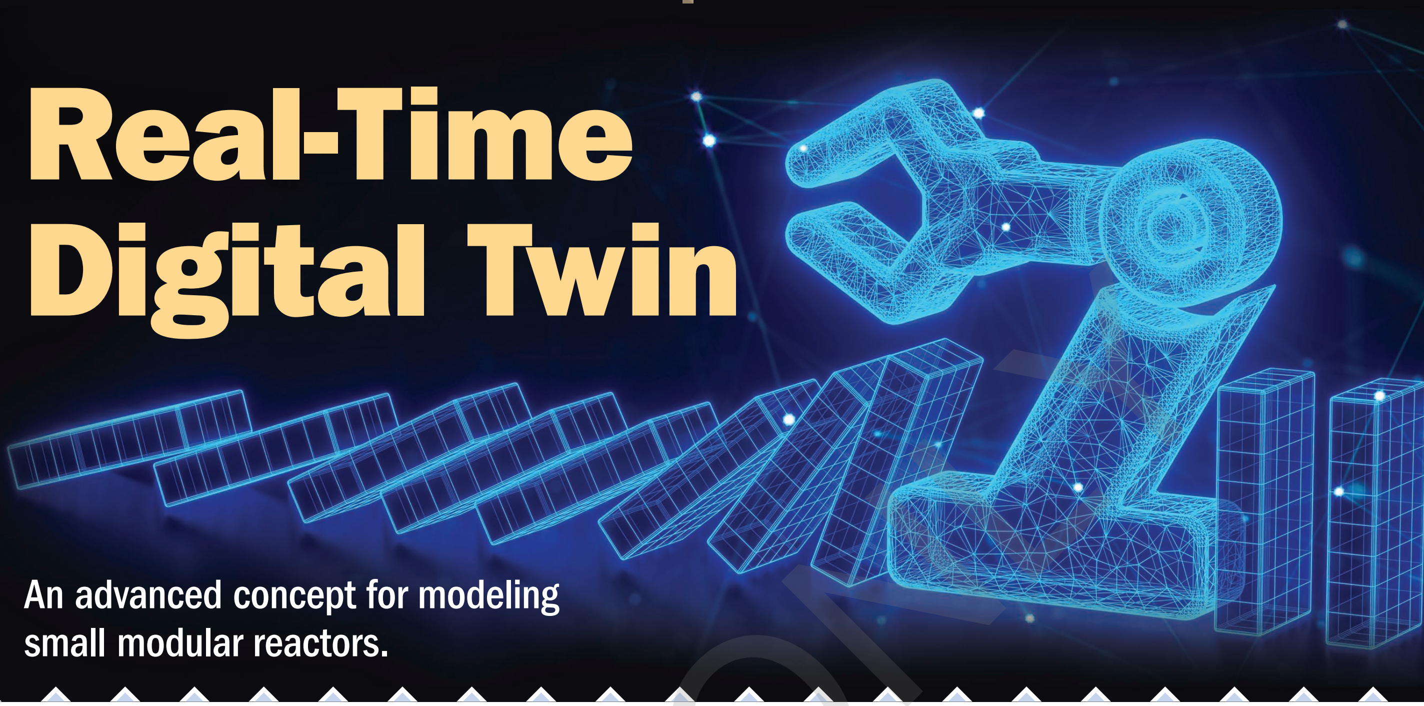
By Weiran Chen and Venkata Dinavahi

Real-Time Digital Twin

An advanced concept for modeling small modular reactors.



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SIMULATION AND DIGITAL TECHNOLOGIES are widely applied across industries, such as cyberphysical power systems, automotive, aerospace, maritime, defense, and nuclear energy. In the design phase of small modular reactors (SMRs), precise numerical simulation algorithms ensure that the neutron chain reactions within the reactor core are theoretically maintained within safe, stable, and controllable ranges. Accurate modeling of the core and other components enables visualization and dynamic monitoring of crucial physical subsystems like thermal hydraulics. During the operation and running phases of SMRs, offline simulations, real-time digital twin (RTDT) emulation, operational platforms, advanced human–system interfaces (HSIs), and instrumentation and control (I&C) systems play a crucial role in training and assessment. Additionally, through real-time monitoring and control, they provide effective protection, ensuring the stability, safety, and responsiveness of SMRs and associated facilities. In February 2022, the International Atomic Energy Agency (IAEA) hosted a conference on SMR I&C systems and computer security technologies, discussing challenges in modern SMR simulation and digital technologies. It was decided to initiate coordinated research projects on this theme, starting in 2024. Looking ahead, advanced nuclear simulation technologies are increasingly trending toward digitalization, intelligentization, integration, and automation. This article briefly introduces the origin and applications of SMRs and advanced digital technologies, and it presents a demonstration prototype design of an RTDT for SMR-based marine propulsion.

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From Concept to Deployment, From Macro to Micro: The Evolution and Future Prospects of SMRs

What is an SMR? Is it simply a miniaturized or downsized version of traditional large-scale nuclear power plants? Is it a prototype reactor meant to validate technological feasibility? The answer is definitely no. SMRs represent innovative reactors designed to provide energy in the range of tens to hundreds of megawatts, tailored to user needs and deployed in novel application scenarios with advanced technological features. In this section, the historical origins of SMRs are briefly outlined, along with the meanings of “small” and “modular.”

Around the year 2000, according to the global development history of nuclear technology, the International Forum on Generation IV Nuclear Reactors divided the evolution of global nuclear reactor technology into four stages, each referred to as a *generation*, as shown in Figure 1. Historically, the development of the first generation (generation 1) began in the 1940s to 1950s, the second generation (generation 2) started in the 1950s to 1960s, the third generation (generation 3) began in the 1980s, and the development of the fourth generation (generation 4) is estimated to begin in the 2020s. It is evident that mature nuclear reactor technology has already progressed through three generations. Currently, generation 2 reactors are supplying a significant amount of electricity worldwide, generation 3 reactors are mostly in the construction phase, and generation 4 reactors are in the research and development stage.

So, what exactly are SMRs (specifically referring to the recently hyped technical term, despite the fact that the concept may not have been new since the 1950s)? According to the authors' perspective, and based on the IAEA's Advanced Reactors Information System database, SMRs of the 2010s onward actually refer to generation 3+ advanced reactors primarily intended for civilian and commercial use, have an electrical output of less than 300 MWe, and are modular in design. Another piece of evidence or milestone event is from 2014, when the 13th edition of the "Utility Requirements Document" ("URD") was jointly released by the U.S. Department of Energy (DOE) and the U.S. Electric Power Research Institute, in which design specifications for small modular light-water reactors (smLWR) were first introduced; selected design specifications are given in Table 1.

SMRs represent innovative reactors designed to provide energy in the range of tens to hundreds of megawatts, tailored to user needs and deployed in novel application scenarios.

Therefore, roughly categorizing SMRs based on their power rating (<300 MWe) is inadequate or can lead to misunderstandings.

The term "small" in this article is understood to have three implications. First, it refers to reactors with an electrical output of less than 300 MWe, with those below 10 MWe often termed "microreactors." Second, in terms of scale, the literature suggests that they are typically between one-third and 1/10th the size of a large nuclear reactor. Third, it denotes the targeted energy market demands of SMRs, often catering to niche areas that large conventional nuclear plants cannot meet. Leveraging their flexibility, SMRs offer alternative power solutions for regions with underdeveloped grids or low electricity demand.

