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Review of integration of small modular reactors in renewable energy microgrids☆

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ABSTRACT

Integration of renewable energy sources in the form of microgrids can increase the resilience of power systems and decrease their carbon footprints. However, renewable energy sources are intermittent in nature, and their availability can vary significantly with weather and the seasons. Energy storage can be used to make up for the resulting imbalance between supply and demand to a certain degree, but installing large-scale storage for this purpose can be uneconomical. Hence, other types of power sources are often still required, and in many systems this power is provided by diesel generators. The emerging small modular reactor (SMR) technologies can potentially replace these sources with cleaner options. These new reactors feature passive safety systems, long refueling intervals, and have provisions for load-following, allowing them to complement the renewable sources and provide a reliable, dispatchable, low-carbon solution for both electricity generation and district/process heat production. Key issues and approaches are examined and existing works are reviewed to show how SMRs can be integrated into microgrids effectively as a clean and sustainable energy supply.

1. Introduction

Sustainability in power generation presents a fundamental challenge that involves balancing many competing factors, including capital expenditures, operating costs, emissions, and environmental impact. To meet the global threat of climate change, attention has increasingly turned to low-carbon energy sources. However, renewable energy sources with low greenhouse gas (GHG) emissions, such as solar and wind, are characterized by relatively low power density, intermittency, and lack of dispatchability. These characteristics add additional complexity, uncertainty, difficulty, and cost to using them effectively in energy systems.

Diverse energy sources can be integrated in the form of a microgrid, combining multiple sources, loads, and energy storage into a self-contained energy system that can operate both with and without the support of a large-scale utility grid [1,2]. These microgrids are controlled locally, and appear to the grid as a single entity. A microgrid can eliminate power transmission losses and provide increased resiliency [3]. Power disruptions during contingencies can be minimized or avoided by maintaining the energy supply to critical loads during grid disturbances by disconnecting the microgrid from the larger grid and operating it independently until the larger grid issues are resolved [4]. Some microgrid designs also include a thermal power loop to support loads such as district heating or greenhouses. While microgrids can be powered by a variety of energy sources, traditionally including fossil fuel sources, most recent activities have been focused on effective integration of renewable energy resources [5].

One application of microgrids is to provide electricity to remote communities, where either the grid does not exist at all, or the available grid power exhibits poor quality and reliability. For example, microgrids have been explored to improve system reliability in applications where long distance transmission lines and grid feeders are subject to natural disasters, such as tornados or tsunamis. For off-grid scenarios, microgrid technology enables the coordination of multiple locally available sources, including intermittent renewable power sources, storage, and demand response resources. As costs of renewable energy sources continue to decrease [6] they become more and more attractive for these applications, however, the intermittent nature of these power sources creates challenges, especially in stand-alone off-grid microgrids.

In these islanded microgrids, the electricity supply must match the

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load demand at all times in order for the frequency and the voltage to remain within the desired limits. However, due to the intermittent nature of renewable resources, it is challenging to achieve such a balance using these sources alone without including controllable power sources or a large amount of storage. As the proportion of renewable sources increases, this problem becomes ever more serious. In addition, there are also predictable daily and seasonal variations in both the load demand and in the availability of the renewable resources that need to be taken into consideration in the system design and during its operation. At present, large storage systems that can deal with these long-term variations are challenging economically. Therefore, there remains a need for some additional controllable sources that can fill the gap between the renewable energy supply and the dynamic load demand.

The most common dispatchable power sources for these off-grid communities currently are diesel generators. However, the isolation of such communities and their dependence on seasonal roads or waterway access for fuel delivery results in high operating costs. Also, the CO_2, NO_x, and particulate emissions from diesel combustion are of increasing concern, so there is more and more pressure to reduce the use of diesel for electricity production.

Dispatchable alternatives to diesel generators in microgrids include hydroelectric systems, natural gas turbines, hydrogen fuel cells, and geothermal systems, which can have lower environmental impacts than diesel. However, dam-based hydro power requires suitable topography/hydrology and involves flooding large areas of land. Run-of-the-river hydro power requires a nearby stream with sufficient flow, limiting it to certain sites, and can be impacted by seasonal flow variations and drought conditions. Gas systems require fuel delivery infrastructure such as pipelines or liquid natural gas storage facilities, neither of which are readily available in many locations, and construction and operation of gas facilities still result in significant GHG emissions. Hydrogen shares the same fuel delivery challenges as natural gas, with the added difficulty of a less developed supply chain for power production. Hydrogen fuel cells produce water as waste, making them a potential zero-carbon solution, but only if the hydrogen fuel is produced using a green production process like electrolysis. Unfortunately most hydrogen is produced today using steam methane reforming, which has a significant carbon dioxide footprint. Geothermal systems can provide both heat and electricity, however, the necessary geological features required to provide the high-pressure steam for power production are found in only certain sites, limiting the applicability of geothermal power.

