises a sparse local communication network where information is exchanged between neighbouring agents, unlike the global communication network used by the conventional centralised approach. The communication used in the DDP algorithm is asynchronous, and it has fast convergence characteristics compared to synchronous distributed algorithms. Since the practical ED problem is non-convex due to the nonlinearity in generator cost characteristics, several distributed[77,80] and decentralised[78] approaches are proposed to address the non-convex ED problem. A fully distributed auction-based algorithm is proposed in Reference 77 to solve the non-convex ED problem. The generating units act as agents and exchange information, that is, output power among the neighbouring agents with the support of the communication network and resolve the auction through consensus protocols. These agents act as both buyers and sellers and evaluate bids in the market-based auction mechanism and minimise the overall generation costs while satisfying the operational constraints. Figure 11A shows a typical IEEE 9-Bus system configuration with the concept of generators acting as agents with a distributed communication topology shown in Figure 11B.

A distributed pattern search algorithm (DPSA) is developed in Reference 80 to address the non-convex ED problem. The information transfer among the agents (generation units) in a self-organised networked system is deeply analysed in this work. At the same time, this analysis is rarely focused in literature where centralised approaches are used. As a sub-routine of DPSA, the topological information in the network is discovered using a flooding-based topology discovery algorithm to make agents aware of what type of information flows in the network. This approach further enables the agents to reach finite-time average consensus in less number of iterations. A three-stage fully decentralised approach is proposed in Reference 78 for solving non-convex ED problem incorporated with transmission losses. This approach is based on a concept of MAS framework where agents are embedded into the control station at each power plant. An undirected ring communication topology is adopted to connect the agents, and flooding-based consensus algorithm is implemented to achieve the consensus among the agents concerning the problem data at stage one. In stage two, a nondeterministic algorithm is chosen for improving the solution quality. Since the metaheuristic algorithms are stochastic, and the agents could produce different solutions, a third stage is incorporated to enable the agents to reach the consensus in choosing the best out of multiple solutions.

A DED strategy is proposed in Reference 79 by considering smart startup and shutdown of the units to handle operational situations like minimum load demand and surplus generation capacity. Decomposition analysis is implemented in the proposed DED framework, which makes each generator agent and load agent independently makes a scheduling strategy based on the piecewise distribution solution. Most of the above reviewed distributed approaches need stringent initial values to achieve the power balance with global coordination among the interconnected generator units. An error in the estimation of this initial value leads to power mismatch, and this approach is subjected to initialisation of the entire procedure for frequent changes in the network configuration. To overcome the problem as mentioned earlier, an initialisation-free approach is proposed in Reference 81, based on consensus protocols and saddle point dynamics. The dynamic average consensus algorithm is employed to estimate the global information corresponding to the total number of buses in the system, along with the communication network topology. With the estimated global information, the optimal values of the Lagrangian multipliers of a convex ED problem are calculated by adopting the saddle point dynamics.

5.2 | Distributed and decentralised control strategies

As an alternative to the traditional centralised dispatcher, a distributed dispatch algorithm is proposed in Reference 82 for adjusting the frequency deviations independently at each generator. The fundamental features of a distributed approach that distinguishes from the traditional approach in aspects of scalability, dynamic adaptability and model independence are briefly discussed in this work. This method automatically adjusts the power imbalance according to frequency deviations and eventually equalises the marginal costs. The distributed optimal load frequency control is designed in Reference 83 by merging the secondary loop (load frequency control) and tertiary loop (ED) of a conventional Automatic Generation Control. In the proposed distributed architecture, each generator is provided with the controllers with communication links among them to obtain the desired optimality. The consensus-based control approach discussed in this work provides an opportunity to study the dynamics of the turbine connected generator more accurately.

A distributed control scheme is developed in Reference 84 by combining frequency control methods with consensus protocols to solve the distributed ED problem. The power balance constraint is satisfied using frequency control methods without relying on the centralised controller. PI frequency controller and NN frequency controller are embedded with consensus protocols, and a robust control method is created to maintain the system at the optimality even during the communication failure. A decentralised approach is proposed in Reference 85 based on consensus algorithm and threshold-based strategy for regulating the system frequency economically. The coefficients of the consensus algorithm are made self-adaptive to increase the robustness of the agents against the system oscillations on the supply side. The threshold-based strategy provides frequency regulation for ancillary services such as contingency reserves on the demand side.