The term "modular," referring to modularization, is one of the most crucial concepts in advanced SMRs. The IAEA defines modularization by borrowing concepts from other well-established industries, such as shipbuilding, automotive, and aerospace, which are known for their highly industrialized technologies. This technique ensures manufacturing quality and improves efficiency through assembly line production, standardized components, and on-site assembly. This, in turn, enhances the safety and economic viability of SMRs. In the design phase, "modularization" refers to the segmentation of

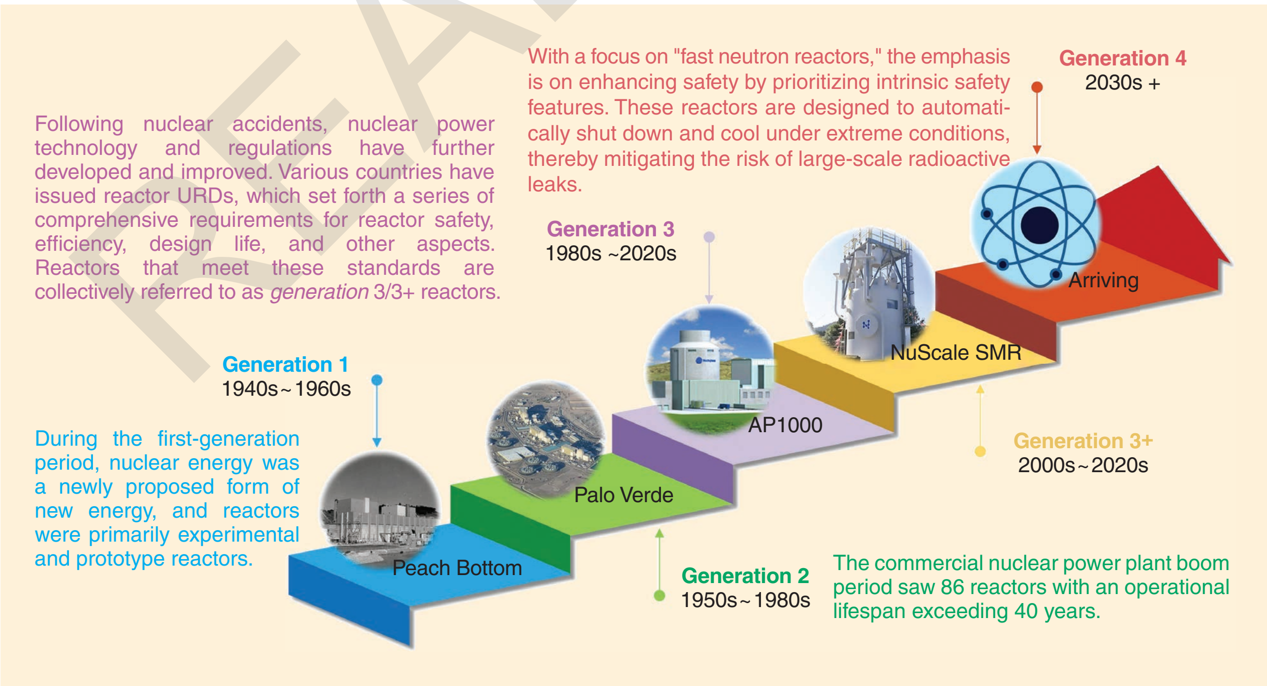

Figure 1. The generations of nuclear reactors.

components and structural designs into modules, making assembly and maintenance more convenient. For instance, certain SMR designs have already integrated various components of the reactor cooling system—such as the core, pressurizer, steam generator, and pumps—into a single reactor pressure vessel (RPV). By integrating these major components into the RPV, the need for large-diameter piping is eliminated, thus reducing the risk of a large-break loss-of-coolant accident. During the construction phase, "modularization" entails offsite fabrication and on-site assembly, which can shorten construction timelines and further enhance economic efficiency. At present, there is no comprehensive or mature modular manufacturing environment or standardized factory for SMRs, primarily due to the lack of sufficient practical and on-site experience and the absence of international unified standards. Additionally, the economic feasibility of investing in the construction of such factories is poor

TABLE 1. Design criteria for smLWRs.

Overall Design Requirements	
Power level	≤300 Mwe
Patented safety features	Passive system not requiring safety-class ac power
Lifetime	≥60 years
Design philosophy	Compact, high safety margin, factory manufactured
Safety and Investment Protection	
Accident resilience	• Thermal margin for fuel (the safety buffer between the operating temperature of the nuclear reactor fuel and the temperature at which the fuel may fail or be damaged): ≥15% • Employ suitable methods (e.g., increasing the total coolant volume) to extend the response time of the nuclear power system. • Utilize the best available materials.
Core damage resistance	Employ suitable methods to prevent core damage from initiating events.
CDF	The probabilistic risk assessment indicates that the CDF is less than 1×10^{-5} per reactor year^{-1}, and the emergency planning zone is limited to the site boundary (the defined perimeter around a nuclear facility, marking the limits of the property and the area subject to safety and security measures), which should include all reactor modules within the site.
LOCA resistance	Utilize integrated design to eliminate the possibility of large-break LOCA accidents.
Prevention of station blackout	At least 72 h and potentially indefinitely without external intervention
Operator actions	Under design basis accident conditions, including station blackout, ensure that core damage criteria are met for at least 72 h without operator action.
Power Plant Performance	
Design utilization efficiency	95%
Fuel replacement cycle	24 months
Unscheduled automatic reactor scram	Once per year
Operating modes	Daily load following
Load shedding	Full-power load shedding does not cause reactor scram or a turbine trip.
Radiation exposure	<100 rem year^{-1}
Design Process and Constructability	
Total duration (from owner's commitment to construction to commercial operation)	≤54 months
Construction time (from first concrete to commercial operation)	≤36 months
Starting design status	Complete 90% of the design.

CDP: core damage probability; LOCA: loss-of-coolant accident.
Retrieved from the U.S. "URD."

given the limited number of SMR orders. Up until 2020, most SMRs were deployed through on-site construction, with prototype test units being simultaneously tested to gain manufacturing experience.

The envisioned future for SMRs is promising, but it is crucial to actively seek a balance between technical feasibility and economic viability. In fact, small-scale pressurized water reactors (PWRs) have had over 70 years of research and use since Westinghouse Electric began developing submarine reactors in 1948. However, the concept of "SMRs" has only just started to become a hot topic since the 2010s. The reasons for this phenomenon include political factors, international dynamics, technical challenges, and economic considerations. Today, 18 countries worldwide have developed over 70 SMR designs, with an increasing number of regulatory documents being issued, as illustrated in Figure 2. Meanwhile, the IAEA is actively initiating efforts, calling on policymakers, regulators, designers, suppliers, and operators to establish standardized regulatory and industrial frameworks for SMRs. This aims to maximize the potential to achieve the 2030 Agenda for Sustainable Development and the goals of the Paris Agreement. Whether net-zero carbon emissions can be achieved by 2050 hinges significantly on the successful implementation of SMRs.

From Terrestrial to Extraterrestrial: Exploring the Versatile Applications of SMRs

The Microreactor

There is no international consensus on the concept of micronuclear reactors yet, but they are generally described in terms of power range and advanced technological features. Typically, SMRs with a thermal power of around 10 MW are referred to as *microreactors*, as summarized in Table 2. The technology utilizes inherently safe reactor designs from generation 4 non-LWRs, heat pipe reactors, and generation 3 LWRs to provide reliable energy for remote areas, bases, space missions, and deep-sea exploration.