One potential solution is to use a Small Modular Reactor (SMR) as a dispatchable energy source [7], which can provide low-carbon power at a cost that is anticipated to be below that of diesel generation. The size of some of these SMRs is more compatible with that of a renewable energy based microgrid, and they can be deployed in remote areas in off-grid applications due to their long refueling cycles. The modern SMR concept is relatively new, though it builds on many years of experience with large power reactors, experimental test reactors, and shipboard nuclear propulsion systems. However, relatively little work has been done on the integration of SMRs into renewable energy microgrids, in part due to the emerging state of the SMR market and a lack of systemic investigations. In fact, SMR/renewable microgrids have the potential to displace diesel power sources in remote community and mining/industrial applications, providing low-carbon electricity and thermal power.

In this paper, several SMR concepts are described, their properties are considered in relation to renewable energy sources, and key instrumentation and control issues involved in integrating SMRs into renewable energy based microgrids are reviewed. This overview also highlights areas where more investigation is needed for the seamless integration of nuclear energy into microgrids. In Section 2, important features of SMRs are examined and different designs are briefly introduced. In Section 3, coordination and control of microgrids that include SMRs is explored, including some of the modeling, simulation, and platform environments that facilitate investigations on these topics. An illustrative example of an SMR/renewable microgrid is then presented in Section 4. In Section 5 several key open issues are identified, and finally concluding remarks are given in Section 6.

2. Small modular reactors

The SMR concept involves the development of relatively small-scale nuclear reactors that can be produced as identical modules in a factory setting rather than built on-site, as is the case for existing nuclear power plants, thus taking advantage of advanced manufacturing technologies. Most of these modular designs have adopted passive safety features that minimize the risk of catastrophic accidents, and also include load-following capabilities. Multiple modules can be deployed at one site to meet different levels of power requirements in the presence of uncertainties and variability associated with renewables, and to provide redundancy during refueling or servicing periods.

Three potential deployment areas have been identified for SMRs: northern/remote communities, heavy industry, and on-grid applications [8]. The small and modular designs allow them to be deployed incrementally in a wide variety of environments and applications, including those that require both electrical and thermal power sources [9]. As the need for power for a specific application changes, modules can be added or removed accordingly to meet the specific load demand situations.

One of the markets where SMRs have the potential to have an impact is in remote northern communities in Canada that currently rely on diesel fuel. The levelized unit electricity cost of diesel, which accounts for capital, operating, and decommissioning costs, is reported to be \$0.466/kWh - \$0.487/kWh [10], and can in some cases exceed \$0.50/kWh. SMRs could provide an economically viable solution to deliver clean energy in these communities, with this analysis suggesting that the levelized unit electricity cost of a 10 MWe light water reactor will be \$0.453/kWh (in 2015 US dollars). In addition, using an SMR solution avoids the production of approximately 2.6 kg of CO_2 for every litre of diesel that is burned.

One or more SMRs can be incorporated into a microgrid to provide reliable low-carbon electric and thermal power, as illustrated conceptually in Fig. 1. In this scenario, a hybrid microgrid provides power to residential, commercial, and industrial loads, and includes solar photovoltaic panels, wind turbines, a battery energy storage system, and a pair of SMRs. A thermal network is also illustrated to supply industrial process heat.

2.1. SMR characteristics

SMRs are classified as single-reactor units rated at 300 MW or lower of electrical power (MWe) output, for example, the 160 MWe/525 MW thermal (MWt) Holtec SMR-160 reactor design. It involves a containment structure that is 36 m tall (above ground) on a 4.5-acre site [11]. Several other SMR designs are sized such that they are well suited for deployment on brownfield sites previously used for comparably rated fossil plants, thus allowing for reuse of existing facilities, including transmission infrastructure. For a microgrid supporting a small community, the electrical power demands might be modest, and are typically between 2 and 10 MWe [10]. Therefore, relatively small SMRs would be more desirable for such applications.

The modular character of SMRs has two aspects: modularity in reactor design, and the ability to link multiple reactor modules together to form a larger system during operation. Design modularity is a key enabler for lowering the construction cost and investment risk [12]. Standardized reactor modules can be mass produced in a factory setting, whereby multiple modules and other supporting systems can be manufactured in parallel, as opposed to being constructed on-site in a sequential manner. In addition, this approach can potentially simplify the site-specific engineering tasks by following a reference design to provide a turnkey facility constructed in a relatively short duration. This modular design approach is also expected to simplify the licensing

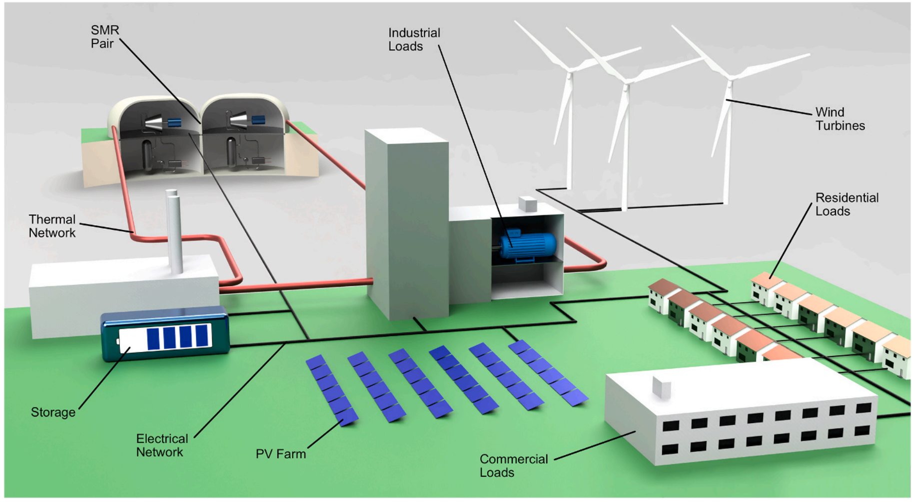

Fig. 1. SMR/renewable microgrid energy system.

