Towards Intelligent Energy Control and Optimization in Energy Internet: A Review

Haochen Hua, *Member*, *IEEE*, and Junwei Cao, *Senior Member*, *IEEE*
Research Institute of Information Technology
Tsinghua University
Beijing, P. R. China
jcao@tsinghua.edu.cn

***Abstract*—This study aims to review system control problems in the field of energy Internet (EI). Based on the existing related works, EI system modelling approaches without and with artificial intelligence (AI) techniques are discussed. Next, optimal energy management issues, robust system stability problems, and the mixed optimal and robust problems in EI are reviewed. The importance of this work is that the specific scenarios and the corresponding advantages and disadvantages of various control methods are analyzed. Finally, it is concluded that the combination of conventional state-space modelling approach and AI techniques is recommended for future study. We claim the future research direction regarding theoretical EI system control and optimization is to apply AI technology to realize an intelligent regulation.**

***Index Terms*—energy Internet, energy router, microgrid, optimal control, robust control**

NOMENCLATURE

AI	Artificial intelligence.
BES	Battery energy storage.
DER	Distributed energy resource.
EI	Energy Internet.
ER	Energy router.
FC	Fuel cell.
FES	Flywheel energy storage.
MG	Microgrid.
MT	Micro-turbine.
NN	Neural network.
ODE	Ordinary differential equation.
PHEV	Hybrid electric vehicle.
PV	Photovoltaic panel.
RES	Renewable energy source.
SDE	Stochastic differential equation.
WTG	Wind turbine generator.

I. INTRODUCTION

Due to the price increase of energy and the limit of fossil fuel, human beings have started to utilize the distributed RESs in addition to the existing power supply systems. The RESs normally refers to solar power, wind power, hydro power, etc. Although RESs have advantages such as clean and renewable, they have disadvantages such as non-linearity, uncontrollability, low inertia, intermittence, etc. [1]. Besides, how to realize an integration between RESs and the grid, and how to achieve a flexible switch and utilization within a variety of DERs are challenging, even after the concept of smart grid is proposed. Nevertheless, it is the concept of EI proposed by Rifkin [2] that provides a relatively satisfactory solution. In [3], the future renewable electric energy delivery and management (FREEDM) system is proposed as an example of EI system.

Nowadays, EI has been regarded as the version 2.0 of smart grid [4], since EI has additional unique features than smart grid does in a variety of aspects [5], [6]. Compared with conventional energy grid, EI can be regarded as an Internet-based wide area network for information and energy fusion. In the scenario of EI, the electrical grid still exists and is treated as the backbone network, whereas the MGs with DERs are viewed as local area network [7]. It is highlighted that within the field of EI, information and energy are integrated, and energy flows bidirectionally from/to utility grids and consumers.

The MG, based on either AC or DC bus, can be viewed as the core element of EI. An off-grid MG is usually composed of power generation devices, energy storage devices and loads. The power generation devices normally includes PVs, WTGs, MTs, FCs, DEGs, etc. [70]. The existence of large proportion of RESs makes the EI dynamical system more complicated than that of the conventional power systems. The usual energy storage device refers to BES and FES. When PHEVs are accessed into the EI, [8] proposes a new energy management system for the DC distribution system. When the architecture of EI is considered, a new type of power electronic device, called ER is proposed [9], [10] following the idea of the core router in the network technology. On one hand, ERs are treated as inter-media via a number of MGs in the scenario of EI, such that all the MGs are interconnected, or they are connected to the main power grid. On the other hand, ERs are powerful tools to balance the power deviation within one signal MG and even the whole EI scenario [11]. In this sense, multiple control and optimization methods can be implemented through ERs [12], [13].

The scope of EI include DERs, power system engineering, energy storage, power electronics, signal processing, cloud computing and big data, system and control, communications, mathematics, distributed computing and networking, business and finance and other disciplines [7]. Now that EI can be viewed as a multi-disciplinary subject, the research with respect to its various aspects has been very popular.