Land-Based SMRs for Civilian Use

In the civilian nuclear power sector, there are over 70 SMR design proposals globally, but only a few have received

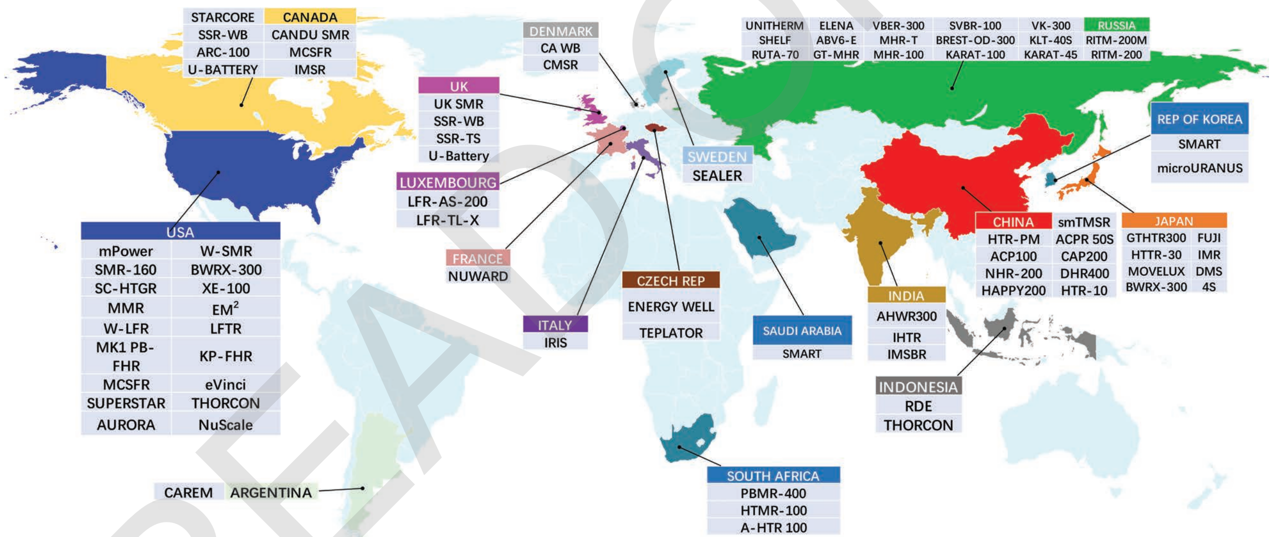

Figure 2. Global SMR technology development. (Source: IAEA Nuclear Energy Series, "Technology Roadmap for Small Modular Reactor Deployment," https://www-pub.iaea.org/MTCD/publications/PDF/PUB1944_web.pdf.)

TABLE 2. Typical international micronuclear reactors.

Name	Country	Reactor Type	Name	Country	Reactor Type
Micromodular reactor	United States	Prismatic-fueled high-temperature gas-cooled reactor	U-Battery	United Kingdom	Prismatic core high-temperature gas-cooled reactor
X-Battery		Pebble bed high-temperature gas-cooled reactor	MoveluX	Japan	Heat pipe reactor
eVinci		Heat pipe reactor	SEALER	Sweden	Lead-cooled fast reactor
Mega Power		Heat pipe reactor	AVR-6M	Russia	LWR
Very Small, Long Life, and Modular		Sodium-cooled fast reactor			

construction licenses, while the majority remain in the R&D phase. As previously discussed, the commercialization of SMRs for civilian use faces several challenges, including

- *Nuclear fuel R&D*: development of more efficient and longer-lasting fuels, such as high-assay low-enriched uranium
- *New structural materials*: requirements for higher corrosion resistance and high-temperature performance beyond water-cooled reactors
- *Advanced manufacturing technologies*: innovations in modular integrated industrial manufacturing techniques and standardized maintenance and repair methods
- *Nuclear fuel cycle*: addressing refueling, transportation, storage, and disposal challenges in remote locations
- *Site selection*: establishing effective regulatory frameworks and safety standards distinct from those for large nuclear power plants, among other issues.

The main parameters of international SMRs are reported in Table 3.

TABLE 3. Typical parameters of international SMRs.

Country	United States		Russia	China
Name	mPower	NuScale	KLT-40S	ACP100
Primary Loop Pressure	14.1 Mpa	12.8 Mpa	12.7 Mpa	15 Mpa
Primary Loop Temperature	320 °C	320 °C	316 °C	303 °C
Rated Thermal Power	500 MWt	165 MWt	150 MWt	385 MWt
Rated Electrical Power	150 MWe	45 MWe	35 Mwe	125 MWe
Design Life	60 years		40 years	60 years
Nuclear Fuel	Uranium dioxide			
Fuel Cycle Length	4 months	24 months	28 months	24 months

Space Nuclear Reactor Power

Currently, space power sources and propulsion technologies based on solar and chemical energy have reached their limits. Space nuclear reactor power, on the other hand, offers high power density, a long life span, strong environmental adaptability, and stable performance. Notably, unlike solar power, it can operate in deep space, shadowed regions, and without orientation toward the sun, allowing for compact designs. The IAEA's 2005 report "The Role of Nuclear Power and Propulsion in the Peaceful Exploration of Space" outlines the applicable power ranges and mission cycles for various space power sources [see Figure 3(a)]. It shows that space nuclear reactors can cover nearly all operational scenarios in terms of life span and power requirements. Currently, they are considered an alternative mainly for low-power (below the kilowatt level) long-duration missions, where radioisotope thermoelectric generators are the optimal choice. Figure 3(b) presents a schematic of NASA's nuclear thermal propulsion spacecraft. Nuclear energy will be widely utilized in various space missions, including deep space exploration, lunar and Mars missions, and Earth orbital applications.

Marine Nuclear Power Platform and Nuclear-Powered Vessels

A floating nuclear power plant is a marine nuclear power platform (MNPP) that integrates SMR technology with marine engineering. These platforms house SMRs on ships or floating platforms, offering flexibility in site selection and a certain degree of mobility. This allows them to provide power, steam, desalinated water, and

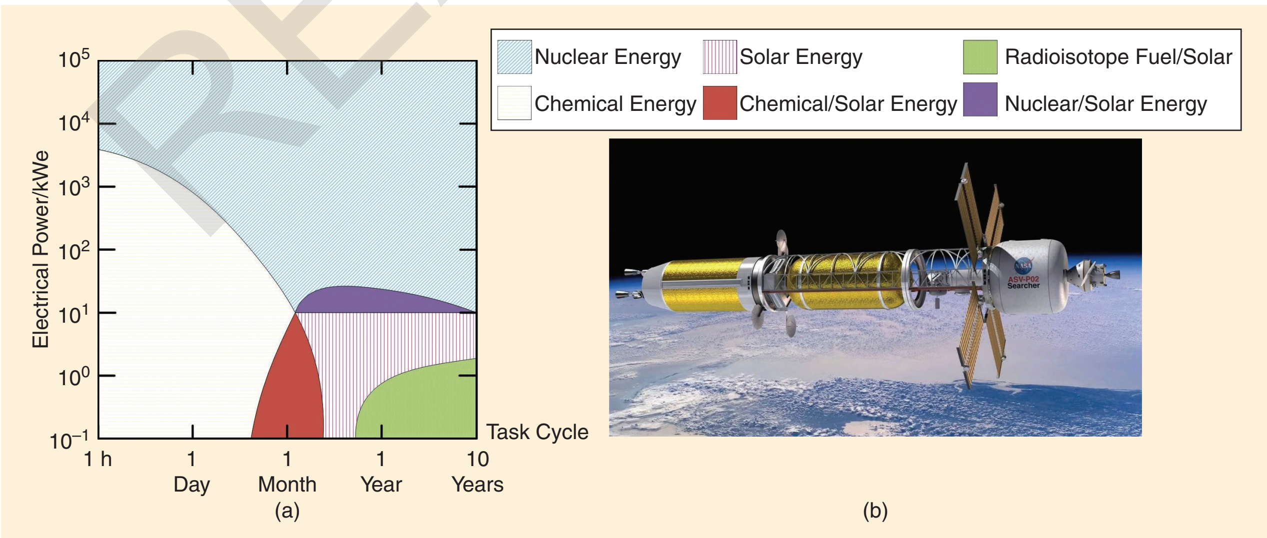

Figure 3. (a) The applicability of space energy sources and mission cycles. (b) A nuclear thermal propulsion spacecraft. (Image source: NASA.)

other energy solutions to remote islands and offshore work platforms. Their power systems utilize high-voltage high-capacity generators and connect to external systems via high-voltage submarine cables, forming an offshore power grid. Figure 4(a) displays the Russian Akademik Lomonosov, the world's first operational MNPP. Its technological development is based on the accumulated experience of nuclear-powered icebreakers, making Russian MNPPs predominantly of the barge type. In 2014, the Massachusetts Institute of Technology (MIT) proposed a cylindrical floating MNPP. France, inspired by submarine design principles, suggested a submersible MNPP, with the reactor placed 70 m deep on the seabed. South Korea introduced the concept of a gravity-based MNPP, using a floating dock-type reinforced concrete structure as the supporting platform, which represents a hybrid approach between land-based and offshore concepts.