process and meet regulatory compliance. Finally, some of the modular reactor design specifications are also chosen to meet constraints imposed by such factors as the size of a shipping container or load limits of the transporting vehicles, thus reducing the total cost and complexity of logistics during construction and installation [13]. For microgrid applications, standardization of such modular designs would allow for simplified system design, construction, commissioning, operation, and maintenance.

The use of multiple modules together in one plant location allows the system to be scaled to the anticipated load demand, and accommodates potential future load capacity changes. Rather than custom designing a nuclear facility to meet the anticipated power system demand, a multi-module SMR facility could be designed to accommodate a set of nearly identical SMRs that can either operate together to meet demands greater than the rating of each individual unit, and/or operate in a staggered or redundant fashion to provide continuity of power supply [14]. As demand grows, for example in a growing remote community, additional modules could be added at later dates on the same premises. Having more than one module also allows swapping or refueling of modules to be staggered, ensuring that most or all of the load demand can be met while some units are out of service.

The NuScale system [15] is based on this approach, with a reactor building that can hold up to twelve modules. By incrementally adding capacity as needed, the up-front cost and construction schedule can be optimized, so that a return on investment can be realized more quickly than for larger site-built nuclear power plants.

Another feature in some SMR designs is to load the fuel in the factory and ship the reactor module as a sealed unit to the site. In this case, all handling of radioactive materials would occur in a controlled, secure setting. The unit would have a fixed operating lifespan, which in some cases reaches 30 years. At the end of this period, the entire reactor module could be removed and returned to the factory for refurbishment and re-fueling. This feature reduces the proliferation risk associated with shipping and handling new and spent fuel and other radioactive materials to and from the site. This, in combination with the use of passive safety systems, will greatly reduce the risk of radiation release to the environment, which could be a significant community concern in some applications [8].

2.2. SMR types

Five major types of SMRs and their key characteristics and design parameters are summarized in Table 1. The typical thermal and electrical power ratings are indicated. The temperature shown is that of the coolant and the reactor output. The level of enrichment is the percentage of uranium-235 in the fuel, with 3–5% being the typical low-enriched uranium (LEU) that is used in existing commercial reactors. Enrichment levels of 5–20% are classed as high-assay LEU (HALEU), and levels above that are classed as highly enriched uranium (HEU). The reactors using more highly enriched fuel can potentially operate for longer periods of time between re-fueling, though note that HEU is extremely restricted and typically for space and military applications only. The

Table 1
Selected SMR types.

SMR Type	Example Design	Rating (MWt)	Rating (MWe)	Temp. (degrees C)	Enrichment (%)	Refueling Interval (yrs)
Integrated Pressurized Water	NuScale	160	60	300	<5	2
	KAERI SMART	330	100	300	<5	3
	Holtec SMR-160	525	160	315	<5	1.5–2
Gas Cooled	General Atomics EM2	500	265	850	12-15[a]	30
	USNC MMR-5/10	15	5	630	9–13	20
	Starcore	28	14	850	19	5
	URENCO U-Battery	10	4	750	20	5
Molten Salt Cooled	Terrestrial Energy IMSR-400	400	195	600	2-3[a], 5–19[b]	7
	Moltex Energy Stable Salt Reactor	750	300	570	Spent fuel	continuous
Liquid Metal Cooled	LeadCold SEALER	8	3	432	20	30
	ARC-100	260	100	500	<20	20
Sodium Heat-pipe	Westinghouse eVinci	3–20	1.9–5	600	19.75	3–10
	NASA KRUSTY/Kilopower[c]	4.3–43 kWt	1-10 kWe	800	93	15

[a] Start-up fuel.
[b] Make-up fuel added during operation.
[c] Experimental reactor to test concepts for space power systems.

level of enrichment for commercial applications should not exceed 20%.

The integrated pressurized water designs resemble some existing nuclear power plants, and have reactor coolant output temperatures high enough for desalination or other low-temperature thermal applications in addition to electricity generation. These designs are expected to be among the first SMRs to be constructed, since they are based on established technologies and use well tested fuels [16].

The even higher temperature outputs of the gas-cooled SMRs, which are typically cooled with helium, can be used for steam methane reforming, biomass gasification, and high-temperature steam electrolysis for hydrogen production [17]. This category also includes several smaller rated units that may be appropriate for remote community applications.

The molten-salt [18] and liquid metal cooled reactors [19] typically operate at lower pressures than other types, simplifying the reactor design and enhancing safety. Some designs also include molten-salt secondary and tertiary cooling loops that can incorporate thermal energy storage. These types of reactors include several fast neutron reactor designs, which have the potential to reuse spent fuels from existing light water reactors. Further discussions of small and medium sized reactor technologies can be found in Ref. [20].