In this paper, we particularly review some recent research outputs in problems of dynamical system control and optimization within EI scenarios. First, some dynamical system modelling techniques are introduced. Second, regarding the problem of optimal energy management, some research results are illustrated and analysed. Third, system robustness issues in the field of EI are discussed. Then, some works analyzing both optimization and robustness issues in EI are discussed. In this review, EI system control approaches are introduced as two categories, one is the so-called conventional control method via classical control theory, and the other is the intelligent control that utilizes AI techniques. Comparisons between the conventional method and the intelligent one are analysed. Finally, research directions with respect to future EI system development are also discussed.

II. Dynamical EI System Modelling

When establishing the system model of an EI scenario, attention should be paid to the modelling of MGs, which has been widely studied in the past decades; see, e.g., [14], [18], [19], [20], [21], [22], etc. When a MG is disconnected with the main power grid, we call such MG is functioning in an off-grid mode, or islanded mode. In recent years, the islanded MG has attracted much attention and is mostly applied into rural places that are far away from the main power grid, since the power transmission is costly [23], [24], [25]. The control problems raised in the islanded MG are more complicated and difficult than the ones within the grid-connected MG. This is due to the defects brought by the access of a large number of the distributed RESs.

For a single islanded MG, power generation only depends on RESs (e.g., PV, WTG), and other distributed power generation devices (e.g., DEG, MT, FC). Since power generation by PV and WTG mainly depends on the weather condition, and the response time of controllable MT and DEG is relatively slow, without the utilization of energy storage devices conventional control strategies implemented on MT and DEG and cannot handle sudden power changes in MG. The energy storage devices are able to compensate power deviations in the MG system quickly [26]. Generally, it is the control and monitoring system that balances the power generations and usage in MG.

For an islanded MG system, ODEs have been used to represent its power dynamics; see, e.g., [14], [15], [16], [17], [27]. Then, power dynamics of each MG component can be rewritten as an integrated mathematical control system in forms of ODEs as follows.

$$dx(t) = Ax(t) + Bu(t) + Cv(t), \tag{1}$$

where vector x is system state, typically referring to power of PVs, WTGs, MTs, FCs, DEGs, BESs, FESs, loads, AC bus frequency or DC bus voltage; vector u is system control input from MTs, FCs, DEGs; v is system disturbance input, referring to solar irradiation, power of wind, change of power consuming behaviour, and A, B, C are system coefficients.

For a specific region, the power change of load mainly relies on the local timing and weather conditions. For different places, diverse geography and economical conditions would also affect the power of load. When a large number of electrical consumers switch on/off the loads independently, naturally, this would lead to a stochastic change in the aggregate load power. The stochasticity of the load power has attracted much attention during the past few years, especially when RESs and PHEVs are widely utilized [28], [29].

Now that the scale of accessed DERs is increasing, the randomness in the power systems has to be considered unavoidably, leading to the popular research of stochastic power dynamics [30], [31]. Mathematically, there exist essential differences between the stochastic power systems and the deterministic ones. In the future scenario of EI where the scale of main power grid becomes smaller, as a matter of fact that power generation and power of load are naturally stochastic, researchers have to pay more attention to analyse the stochastic power dynamics.

In [32], load power deviation is written as a SDE driven by Brownian motion. In [33] and [34], the MG power dynamics are written of the following form,

$$dx(t) = [Ax(t) + Bu(t)]dt + [Cx(t) + D]dW(t), \tag{2}$$

where stochastic process $[Cx(t) + D]dW(t)$ originates from the random power deviation of PV, WTG and loads. In the field of EI, communication time delay exists objectively [35]. When system communication time and parameter uncertainty are considered simultaneously, a stochastic dynamical system is introduced in [36]. Other linearised modelling approach has been reported in e.g., [37].