Nuclear energy will be widely utilized in various space missions, including deep space exploration, lunar and Mars missions, and Earth orbital applications.

Another major application of SMRs is to provide power and energy for ships, widely used in both civilian and military fields as icebreakers, commercial vessels, aircraft carriers, and submarines. The power trains in these ships may use either saturated steam turbine gear units or steam turbine generator sets paired with electric propulsion devices. Each method has its advantages and disadvantages. The latter reduces the noise of the gear units, enhancing stealth and extending the effective range of the vessel's sonar system, though it increases weight and size. In addition to providing propulsion, SMRs support the ship's power needs with auxiliary diesel generator sets, converter units, and batteries, ensuring a power supply for lighting systems, desalination equipment, ventilation machinery, steering gear, anchor winches, and life support systems. Figure 4(b)–(d) presents examples of typical nuclear-powered ships.

From Blueprint to Deployment: Modeling, Simulation, and Operation for SMRs

The modeling, simulation, and analysis of SMRs primarily focus on the primary and secondary loop systems,

Figure 4. (a) Akademik Lomonosov, a Russian floating nuclear power station. (b) A Project 22220 icebreaker. (c) A *Columbia*-class nuclear submarine (USS *Columbia*, SSBN-826). (d) The *Charles de Gaulle*, a nuclear-powered aircraft carrier.

including components such as the reactor core, steam generator, pressurizer, turbine, condenser, and so on, as described in Figure 5. The fundamental operating principle is that heat is generated from neutron fission in the reactor core. The coolant, driven by the primary pump, circulates through the primary loop and enters the steam generator, where it heats the secondary loop water to produce superheated steam. This steam then drives the turbine to perform work. The following discussion provides a comprehensive overview of the main simulation and modeling methods for SMRs, along with advanced digital technologies used in these processes.

Numerical Computation of Reactor Core Physics and Other SMR Components

The physical processes within a reactor are intrinsically linked to the motion and spatial energy distribution of neutron populations, making the analysis of the neutron density distribution function critically important. Consequently, various models and analytical methods have been developed. For an individual neutron, its trajectory is random and chaotic until it is either absorbed or escapes the reactor surface. What is of primary concern is the macroscopic expected distribution of neutron density at different points in space. The fundamental equation governing this distribution is known as the *neutron transport equation* (NTE). This is a first-order partial differential–integral equation describing the neutron density $n(r, E, \Omega, t)$, where $r(x, y, z)$ represents the spatial coordinates, E is the energy, $\Omega(\theta, \phi)$ denotes the neutron direction of motion, and t is time, given as

$$\frac{1}{v}\frac{\partial\psi}{\partial t} + \Omega\cdot\nabla\psi + \Sigma_t(r,E)\psi = \left\{\int_{4\pi} d\Omega' \int_0^{\infty} dE' \Sigma_s(r, E' \to E, \Omega' \to \Omega)\psi(r, \Omega', E', t) + S(r, \Omega, E, t) + Q_f(r, E, \Omega, t)\right. \quad (1)$$

where v is the neutron velocity vector, angular neutron flux $\psi = \psi(r, E, \Omega, t)$, $S(r, \Omega, E, t)$ is the neutron source term, and $Q_f(r, E, \Omega, t)$ is fission reaction-induced production rate. Even under steady-state condition, the complexity and heterogeneity of the geometry and structure in practical problems make it nearly impossible or extremely difficult to obtain an exact solution to this equation. Consequently, approximate methods are often employed to solve practical computational problems. Nowadays, numerical discretization methods and their corresponding software/hardware programs and platforms have

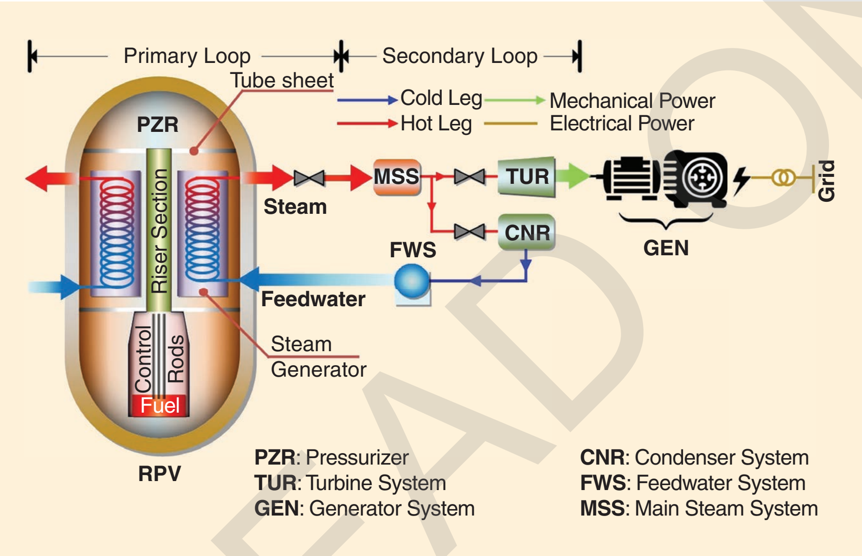

Figure 5. The integral PWR.

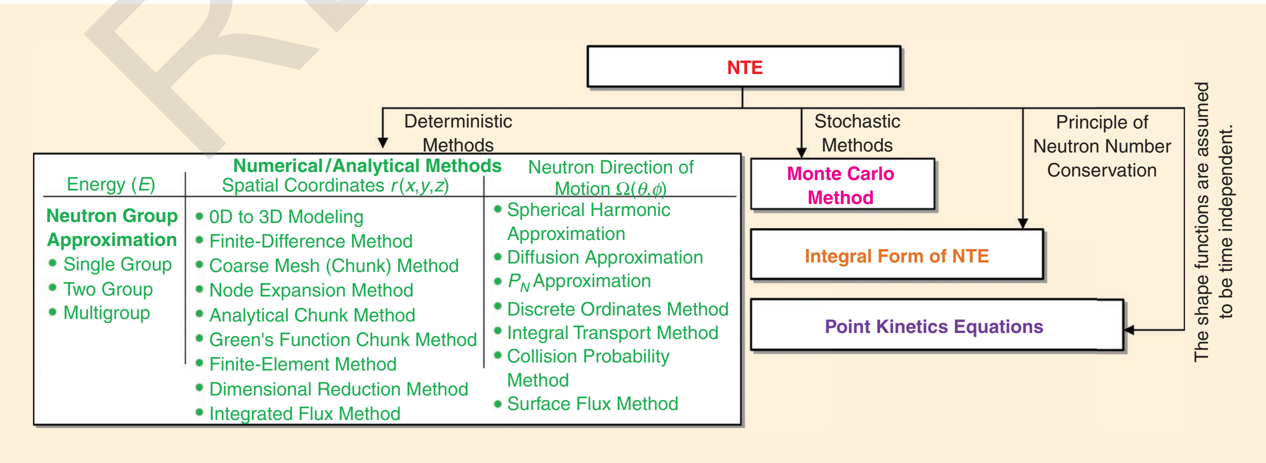

Figure 6. Core modeling and numerical calculation methods.

become indispensable tools and techniques for reactor physics design. There are numerous methods for solving the NTE. A brief introduction to these methods is as follows (see also Figure 6):