While SMRs are generally understood to be reactors rated lower than 300 MWe, the terminology for reactors on the lower end of this scale, for example less than 10 MWe, is less standardized. These SMRs are sometimes referred to as micro-modular reactors (MMRs), Micro-SMRs, very small modular reactors (vSMRs), or simply micro-reactors [21,22]. For example, the Westinghouse eVinci heat-pipe reactor design is rated at 1.9 MWe and has the potential to operate for up to 10 years without refueling. There are also some designs that are even smaller in size, such as NASA's experimental 1 kWe KRUSTY/Kilopower Stirling engine heat-pipe reactor [23]. This HEU fueled design is intended for space applications, where the weight of the reactor module is a critical factor to be considered in the design.

While some of these vSMR concepts include a traditional steam cycle for power generation, others include less common power conversion technologies, including Stirling generators and supercritical CO_2 (sCO_2) Brayton cycles. These technologies require temperature, pressure, and materials tradeoffs, but can potentially generate electricity more efficiently than a traditional Rankine steam cycle, and a sCO_2 turbine can be much smaller in size for the same power rating [24].

Solid-state thermal to electricity conversion relying on the heat from plutonium radioactive decay has also been explored, but these thermoelectric technologies suffer from low conversion efficiency and are typically only used for low-power, long-lifespan nuclear battery designs, such as the Multi-mission Radioisotope Thermoelectric Generator found in the Mars rovers Curiosity and Perseverance. This approach has, however, been proposed as a source of auxiliary power in a sodium-cooled heat pipe reactor design, effectively making use of otherwise non-recoverable heat [25] for powering instrumentation and control subsystems in a plant.

Adoption of a specific type of SMR in a particular situation depends greatly on the specific requirements of the application. For example, the smaller rated gas- and liquid-metal cooled designs with long refueling intervals would be well suited to remote community applications. However, for industrial processes, such as steam methane reforming or natural gas cracking, only the gas-cooled reactors are able to reach the needed high temperature output [26]. Another key selection criteria is the ability and rate with which an SMR can maneuver its power output level. This is particularly important for integrating with renewable energy sources in a microgrid.

2.3. SMR operation

As an illustrative example, a small modular pressurized light water reactor and its supporting Rankine-cycle based balance of plant components are shown in Fig. 2. Inside the reactor vessel, neutron absorbing control rods are used to adjust the reactivity and thus the reactor power level. Primary coolant circulates inside the reactor vessel by convection, moving up through the core and extracting the heat, then flowing downward through the coils of the helical steam generator, where the heat is transferred to the secondary loop. The steam then drives a turbine, which is connected to a synchronous generator to produce electricity. The steam from the turbine outlet is then condensed back into water using an external cooling loop. Finally, the condensed water is pumped back to the steam generator to complete the cycle. A valve-controlled steam bypass path can divert the steam away from the turbine to quickly adjust the electrical output power level, if needed. Note that this simplified illustration omits the multi-stage turbine and reheaters that are typically present in a practical system.

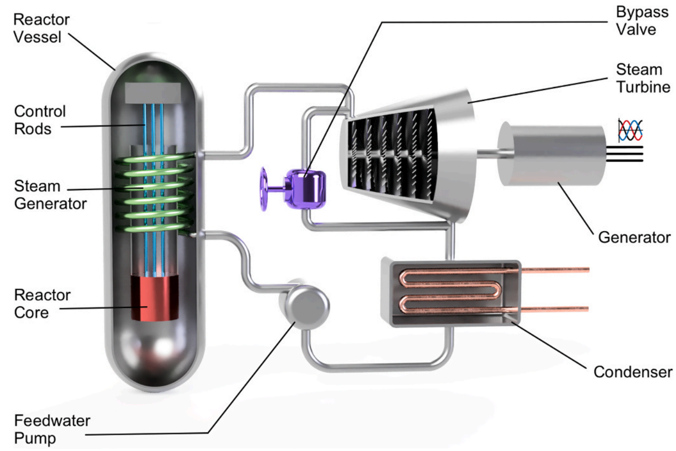

Fig. 2. A simplified small modular reactor system.

Large-scale nuclear power plants are traditionally operated near their rated power level to support baseload for economic reasons, since their fuel cost is relatively low and the capital cost for plant construction is very high. However, for SMRs operating in microgrids the ability to quickly adjust their power outputs is an essential feature that complements the characteristics of renewable energy resources. They can adjust their output power, subject to ramping constraints, and can therefore perform at least some degree of load following [27]. There are several mechanisms that can be used to regulate the output power of a SMR in response to rapid load changes and renewable power variations, or alternatively to adjust the electrical output power of the system while maintaining the reactor thermal power at a constant level. These include control rod adjustments, feed water flow rate modifications, and steam bypass initiations. The control rod movements directly influence the amount of thermal power through the rate of the fission reaction. The chain reaction processes can be complex and include transient behavior that can limit the maneuverability of the reactor with large power level changes [28]. The feed water flow rate has a more indirect effect by adjusting the rate of heat removal from the core, which then affects the core reactivity.