In real-world engineering practice, engineers prefer to approximate the nonlinear system into the linear one, in the sense that the simplified problem can be solved more flexibly. However, such approximation itself would bring additional system modelling error. To reveal such system nonlinearity, [38] considers a nonlinear stochastic islanded MG system, in addition to system parameter uncertainty. For illustrative purpose, such dynamical state space system is given below,

$$\begin{aligned} dx(t) &= [(A + \Delta A(t))x(t) + Bu(t) + Cv(t) + f(x,t)]dt \\ &\quad +[(D + \Delta D(t))x(t) + Ev(t)]dW_1(t) \\ &\quad +g(x,t)dW_2(t), \end{aligned} \tag{3}$$

$$z(t) = Fx(t), \tag{4}$$

where $\Delta A(t)$, $\Delta D(t)$ are time varying parameter uncertainty, $f(x,t)$ and $g(x,t)$ are system nonlinear terms. In (4), $z(t)$ is denoted as the controlled output, which refers to DC bus voltage deviation. Here, we emphasize that system equation (1) and (4) are popular in robust control analysis, whereas (2) without disturbance input is frequently used in optimal control control problems.

Apart from the aforementioned methods that mainly uses mathematical differential equations to represent the power dynamics, in recent years, AI techniques have been popular in system modelling within EI. The back propagation NNs have been used to predict load power in [39]. In [40], the short-term load power is forecasted based on extreme learning machine and improved gravitational search algorithm. Other short-term load forecasting methods can be found in [41], [42], [43], etc.

In [45], it is pointed out that the dynamical EI system formulated by differential equations can only represent the power deviation for a relatively short term. When the investigated time period is longer, e.g., two hours, one explicit ODE or SDE can hardly describe the full power dynamics. On the other hand, according to [45], the prediction power via NNs can cover such weakness, but the stochastic variation is difficult to be presented by NNs. Thus, a new hybrid modelling method for power of PVs and loads combining both the techniques of SDE and NN has been proposed in [45]. The similar hybrid modelling method has been reported in [53], where the method of combining both SDE driven by Ornstein-Uhlenbeck process and recurrent NNs has been utilized.

To summary, there are mainly three types of dynamical system modelling approach for EI system. The first is to use dynamical differential equation only, i.e., ODE or SDE. The second type replies on AI techniques. The third one can be viewed as the combination of the aforementioned two types. Each type has its advantage and defect, depending on the specific research problem. Currently, the mainstream research technique is to use ODEs to describe power dynamics, then frequency domain approaches can be applied to solve the related control problems. When the technique of SDEs is utilized, the related system control problem can only be solved in time domain approach. It is notable that for both ODE and SDE approach, its related system coefficients are difficult to be obtained accurately, and system parameter uncertainty is unavoidable. For some works that use AI techniques only, the obtained model is somehow difficult to be used for optimization problem solving, and such model might not be able to describe the system stochasticity well. In order to obtain a reliable EI model, the technique of hybrid modelling is recommended.

III. Optimal Energy Management Problems

After introducing the mainstream system modelling approaches, the related various energy management problems are reviewed and discussed in this section.

First, we review the works that solve the optimal energy management issues without AI techniques. A multiagent-based consensus algorithm for distributed coordinated control of distributed generators in EI is proposed in [54]. How to realize the bottom-up energy management principle is studied in [53] in which such physical problem is transformed into a stochastic optimal control issue and is solved via dynamic programming approach. The optimization and implementation for a special EI scenario has been studied in [44]. In [45], the target of extending the service life of BES has been achieved, and the optimal control laws are set in controllable power generation devices only, instead of setting controllers in BES directly. Data-driven planning and management DERs amidst socio-technical complexities has been considered in [47]. In [48], a two-layer network and distributed control method is proposed, where there exists a top layer communication network over a bottom layer MG, such that optimal power dispatch for islanded MG can be achieved. When multiple MGs are interconnected, distributed economic model predictive control strategy is implemented, such that system wide operating cost can be reduced [49]. The research of energy access administration based on a linkage routing network in EI has been investigated in [46]. The decentralized optimal control algorithm is designed for the distribution management system of multiple MGs [50]. Optimization of thermal energy storage systems has been studied in [51]. Distributed coordination for optimal energy generation and distribution in cyber-physical energy networks has been reported in [52].