- *Integral form of the NTE*: Based on the principle of neutron conservation, an integral form of the NTE can be derived from a different perspective. Mathematically, it is equivalent to the differential form. Generally, the integral form of the NTE is less commonly used because the differential equation is easier to solve numerically. However, for specific physical problems, such as the calculation of heterogeneous lattices and fuel assemblies, the integral form can be more straightforward and accurate.
- *Deterministic methods*: These methods involve establishing a definitive mathematical model to describe the physical properties of the problem. They can yield exact or approximate solutions to the NTE. These methods discretize and approximate the variables E, Ω, and r, utilizing approaches such as the finite-difference method, nodal expansion method, analytic nodal method, coarse mesh finite-difference method, two-group diffusion approximation, and finite-element methods, among others. Specifically, the point reactor kinetics equations represent the simplest reactor dynamic model equations. Although they cannot capture spatial effects during transient processes, they can quickly provide an "overall" or "average" estimation of neutron flux density or power. Therefore, they are the most convenient and important equations when discussing reactor dynamics and power transients, playing a crucial role in reactor safety analysis and control.
- *Stochastic methods*: This is an important branch of computational mathematics that solves mathematical problems through random simulations and statistical trials. The most renowned stochastic method is the Monte Carlo (MC) method, also known as the *random sampling technique* or *statistical trial method*. It is particularly suited for solving physical phenomena that are inherently stochastic, such as particle transport problems. In nuclear reactor physics, the MC method is primarily used for calculating neutron and γ-photon transport or shielding in systems with complex materials and geometries, where deterministic methods are often challenging to apply.

For dynamic simulation of other parts of the SMR, such as reactor thermal hydraulics, Mann's model is widely used to represent the thermodynamics of the reactor core. This model employs two well-stirred coolant lumps for each fuel node to describe the processes of heat generation and transfer. It is also referred to as the *nodal model*, where one fuel node and two coolant nodes are considered. Regarding steam generators, U-tube steam generators and helical coil steam generators are commonly used among SMRs. For components such as condensers and throttle units, which involve mechanical and electrical aspects, macroscopic energy distribution or long-term simulations can be approximated using inertial elements or transfer functions. This is because their time inertia constants are relatively small compared to thermodynamic processes. However, in special cases, such as under fault protection scenarios, more detailed modeling may be required. Interested readers can refer to the "For Further Reading" section for more information.

Advanced Computer Simulation Technologies: Existing Offline Simulation Tools

Apros Nuclear

This is a multifunctional reactor simulation software jointly developed by the Finnish National Academy of Sciences and Fortum. Its core consists of 1D and 3D real-time core neutron models based on the two-group diffusion equations, allowing for the creation of corresponding core models according to different reaction cross sections. The software can also simultaneously calculate the concentrations of important isotopes, such as Iodine, Xenon, Radium, and Promethium. Additionally, it can be coupled with thermal hydraulic models to consider fuel rod temperature, coolant density, coolant void fraction, and control rod reactivity during core transients.

GSE Systems

This company provides educational and simulation services for industries including nuclear energy, fossil power utilities, chemical engineering, and petrochemicals. Its Real-Time Multi-Group Advanced Reactor Kinetics model is a 3D time-dependent two-energy-group diffusion theory model that meets the industry's real-time simulation needs. It employs a core discretization scheme instead of a nodal method, using coarse grids in the x, y, and z directions to describe the core geometry. An advanced thermal hydraulic code for real-time simulation applications, THEATRe, is also offered by the company. This code can simulate and analyze the primary loop system and the steam generator.

WSC

This company has developed the 3KEYMASTER real-time simulation software, which is widely used for core modeling, thermal hydraulic analysis, and severe accident modeling. It provides powerful graphical workstations and real-time simulation support systems. Additionally, it integrates the Severe Accident

Analysis Program MELCOR code from the U.S. Nuclear Regulatory Commission and the reactor transient analysis program RELAP-3D developed by the Idaho National Laboratory.

IAEA

To support the human resource development of its member states, the IAEA has established educational and training programs in nuclear technology, providing member states with basic nuclear reactor simulation software, data, and technical manuals. Among these resources is an integral PWR (iPWR) simulator, developed in 2017 with technical support from Tecnatom. This simulator can model various fault transient events, power changes, reactor scrams, and other operational conditions.

Other Simulation Software

OpenMC

Developed collaboratively by MIT and the open source community, OpenMC is an MC software capable of modeling complex reactor cores. It offers numerous convenient interfaces, supports input written in Python, and allows for both distributed and shared memory parallelism.

ATHLET

Codeveloped by the Karlsruhe Institute of Technology and Shanghai Jiao Tong University, ATHLET is capable of transient safety analysis for small modular natural circulation lead-cooled fast reactors.

SAS4A/SASSY-1

Developed by Argonne National Laboratory, this software has established a primary loop system model for the European Lead-Cooled Training Reactor.

In addition to the advanced simulation software mentioned above, numerous other simulation tools developed by laboratories, universities, and industries exist but are not detailed here. Several of the simulators mentioned are illustrated in Figure 7.

Advanced Digital Technologies

The innovative design of SMRs also relies on advanced HSIs and I&C systems. To facilitate deployment in remote areas and reduce the number of on-site personnel, continuous and reliable remote monitoring, secure communication between the site and support centers, and automation are essential. Intelligent remote supervision, control, and maintenance are also heavily dependent on advanced digital technologies and hardware support.

Artificial Intelligence and Machine Learning

Artificial intelligence (AI) technologies significantly improve the efficiency of managing complex systems and fault scenarios in nuclear facilities. AI can enhance fault detection and diagnosis by enabling timely interventions

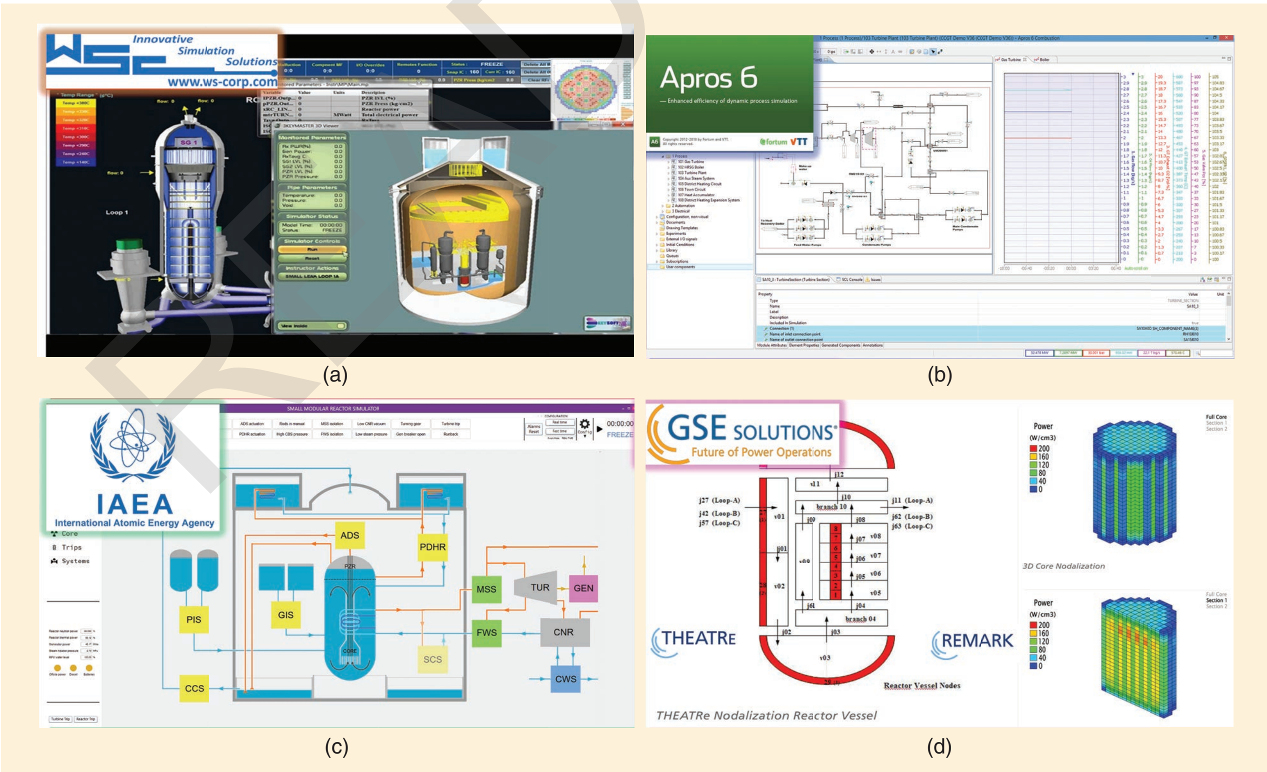

Figure 7. Advanced simulation software for SMRs. (a) WSC simulation software. (b) Apros simulation software. (c) Main page of IAEA's iPWR simulation software. (d) GSE simulation software.