An SMR system can operate either in a turbine-follows-reactor mode, where the system dispatches a fixed amount of power specified by a setpoint, or in a reactor-follows-turbine mode, where the reactor power level is changed based on the power needed by the load demand, allowing for true load following.

Additionally, the steam bypass mechanism can be used to quickly reduce the electrical output power of the generator by diverting some steam away from the turbine to the condenser. This simplifies control and operation of the reactor, and shortens the response time to load changes, because the turbine-generator system is a much faster acting system than the heat transport system. However, its use for large power level changes wastes a significant amount of energy and could also cause considerable stress on the condenser and its cooling system.

3. Coordination and control of SMR/Renewable hybrid energy systems

When SMRs and renewable energy resources are integrated to form a microgrid, for example as shown in Fig. 3, the control systems for the SMR must also be coordinated with other control systems in the microgrid. Typical microgrid control strategies allow various power sources to contribute to the load demand in the desired proportions while maintaining frequency and voltage limits [29]. Intermittent renewable sources introduce additional complexity to implementing these strategies, since rapid fluctuations of renewable sources must be mitigated by either the SMR or an energy storage system. Control systems should be designed to deal with such scenarios, and must incorporate reactor power regulation into the overall microgrid control scheme. In addition, flexible thermal loads and the coordination of multiple SMR modules, when present, also need to be considered in the design of such control strategies. Since SMR technology is still emerging, modeling and simulation approaches play a critical role in designing and testing these control strategies and exploring the instrumentation and control architectures that must be developed to implement practical SMR/renewable energy hybrid systems. These topics are further discussed in the following subsections.

3.1. Traditional microgrid control

Microgrid control strategies are commonly organized into a hierarchy. At the lowest level are the real-time control loops operating within each energy source, which regulate the power electronic switching signals for inverter-based units such as renewables and battery energy storage systems. The primary layer deals with power sharing among the different units, ensuring that various sources provide the correct amount of real and reactive power. In the secondary layer, the overall frequency of the microgrid and the voltage levels are regulated for dynamic stability. Finally, the tertiary layer orchestrates the overall operation and effective energy management of the microgrid for long-term viability and coordinates operation possibly with a larger grid or other microgrids where present [30].

At the primary layer, both centralized and distributed mechanisms

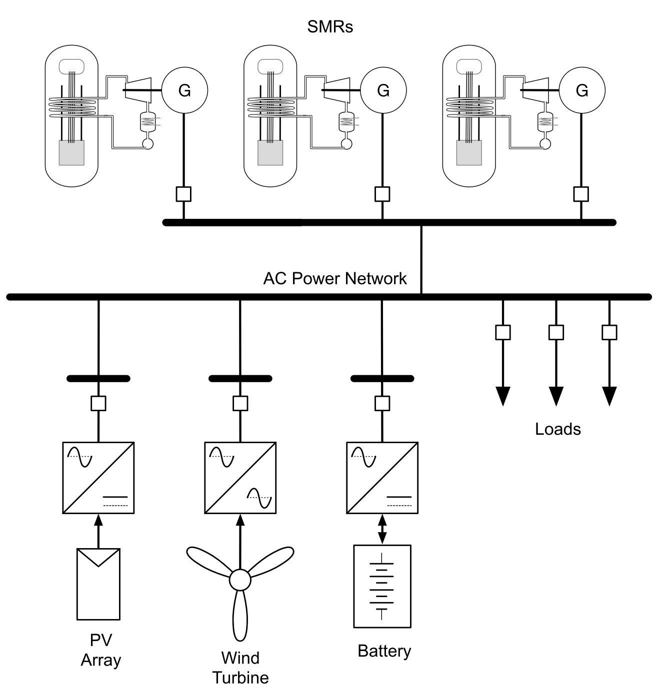

Fig. 3. SMR/renewable microgrid configuration.

have been investigated, with power/frequency droop-based approaches generally being adopted to minimize the dependency on high-bandwidth communications among different units [31]. In these approaches, the system frequency decreases, or “droops”, as the power demand increases. This approach has been extended to a multi-segment adaptive droop approach, which accommodates battery charge limits and PV curtailment [32]. At the secondary layer, system setpoints can be adjusted over low-bandwidth communication links to achieve desired voltage profiles and pre-determined power sharing among different resources [33]. At the tertiary level, the energy management scheme determines dispatch schedules for different energy storage, management of storage, and coordination of demand response, including the use of weather forecasts to predict future renewable power production levels to improve the power availability to critical loads under various contingencies [34].

3.2. Reactor power regulation in microgrids

If the SMR is operated in the turbine-follows-reactor mode, selecting when and by how much to change the SMR output power level is the responsibility of the microgrid energy management system (EMS), which may have to deal with multiple objectives and constraints to determine the optimal operation strategy for the whole microgrid. These considerations can include fuel costs, thermal stress on heat transport systems, efficiency, reserve capacity, reliability, and equipment conditions. For example, predictions of the overnight load demand can be used to schedule output power level adjustments for the SMR over that period, while the battery can be used to compensate for any short-term mis-matches between the available power and the load demand.