5.3 | Application of distributed algorithms in microgrids

A distributed power dispatch strategy is proposed in Reference 86 to manage a set of DGs deployed at a residential community with an assumption of the cyber-physical interface at the distribution substation level. The dual of classic dispatch problem is considered to leverage the Lagrangian decomposition concept, which can aid in enhancing computational efficiency of the proposed distributed approach in real-time. This strategy enables the local DGs (sub-agents) to make independent dispatch decisions based on the periodical broadcasted data from the utility (master agent). A decentralised approach based on an alternating direction method of multipliers (ADMM) is proposed in Reference 87 for the optimal allocation of multiple DGs in real-time. The dynamic model is considered to match the output of fast-reacting DGs with the fluctuating output of the wind power generation. The proposed ADMM in this article is tested on a distribution system consisting of multiple fast-reacting DGs and wind power generation to validate the obtained distributed solution. A distributed strategy based on dynamic average consensus (DAC) and laplacian gradient dynamics is proposed in Reference 88 for dynamic dispatch of DERs with storage units. The DAC algorithm tracks the power mismatch between the injected power from DERs and load demand over the finite time horizon and DERs send/draw power from storage units with the aid of distributed communication topology. The aggregate costs are optimised using laplacian non-smooth gradient dynamics, and the total power injection is dynamically adjusted for every perturbation of adding/

removing a DER from the network. The centralised controller in Microgrids (MGCC) is responsible for the coordination of all micro-sources and optimising the overall operation cost by issuing control signals to all units from a central node. However, this centralised control architecture is prone to single-point failures, and it cannot accommodate the plug-and-play nature of DGs, and it is usually less robust, time-consuming to analyse and compute the complex operational tasks. Hence, the distributed computation has gained much importance in recent years for the optimal operation of MGs.

The traditional lambda-iteration algorithm is generalised as distributed lambda-iteration in Reference 89 based on leader-following consensus strategy. Unlike the centralised approach, MGCC only communicates with the selected (pinned) DG sources and rest of the sources to share the estimated value of optimal incremental cost among the neighbouring units using a local wired/wireless network. In Reference 90, a cooperative reinforcement algorithm is proposed for distributed ED of MGs. The global optimisation with power balance constraint is achieved by coordinating actions among neighbouring agents (DG units) and updating parameters in a dynamic environment. The combined environmental, ED problem is considered in Reference 91 to solve with a distributed consensus protocol. The proposed algorithm calculates the consensus costs and estimates the global power mismatch with a practical communication network which includes time-varying communication topology, delay and noise. From the perspective of network control systems, the SGs are generally modelled as multi-agent systems of which, the generator units are considered as an agent and the consensus in their operation is usually met by employing distributed and decentralised control algorithms. The incremental cost consensus algorithm is applied in Reference 92 to solve the centralised ED problem in a distributed manner. The computational performance under various communication network topologies is briefly analysed in this work. In Reference 93, the ED problem is investigated using an adaptive weight-adjustment technique to secure the system against communication uncertainties. A distributed approach based on game theory is proposed in Reference 94,95 to solve the RTED with a formulation of local augmented Lagrangian function.

6 | CONCLUSION

This article provides a comprehensive review of various strategies and frameworks in the light of the optimal operation of DERs subjected to uncertainty and variability. A detailed literature survey is carried out on several probabilistic, stochastic and robust optimisation techniques along with distributed and decentralised approaches for the first time. This literature review covers an extensive range of methodologies and research works conducted on the optimal scheduling of various non-dispatchable sources interconnected in the SG domain for the past decade. At first, the brief review of a real-time, intra-hour, intra-day and day-ahead scheduling problems associated with Solar PV, Wind Energy, Energy Storage along with EVs are discussed in detail and the comparison of objectives and methodologies. Then, in the EM point of view, various centralised and decentralised control strategies applied to microgrid hierarchy and DSM are elaborately presented. Finally, a detailed review of distributed and decentralised approaches for economical operation in both the conventional grid and SG domain is discussed extravagantly. Authors believe that the present literature survey can be beneficial to the scientific community for developing further investigations in the related research fields. Based on the conducted survey, the author's perspective is put forward to discuss potential future developments.

- Although numerous efforts have been made to enhance the planning, operation and control of MGs, there is still room for innovations and improvements to develop and apply various modern control strategies.
- A better tradeoff option between centralised, decentralised and distributed architectures is necessary to ease the operations management for individual players in the emerging power markets.
- Risk limiting dispatch models need to be developed for future energy communities like Virtual Power plants and Resilient-Microgrids. Those models will leverage the hardware innovations in the information and communications technology to provide a robust solution to the operator while dealing with the system dynamics.
- Investigation of the battery management system to reduce the monetary costs of DERs integrated with the utility level is one of the prominent research areas to decide the marginal value of ESUs for a given SOC.
- The emerging smart cities in many developing countries require new pricing strategies to be designed for integration and coordination among different urban services.

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How to cite this article: Rangu SK, Lolla PR, Dhenuvakonda KR, Singh AR. Recent trends in power management strategies for optimal operation of distributed energy resources in microgrids: A comprehensive review. *Int J Energy Res*. 2020;1–23. https://doi.org/10.1002/er.5649