through system training and predefined response plans. Meanwhile, machine learning (ML) techniques use big data to rapidly predict future trends in critical parameters and system outputs. Over the years, the nuclear industry has aimed to optimize complex functionalities and increase operational efficiency by integrating digital simulations of nuclear facilities and AI systems. However, this approach also introduces potential risks, such as vulnerability to cyberattacks, where manipulated data could lead to faulty AI decision making.

The goal of modernization and digitization is to replace outdated analog technology to enhance the functionality and safety of nuclear power plant operations.

DTs

In various industries, alliances, academia, and research fields, many different definitions of DTs have been developed. According to the definition of the IEEE Power & Energy Society, a DT is a high-fidelity visual and virtual representation of a physical system and its underlying characteristics and operational state. It enables users to understand the current system and predict its behavior under different scenarios/conditions, taking into account the context. DTs can be either online (real-time) systems for operational purposes or offline systems for planning, with each type requiring different information dimensions and levels of detail. A virtual representation of any system may include multiple information dimensions, such as real-time and historical data, physical models, attributes, structural models, and environmental datasets. DT platforms allow users to conduct simulations and build AI/ML models by leveraging multidimensional information (both structured and unstructured data), providing a comprehensive understanding of the impact of each scenario on the system and potential cascading effects.

DT technology enables real-time monitoring and management of the physical systems of nuclear power plants and SMRs, simulating the impact of various factors on their operation. DTs overcome the limitations of most existing nuclear power system analysis and simulation tools, which are often restricted to specific dimensions within specialized software applications. They allow for cross-domain simulations, including structural, maintenance, protection, temporal, and network aspects, providing comprehensive multidimensional analysis. By integrating and executing various simulations and cosimulations, DTs can assist decision makers in gaining deeper insights into the behavior of nuclear power and SMR systems, predicting potential cascading effects, and optimizing operational and maintenance strategies. Moreover, a mature DT architecture can achieve vendor-independent modular design through open standards, offering scalability to meet the evolving needs of the nuclear power and SMR sectors.

Many applications of DTs are highly dependent on the quality of input data, system maturity, architecture, and organizational requirements. To effectively leverage DTs, organizations need to understand the requirements, limitations, and maturity of different DT products, enabling them to develop effective IT and operational technology strategies. The maturity of DTs can be categorized into five stages:

1) Descriptive twins provide real-time design and construction data.
2) Informative twins integrate sensor data to offer more contextual information.
3) Predictive twins use data to forecast future events.
4) Comprehensive twins can simulate "what-if" scenarios.
5) Autonomous twins assist in real-time decision making (for more information, see "For Further Reading").

More mature DT architectures can seamlessly connect physical and digital environments and achieve vendor-independent modular design through open standards, allowing them to adapt to the evolving and changing needs of the nuclear power and SMR fields.

Advanced HSI and I&C Systems: Hardware-in-the-Loop Real-Time Emulation

Using simulation instruments for testing control instruments, control algorithms, and embedded systems; verifying human–machine interfaces; and training and certifying licensed reactor operators is referred to as *hardware-in-the-loop (HIL) real-time simulation* and *operator in the loop*. Simulator hardware includes a host computer, operator workstation, network switch, control rod operating system, and a large human–machine interface (HSI) display panel. The simulator serves as a dynamic test bed for testing and validating the control logic of the reactor regulating system. Platforms that implement real-time reactor kinetics and thermal hydraulics mathematical models are often developed using LabVIEW, field-programmable gate array (FPGA), or other embedded parallel hardware operating systems, interacting with the host through human–machine interfaces to manage user commands. The dynamic test bed runs and displays plant dynamics in real time based on reactor detection signals. Figure 8 depicts the Human Systems Simulation Laboratory (HSSL) at Idaho National Laboratory, established by the

DOE, which is a full-scale virtual nuclear control room. It is widely recognized in the industry that fully modernized control rooms, improved design, and digital upgrades are essential to achieving the highest safety goals. The HSSL includes state-of-the-art glass-top touch panels. These virtual controls are fully reconfigurable to replicate the control room of any operational nuclear reactor. The displays can emulate hundreds of analog control boards, allowing real nuclear operators to interact with them. The goal of modernization and digitization is to replace outdated analog technology to enhance the functionality and safety of nuclear power plant operations.

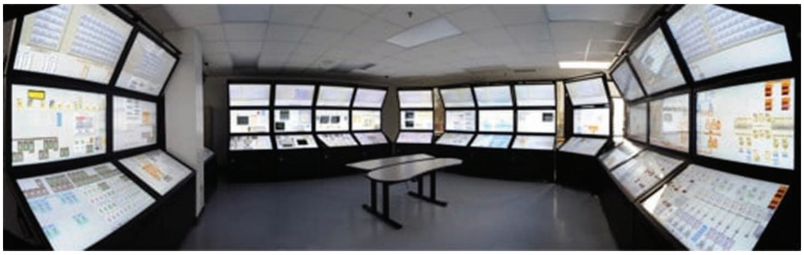

Figure 8. The full-scale layout of the Human Systems Simulation Laboratory glass-top simulator. (Source: Idaho National Laboratory.)

Another representative of the new digital technologies that began to gain prominence in the 2020s is DT. A DT is a high-fidelity visual and virtual representation of a physical system, capturing its fundamental characteristics and operational states. It enables users to understand the current system in context and predict system behavior under various scenarios and conditions. A DT combines real-time simulation, offline planning, and AI/ML models to predict system behavior, leveraging multidimensional information to comprehensively understand the impact of different scenarios on the system and potential cascading effects. Recently, DTs have been widely applied in fields such as power systems and industrial automation. In the nuclear energy field, researchers have begun developing DT-based fusion energy research platforms to conduct efficient virtual simulations and assess the state of plasma and magnetic coils.

Demonstration Example: RTDT HIL Emulation for SMR-Based Marine Propulsion

An RTDT HIL FPGA-based emulation platform for an SMR-based marine propulsion system is demonstrated in this section as a learning example. This design pertains to the prototype testing simulator for SMR RTDT emulation, ultimately achieving a simulation speed that is 12.5 times faster than real time. This enhanced simulation capability provides engineers with an efficient tool for validating control algorithms, operating conditions, and fault prediction. Due to space limitations, further details can be found in Chen et al. in "For Further Reading." The electrical system and the SMR make up the two primary parts of the model. An iPWR-type SMR with a 150-MWth/45-MWe nonlinear 25th-order mathematical model is included in the SMR. Table 4 lists the parameters that were taken from the IAEA's iPWR simulation program. A hypothetical open access real-time 12-kV medium-voltage dc (MVdc) shipboard power system (SPS) simulation benchmark is chosen and modified for the electrical system in order to integrate with the suggested SMR model. This benchmark was created by RTDS Technologies using Simulink/Speedgoat.