In EI scenarios, when the complexity of power systems increases, conventional control approach might lead to poor control performances, which is the motivation of implementing AI techniques. Next, regarding the energy optimization issues, some works using AI techniques are illustrated. Deep learning-based distributed optimal control for wide area EI has been investigated in [13] where the graph theory approach is used. In [55], the EI system operation cost minimization problem is formulated as a stochastic optimal control problem and is solved by deep learning approximation approach. When reinforcement learning is applied to BES energy management, readers can refer to [56]. In [57], the EI energy management issue is solved via model-free approach, and the deep reinforcement approach has been applied to obtain the optimal controller. For other works using reinforcement learning algorithm in EI, reader can consult [58], [59], etc.

Indeed, some conventional approaches can give solution to vast optimal energy management issues. However, most of these problems are formulated to a certain form, such that conventional methods can be applied. At this stage, some approximation is unavoidable, and some system constraints shall be omitted. Otherwise, the conventional methods might appear to be inapplicable. Similar comments have been given in e.g., [57]. When AI techniques are applied, the model of the physical problem in EI can be revealed with various system constraints. Meanwhile, the complicated optimization problem can still be solved numerically, which is denoted as an advantage of AI approaches.

IV. System Stability and Related Robust Control Problems

In this section, system stability issues in EI are reviewed and discussed, mainly from the perspective of robust control theory.

For the transient stability issues in conventional power systems, the Lyapunov function approach and the time domain simulation are popular [60], [61]. A novel energy function-based stability evaluation and nonlinear control approach for EI is investigated in [68]. The classical control theory and intelligent control methods have been applied into the field of

EI; see, e.g., [16], [22], [26], [37], [62], in which the trade-off between nominal performance and robust performance is difficult to be achieved. In the above literatures, the heuristic control strategies or the intelligent control methods cannot maintain the system's stability requirement as well as its robust performance when there exit internal parameter uncertainty and external disturbance input. In the scenario of EI, due to the existence of numerous MGs, whose sizes are smaller than the conventional power grids, robust control schemes are applicable to ensure the system robustness.

In the future scenario of EI, there would exist a large number of PHEVs, the access of which would bring conspicuous frequency deviation to the interconnected MGs [65]. A common solution to this issue is to design control laws in the controllable power generation device which might normally refers to MT. It is notable that the dynamic response of MT is relatively slow, thus MT may not remedy the real-time load power oscillation adequately. Due to the limit of the MT controlling effectiveness, the electrolyzer can be used as an auxiliary power deviation absorber, due its quick dynamic response (in the level of millisecond) [16]. The role of electrolyzer in MG is to generate hydrogen for FC's power generation purpose. The control issues of MT and electrolyzer for the islanded and grid-interconnected MGs are studied in [64] and [66], in which the control parameters of MT and ES are set to be adjusted separately. In [64] and [66], such setting might not ensure the coordination controlling effect of MT and electrolyzer.

Notably, system uncertainties for example parameters uncertainty and modelling error are not considered in [64] and [66]. When conspicuous system uncertainty occurs, which is quite common in reality, the desired system frequency stability may not be achieved by the designed controllers of MT and electrolyzer in [64] and [66]. To overcome such dilemma, the robust control approaches have to be considered. As one of the robust control methods, H_∞ control takes the external disturbance input into account. Some works using H_∞ approach is illustrated as follows.