The Electric Power Research Institute User Requirements Document for SMRs specifies a 24-h load cycle of 100% down to 20% and back to 100%, a ramp rate of 40% per hour, and a step change of 20% in 10 min [15]. Given these ramp rate constraints, with this approach it is important to obtain as accurate forecasts as possible for the renewable energy production so that the EMS can pre-schedule the power outputs of the SMR to match the desired setpoints adequately.

For the reactor-follows-turbine mode, the generator output of the reactor subsystem must participate in whatever power management scheme is being adopted in the microgrid, which is typically in the form of droop control. In this case, the behavior of the programmed droop controller will determine the exact portion of the load demand being served by the SMR relative to the other sources/storage in the microgrid. The controller can then adjust the steam bypass valve and control rods to lower or raise the reactor power output level accordingly. However, the ramp rate constraints of the reactor still need to be considered, so the system designer must consider practical intermittent renewable resources and load demand changes to design the system accordingly to ensure that these limits are respected.

In one example, a dynamic model of a 100 MWe PWR with a helical coil steam generator is developed in Ref. [35], which is based on a scaled-down version of the International Reactor Innovative and Secure (IRIS) reactor. An interval-based approach is used for constraint specification in the nonlinear dynamic inversion (NDI) framework to achieve coordinated control of the turbine inlet pressure and the control rods for both reactor-following-turbine and turbine-following-reactor modes. The controller has been tested in a hardware-in-the-loop simulation environment, with a real-time model of the reactor running in Opal RT and the analog-interfaced controller being executed on an embedded system programmed in the MATLAB/Simulink environment.

3.3. Variable thermal loads

An alternative approach to adjusting the SMR power level is to keep the reactor at full power and redirect a portion of its thermal output to another down-stream process [26,36], thus effectively adjusting the electrical power output without changing the reactivity. Several variations of this approach have been proposed, including a combination of electrical and thermal outputs for hydrogen production using a high-temperature electrolysis process, which is more efficient than conventional electrolysis [37]. Since the electrolysis process can start and stop on demand without significant impact on the quality of the hydrogen production, it becomes a good reservoir for absorbing excess reactor output. The hydrogen serves as an energy carrier, which can later be reverted back into electricity using a fuel cell power module or burned directly for process heat. Taking this approach can lead to a faster return on investment than nuclear-electricity-only applications [38]. Related approaches have also been proposed to use the excess heat energy to produce synthetic gas [39] and to operate desalination plants for potable water production [40,41]. In cases where these alternative thermal applications are available, the dynamic models of these processes should be considered in the overall microgrid operating strategy.

3.4. Coordination and control of multiple modules

Since the modular design of the SMR facilitates multiple reactor modules within a facility, the coordination and control of these modules becomes critical. In some cases, for example NuScale, each module is coupled with a dedicated turbine and a synchronous generator. This type of configuration is examined in Ref. [42], which presents a thermohydraulic model for the reactor and demonstrates the indirect coupling between the reactors that occurs for several operating scenarios. In other configurations, the steam outputs from multiple reactors are fed into a common steam header [43], where two IRIS SMR modules are feeding a common steam header, steam turbine, condenser, and pumps. The control strategy is based on using the measured steam pressure of each unit and to adjust the turbine control valve to regulate its steam flow rate. The feed water flow rate is controlled based on the power demand. A more detailed development of a nonlinear differential-algebraic model of the secondary fluid flow network for a pair of thermally-coupled modular high-temperature gas cooled reactors (MHTGRs) has been carried out in Ref. [44]. This work considers a configuration with a common main steam valve and feedwater pump with independently controlled feedwater valves for each reactor, and uses a distributed adaptive strategy to adjust the valve setpoints. The non-linear modeling of the secondary fluid flow network is developed, and simulation results show the effectiveness of the proposed approach in integrating the two reactors.

3.5. Modeling and simulation of integrated renewable energy/SMR systems

Given the early stage of SMR development, much of the current effort on integrating SMRs with renewable microgrids has focused on modeling and simulation. The expected behavior of microgrids that include SMRs can thus be explored in the lead up to commercial deployment, leading to the development of effective control strategies and evaluation platforms for these systems. Successful design of control systems for microgrids and simulation of various operating and contingency scenarios requires accurate and realistic SMR models. While these models are generally focused on the electrical-side behavior from a microgrid point of view, the coupled nature of SMRs and renewable energy resources does require special consideration.

Oak Ridge National Laboratory (ORNL) has undertaken SMR modeling activities that focus on the use open standards model-based engineering tools to enable large-scale collaboration. They have used a combination of Dymola, a commercial modeling and simulation environment that relies on the open Modelica language for model description, and Modelon Functional Model Interface (FMI) tools, a technology that allows compiled models to be executed independently from the tools used to create them. Such tools have been used to develop models for an advanced liquid metal reactor, including the direct reactor auxiliary cooling system, the primary heat transport system, the intermediate heat exchanger, the intermediate heat transport system, the steam generator, the power conversion system, and the electrical power grid [45,46]. Results of coolant flow and temperature profiles have been demonstrated under step changes in the power level. The intent is that these open models can be easily shared and executed on a variety of platforms.