The offline simulation of the entire model is built on Simulink, as demonstrated in Figure 9(a), while the system consists of two zones, including

1) *Power generation*:
   - *Number 1 power generation module (PGM)*: SMRs, synchronous machine (SM), and ideal ac–dc rectifiers
   - *Number 2 PGM*: ideal dc power
2) *Power distribution*: cable sections, ideal switchboard, and ideal dc–ac inverter
3) *Load*: power conversion module and propulsion motor module (PMM).

The SMR generates mechanical power and drives the SM to produce electricity. And then the SM feeds back the rotor speed to the governor to regulate the output thermal power of the SMR, thereby adjusting the output electrical power and frequency at the ac terminal to vary with changes in the load. For the modeling of the modular multilevel converter (MMC), the arm level-averaged MMC model is utilized, which approximates submodules.

TABLE 4. Thermal hydraulic parameters of an iPWR.

Thermal Hydraulic Variable	Value	Unit
Pressure vessel	80.78	Cubic meter
Pressurizer	8.078	Cubic meter
Average liquid density	746	Kilograms/cubic meter
Average steam density	102.8	Kilograms/cubic meter
Thermal power	150	Megawatt thermal
Generator power	45	Megawatt electrical
Pressurizer pressure	15.5	Megapascal
Steam pressure	2.7	Megapascal
Cold leg temperature	255.51	Celsius
Average coolant/core temperature	287.5	Celsius
Hot leg temperature	320.36	Celsius
Saturation temperature at 15.5 MPa	344.8	Celsius
Average fuel temperature	849.84	Celsius

During the switching period, the MMC arms are ideal coupling dependent *V-I* sources. A regulated current source represents the SMR–SM–MMC integrated model's loading terminal. An *RL* two-port network can be used to simplify the two-zone MVdc SPS power distribution system. An average-value dc–ac inverter is used for the PMM, which uses space vector pulsewidth modulation to transfer power to the permanent magnet synchronous motor (PMSM).

This design is mainly implemented in C language on Vitis HLS. The main idea of using high-level synthesis (HLS) is to utilize software-based languages, along with rich software libraries, to develop hardware modules, which significantly accelerate the development process and simplify the design. Through HLS function synthesis and interface synthesis, the top-level function is synthesized into a hardware module, which includes a body that implements the module's task and a set of input–output (I/O) ports for exchanging data. Each port has an associated protocol attached to its interface that implements its communication mechanism. The generated packages or intellectual property (IP) cores would be imported in Vivado design suit software for logic synthesis and then bitstream generation based on hardware description language.

The hardware configuration appears in Figure 9(b). The Xilinx Virtex UltraScale+ VCU118 Evaluation Platform (part number xcvu9p-flga2104-2L-e) in Vivado was used to implement the IP core of the model created by HLS. With 6,840 digital signal processors (DSPs), 2,364,480 Flip-Flops (FFs), and 1,182,240 lookup tables (LUTs), this FPGA board provides the full model implementation without requiring any extra hardware. The DSP, FF, and LUT utilization rates are 7.1%, 2.5%, and 5.4%, respectively. The system clock frequency was adjusted to 300 MHz. It is estimated that the floating-point arithmetic results are updated every 769.23 ns, based on the longest path's delay. One cycle buffering is included to provide stable data reception; this leads to a data update time of about 800 ns. In terms of the I/O, data are sent to DAC34H8 via the FPGA mezzanine card - digital-to-analog adapter in double-data-rate mode after converting IEEE 32-b single-precision floating-point numbers to 16-b signed hexadecimal numbers. Waveforms are then displayed on an oscilloscope. Once the necessary I/O pins have been configured, Vivado on the host computer generates the bitstream, which is then downloaded to the target FPGA via USB–Joint Test Action Group to finish the design.

The real-time emulation aims to validate the system's real computational speed, following the Simulink/Speedgoat electric ship real-time emulation benchmark, with a 30-s offline simulation time, with $h = 10\ \mu s$, involving full-speed-ahead and crash stop operation. This test scenario aims to assess the behavior of the driver during quadrant 2 regeneration, as depicted in Figure 10(f), where a stylized piecewise linear torque–speed curve is illustrated, highlighting an incursion into quadrant 2 during the crash stop maneuver. Figure 10(a)–(e) shows real-time oscilloscope emulation waveform captures. The upper and lower subscreens, respectively, show a magnified view of a particular section in a 1:1 ratio and the entire emulation waveform for one full cycle. With a 3-s/division offline simulation time the *x*-axis scale, the emulation time of the upper subscreen depicts the mapping of the 30-s offline simulation time. To ensure clarity and conciseness, the term "time" used from now on refers to the offline simulation time.

During initialization, the SMR is assumed to operate at the rated power, and then the simulation begins. During the time interval 0~5 s, the ship remains stationary, resulting in almost zero power consumption. In Figure 10, it can be observed that for approximately the first 1.8 s, due to

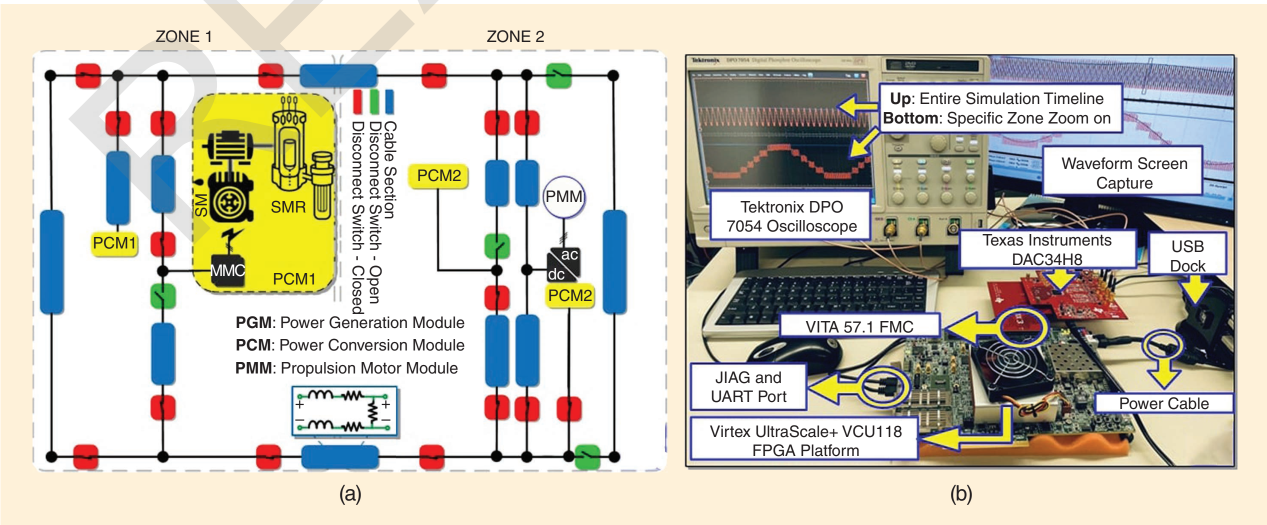

Figure 9. (a) A modified conceptional two-zone MVdc SPS equipped with an SMR. (b) An SMR RTDT on an FPGA prototyping platform. JTAG: Joint Test Action Group; UART: universal asynchronous receiver–transmitter.

the larger thermal time constant and the presence of hysteresis control, there is little variation in ρ, n, and temperature. The reactor output power is regulated by the turbine, and as y rapidly decreases, P_m also decreases. Meanwhile, P_s increases since the thermal power remains nearly unchanged. Subsequently, the SMR controller takes action, introducing negative ρ and causing a rapid decrease in n. As a result, the fuel temperature decreases, while the coolant temperature rises. Due to the inherent islanding nature, the system is operated based on the droop control and powered by PGM1 and PGM2. As a result, the output power of the SM in PGM1 decreases, and the frequency of the ac portion increases to approximately 1.076 per unit.