In [18], a robust H_∞ control strategy for power sharing in MG is investigated in both grid-connected and off-grid modes. Similarly, a robust H_∞ two-degree-of-freedom control strategy for an islanded MG is studied in [77], and the stability analysis of an autonomous MG is considered in [19]. Nevertheless, under most circumstances the obtained high-order H_∞ controller is difficult to be implemented in practical scenarios [78], [79]. On the other hand, the practical proportional-integral (PI) compensator is simple and its order is low, thus sometimes the PI controller is preferred for implementation convenience. For an islanded MG, research with respective to robust frequency control can be found in [14] where H_∞ approach is shown to be more effective than μ-synthesis method. The μ-synthesis method is also popular when designing robust MG controllers. In [74], a μ-based robust controller is proposed to regulate the MG frequency deviation. For more literatures focusing on μ-synthesis approach in MGs, reader can consult [75], [76], etc.

System stability issues are fundamental problems in EI, and it is frequency or voltage that is aimed to be controlled. In [69], the frequency and voltage deviations are successfully controlled to be stable against power deviation in load and power generation. For the islanded MG which includes a variety of DERs, the decentralized robust control scheme is studied in [71], where the controller is set in all of the power generation devices. If a MG is functioning in a off-grid mode, then the centralized schemes shall be suitable [14]; if the MGs are connected with the main power grid, then the decentralized structures are more applicable [70]. The online PSO-based fuzzy tuning approach has been used to control the frequency deviation in an AC MGs [62]. Meta-heuristic optimization algorithms are used to regulate frequency deviation in [72]. For other approaches to the frequency control problem in EI, reader can consult [72], [73], etc.

V. Mixed Optimal and Robust Control Problems

When both problems of optimal energy management and system robust stability are considered simultaneously in EI, the mixed H_2/H_∞ control approach has been popular. In this section, some works focusing on both system optimization and robustness are reviewed.

When PHEVs are considered in EI systems, in order to strengthen the tracking performance and the system robustness against parameter uncertainties, a mixed H_2/H_∞ controller is designed in MT and electrolyzer for frequency stabilization [16]. A similar mixed H_2/H_∞ control approach is used for designing the proportional-integral-derivative (PID) controllers of heat pump and PHEV [63]. When the fluctuating charging power from PHEVs and the system parameters uncertainty are considered simultaneously, [16] proposes on a robust mixed H_2/H_∞ controller, such that the MG system frequency can be stabilized and the tracking error is minimized. The mixed H_2/H_∞ controller for MT and electrolyzer in [16] appears to be superior than the conventional ones in [64] and [66]. To optimize system operation cost and to regulate AC bus frequency in frequency domain, particle swarm optimization approach has been applied in [67]. When designing control method for ERs, system robustness and rational energy management are considered to be realized simultaneously [81]. Seamless formation and robust control of distributed generators in MGs via direct voltage control and optimized dynamic power sharing has been achieved in [80].

The mixed optimal and robust control problems in EI is complicated than problems considering only system energy optimization or the ones focusing on system robustness. Indeed, apart from the difficulty of such synthetic problem it self, one important reason that most of the existing works do not take these two issues into account simultaneously is because normally these two problems are considered in two different perspectives or dimensions. For most robust control issues in EI, research focus is always put on short-term system dynamics, whereas for most optimal control problems, researchers aim to solve the optimal energy management problem for a relative long term. Regarding the operation of wide area EI in the long run, or from a global perspective, the transient system stability issue is always assumed to be satisfied and is not considered; see, e.g., [47]. [57].

VI. Conclusion

In this paper, dynamical EI system modelling and control problems are considered. Three types of control approaches are reviewed, including optimal control, robust control, and the combination of these two. Particularly, AI approaches are especially paid attention, compared with the conventional methods. The advantage and disadvantage of AI approaches are analysed. For current research outputs, the ones that utilize conventional modelling and control methods can be implemented to real-world engineering practice more easily as well as flexibly. For problems that considers various system constraints as well as multiple control targets, we claim such research is closer to the real EI scenario, but how to solve these complicated problems is rather difficult, and the conventional control approaches might appear to be inapplicable. In this sense, advanced AI technology shall be developed and implemented to such problem. In summary, it is concluded that for future research in the field of EI, AI techniques should be combine with the conventional control methods, such that more system management issues in the field of EI can be better solved.

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