A Simulink model of a passively-cooled SMR based on the NuScale design has been developed in Ref. [47]. The model uses a point kinetics equation for the reactor core, along with coolant mass flow models, and a linear steam generator model. The model has further been improved by incorporating a pressurizer, a steam turbine, and a nonlinear model of the steam generator that allows the simulation to be performed over a wider power range [48].

The review of advanced core modeling and control in Ref. [49] provides a helpful categorization of the different model types, including point, single-dimensional, multi-mode, 3-dimensional, fractional, multi-model, and intelligent system identification approaches. Various approaches to power output regulation control are also discussed, along with approaches to load following control.

Software simulators for hybrid energy systems involving both nuclear and renewable energy parts are discussed in Ref. [50], with the focus on larger systems that include industrial processes. This work has also considered the properties of traditional nuclear fuel cycle simulators, and the relationship between and applications of the two types of analysis tools.

3.6. Instrumentation and control architecture

Another area of importance related to the integration of SMRs in microgrids is the need to develop new instrumentation and control (I&C) infrastructure [51]. While traditional NPPs are required to be operated by qualified human operators, several SMR designs consider scenarios for tele-operation. This is particularly attractive for deployment in remote locations. This places even more stringent requirements on the instrumentation and control systems for on-line monitoring and a higher degree of autonomous operation capabilities. Several key I&C issues for SMRs are identified in Ref. [52], including the need for additional self-calibrating in-vessel sensors, electronic signature analysis for fault detection/identification, remote monitoring and operation, and autonomous fault-tolerant control strategies. The need for SMR-focused I&C testbeds is also identified, which are essential for validating various new concepts, particularly with respect to how SMRs interact with other energy sources. Some initiatives to address the above topics have been commenced by the U.S. Department of Energy [53].

These new requirements will also call for an I&C architecture that can accommodate the complexity of these functions in an autonomous context. A high-level control framework for autonomous control of advanced reactors has been investigated recently [54], which also includes a discussion of key issues, such as automated decision making, that need to be investigated thoroughly before the automated operation of systems that include such reactors can become a reality.

4. SMR operation scenarios

To illustrate two approaches to SMR operation in a renewable energy microgrid, consider the ac microgrid configuration shown in Fig. 3, and the corresponding 24-h per-unit power profiles illustrated in Fig. 4. The load profile herein, P_{load}, exhibits morning and evening peaks in a typical residential setting. The illustrative solar (P_{pv}) and wind power (P_{wind}) outputs shown in Fig. 4 are based on recorded data, and vary due to changes in the weather conditions. Notably they do not match the load profile, as illustrated by the dashed line showing the difference between the electricity supply and the demand. Therefore, the PV and wind sources alone will not be able to meet the load demand, and additional power from controllable sources and/or storage are needed to maintain the supply/demand balance.

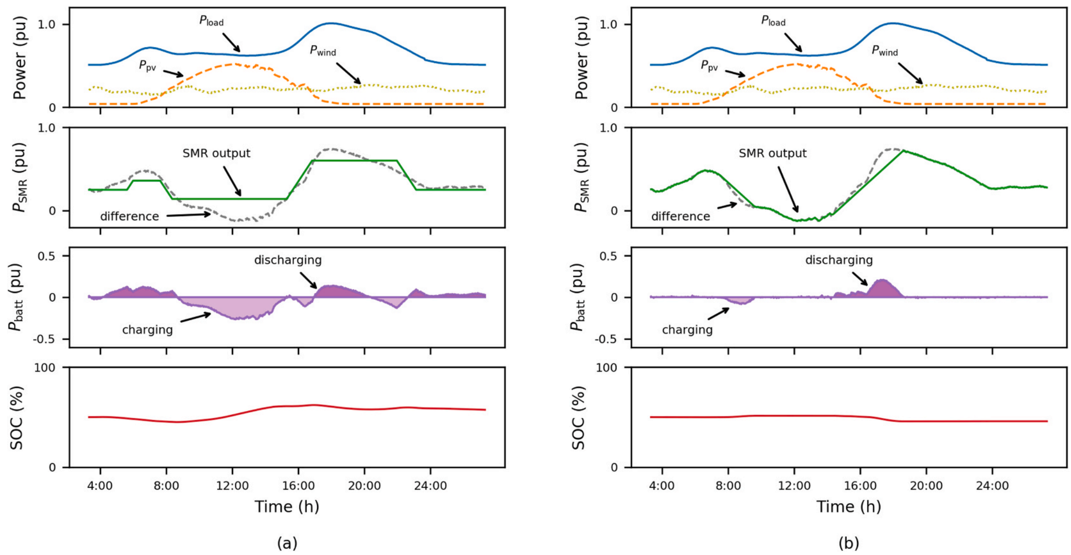

Fig. 4. Operation scenarios for a microgrid incorporating SMRs, renewable sources, and a battery energy storage system. (a) In the turbine-follows-reactor mode the SMR power level is ramped up and down to approximately meet the load demand and renewable resources, and the battery balances the short-term supply with the demand. (b) In the reactor-follows-turbine mode the SMR adjusts its output power to try and follow the changing load, and the battery is used to ensure that the ramp rate limits of the reactor are met.