At 5~15 s, P_e increases to 0.45 of the rated power, while the ac frequency decreases and eventually stabilizes at approximately 1.05 of the rated frequency. Although there is some lag in the turbine's mechanical power output, it still manages to stably follow the SM's demand. As a result, ρ increases, leading to an increase

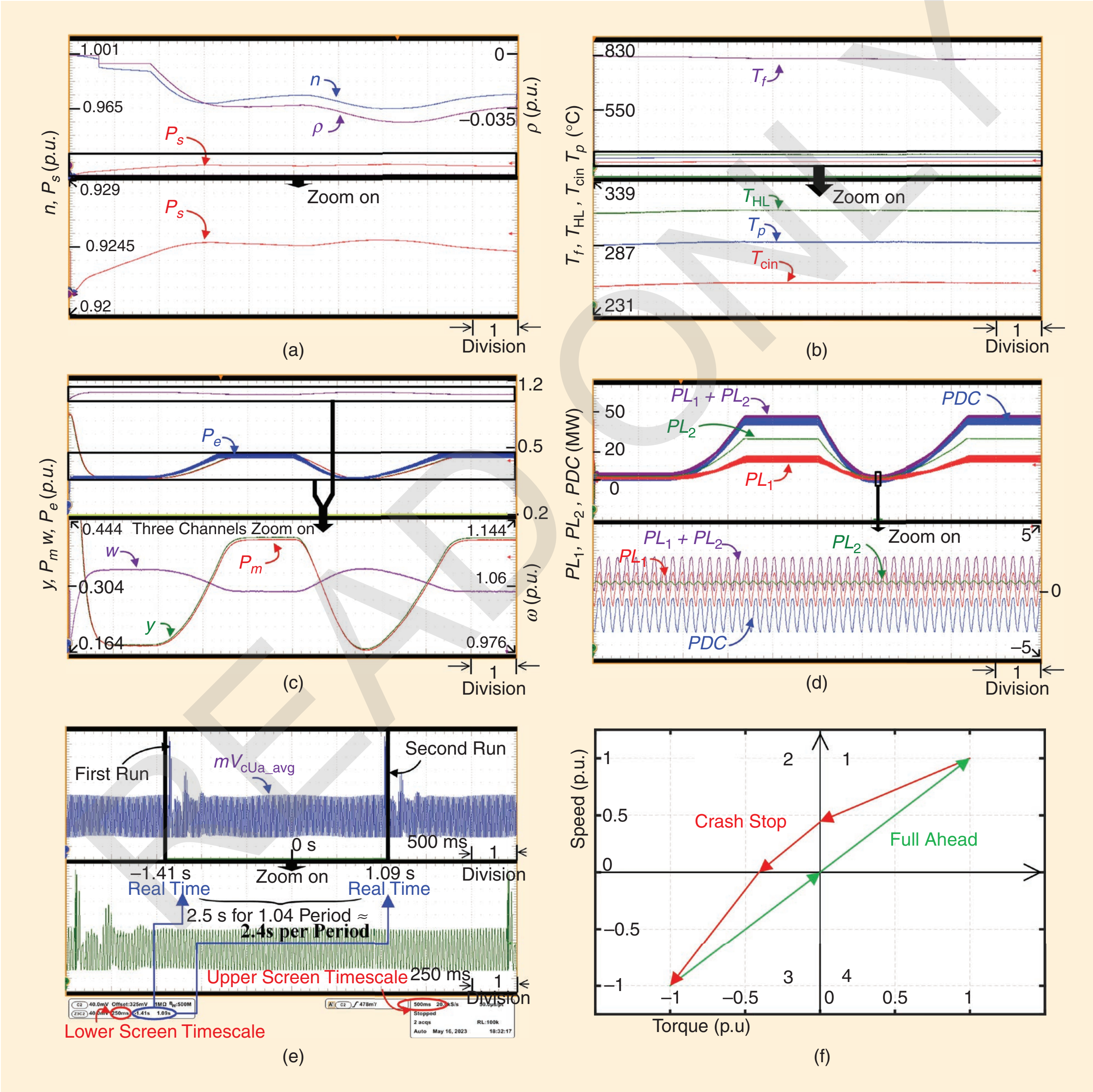

Figure 10. (a)–(e) RTDT emulation oscilloscope results with the entire emulation period (top) and a zoomed-in view (bottom). (a) The SMR's mean prompt neutron density n, the core reactivity ρ, and steam pressure P_s. (b) The SMR fuel, coolant in the hot leg, cold let, and in steam generator temperature T_f, T_{HL}, T_{cin}, and T_P. (c) The SMR valve position y, output mechanical power P_m, SM rotor speed w, and active power P_e. (d) The PMSM power PDC, PGM1 dc power PL_1, and PGM2 dc power PL_2. (e) The FTRT emulation. (f) Test scenarios. Real-time x-axis scale: top: (a)–(d): 240 ms/division; bottom: (a)–(c): 240 ms/division; (d): 2.4 ms/division. Real-time span of oscilloscope capture: top: (e): 2.4 s; bottom: (e): 12 ms. p.u.: per unit.

in n and a decrease in P_s. According to the design, the droop ratio between PGM1 and PGM2 is 2:1. As can be seen from Figure 10(d), PL_2 provides approximately twice the power compared to PL_1, and the combined power of both can stably meet the power requirements of the load.

At 15~30 s, the ship performs a crash stop maneuver. During approximately 18~20 s, the driver operates in the second quadrant. By examining the zoomed-in subscreen in Figure 10(d), the motor is observed to consume negative power, indicating regeneration. This confirms that the design functions correctly. For SMR dynamics, during the forward deceleration stage, as PDC and P_m diminish, the valve y opening contracts, leading to a reduction in steam outflow. This decrease in steam outflow contributes to an elevation in internal pressure P_s, consequently causing a decline in the output thermal power n. In the reverse acceleration stage, as PDC and P_m escalate, the opening of the valve y enlarges, contributing to a decrease in internal pressure P_s, subsequently leading to an augmentation in n. In the steady-state operation stage, PDC, P_m, and y remain constant. Due to the larger time inertia constant, P_s and n exhibit a stable trend. During the entire full-speed/crash stop period, the presence of average coolant temperature control ensures minimal fluctuations in the temperature T_f, T_{HL}, T_P, and T_{cin}.

Since the offline simulation time is 30 s, with $h = 10\,\mu$s, it can be calculated that 3 million calculations are needed to obtain the entire simulation waveform. Next, the validation of the emulation time used proceeds, where “time” refers to real time. Figure 10(e) demonstrates the actual operation time and scale, with the lower subscreen showing the time interval between two operating cycles, approximately 2.4 s. Considering the calculation latency of this design, each data update takes approximately 800 ns, and the total calculation time of 3 million iterations amounts to about 2.4 s. Thus, it can be confirmed that this design achieves an acceleration ratio that is approximately 12.5 times faster than real time. This achievement demonstrates the effectiveness and efficiency of the proposed emulation platform and its practical applicability, providing valuable insights and practical solutions for nuclear-related studies.

Conclusions

SMRs hold vast potential for application and possess irreplaceable advantages over other energy sources, making them a critical support infrastructure for achieving national strategic goals. In light of the aforementioned summaries and discussions, the following prospects for the development of SMRs are proposed:

1) Strengthen intelligent operation management by leveraging big data, intelligent, and digital-twin technologies to enhance the performance of nuclear power plant operations. This includes optimizing and controlling the entire nuclear power operation process to ensure more stable and safer operation, reducing the probability of unplanned shutdowns and shortening maintenance times.
2) Aim for the early deployment of third- and fourth-generation nuclear power. This entails actively and systematically developing nuclear power, strengthening international cooperation and the exchange of cutting-edge technologies, and working together to address bottleneck issues to make SMRs standardized and economical.

For Further Reading

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