When SMRs are introduced into the supply mix, one operating strategy, as illustrated by P_{SMR} in Fig. 4(a), is to have the EMS adjust the SMR power level setpoints to approximately follow the peak demands while operating in the turbine-follows-reactor mode. This maneuverability is, however, constrained by the physical and safety limits of the SMRs and depends on the accuracy of load predictions, and is therefore not able to precisely match the supply/demand difference on its own, especially when there is excess solar power production and the reactor lower power limit has been reached. In such circumstances, one option is to use a steam-bypass mechanism to quickly trim the turbine-generator power output without further adjusting the power output of the reactor itself.

An effective solution to the above issue is to use a relatively small capacity battery energy storage system to compensate for any remaining mis-matches between the demand and the supply, as shown in the P_{batt} plot in Fig. 4(a), where

$$P_{batt} = P_{load} - \left(P_{pv} + P_{wind} + P_{SMR}\right). \tag{1}$$

In this case, the battery charges whenever there is surplus PV power available, and discharges if the combined renewable resources and SMR outputs are unable to meet the total load demand. Sudden unexpected changes in the power balance are dealt with by the battery, which can react quickly as long as it is operating at an intermediate state-of-charge (SOC) level where it can both supply and absorb power as needed, as shown in the SOC plot in Fig. 4(a).

When operating in the complementary reactor-follows-turbine mode, the reactor tries to follow the net load demand, adjusting its power level to maintain the system frequency. When the rate of change exceeds the ramp rate of the reactor, the battery is controlled to maintain the power balance until the reactor responds, as shown in Fig. 4(b). This results in larger reactor power variations and less use of the battery than in the previous scenario.

5. Open issues

Incorporation of SMRs into renewable energy microgrids is an emerging area of research, and as such there are several open questions that need to be investigated in depth. Such research will be multidisciplinary in nature, attempting to address the electrical, thermal, nuclear, and information and control problems in a holistic way. The following topics are particularly important in the short term, with the earliest pilot projects planned for 2026.

5.1. Dynamic behavior of SMRs in microgrids

At the lower layers of the control hierarchy, the SMRs will interact with other components of the microgrid to effectively share the load demand and compensate for variations in renewable energy resources. While this interaction will make use of established control strategies, the degree of coupling between the SMRs and the power-electronic interfaced sources will need to be evaluated, and appropriate control approaches will need to be determined to ensure stability of the microgrid and power quality within the entire system. When thermal loads are considered, the coordination of the thermal and electrical sides of the system will need to be explored, including potential use of thermal storage subsystems.

5.2. Sizing of SMR/Renewable microgrid components

A fundamental design concern is the appropriate sizing of different elements in such a microgrid. For a given deployment scenario, such as a remote community, the nature of the load, solar, and wind profiles must be understood under a variety of weather conditions and for different seasons. With this information in hand, the optimal size of the SMR(s), the renewable power sources, and the required size of the storage subsystems can be determined. This type of analysis is well established in the microgrid field [55–57], but it must be extended to include the operational behavior and constraints of SMRs. Also, since the performance of an SMR changes over time, this aspect must be considered as well [58]. Where more than one SMR is to be deployed, the strategies for managing individual units, as well as interactions among different units, need to be considered, including approaches that combine fixed output units with load following units [59]. This sizing problem must also consider future scenarios to allow for introduction of new power generation technologies or reconfiguration of the existing sources as the load demand changes with time.

5.3. Remote operation of SMRs in microgrids

Finally, the demands for autonomous operation and minimal maintenance will require the development of highly reliable sensing and management solutions. These solutions will have to be validated for different design features on I&C testbeds that can run multiple simulated operating scenarios [52]. Several SMR designs include proposals for remote operation, and will therefore require remote monitoring technologies for detecting anomalies during system operation, diagnosing the causes, and accommodate them by either reconfiguring or shutting down the reactor if needed [54]. These proposed operating scenarios will have to be evaluated for both technical soundness and regulatory compliance, and will ultimately lead to the development of new standards and regulatory guidance.

6. Conclusions

Small Modular Reactors (SMRs) can be effectively used with renewable energy based microgrids to provide sustainable power sources for various applications, including supplying both electrical and thermal loads. It is concluded that SMRs have significant advantages for microgrid applications owing to their modular design and modular deployment to meet various power requirements of different applications. Their load-following capability allows them to compensate intermittency associated with renewable energy resources, which leads to a considerable reduction in the size of energy storage systems. Also, SMRs not only provide electrical power, but also thermal power for many different non-traditional applications, such as district heating, or desalination. In fact, these non-traditional thermal applications can be used as an energy buffer to assist in maintaining frequency and voltage on the electrical side of the microgrid. Furthermore, recognizing the fact that SMRs are still in their infancy, this paper has highlighted several key issues relating to unit sizing, real-time control and operation, the role of thermal processes in electrical power maneuvers, and coordination of other energy sources in the entire microgrid. Several open problems on integration of SMRs in renewable energy microgrids have also been highlighted as food for thought moving forward. However, no attempt has been made in this paper to be exhaustive in covering the existing literature on this subject.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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