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Review

Technological Developments in Control Models Using Petri Nets for Smart Grids: A Review

Jose Ulises Castellanos Contreras [1,*] and Leonardo Rodríguez Urrego [2]

1 Engineering Faculty, Cooperative University of Colombia, Av. Caracas #63-04, Bogotá 110311, Colombia
2 Engineering Faculty, EAN University, Carrera 11 #78-47, Bogotá 110221, Colombia; lrodriguezu@universidadean.edu.co
* Correspondence: jose.castellanos@campusucc.edu.co; Tel.: +57-3004310840

Abstract: Nowadays, energy generation systems that include renewable energies, substations, distribution, transmission, control, measurement, and storage applications, among others, and are interrelated are known as Smart Grids. All these techniques and technologies involve extensive research and development, which allows for the solving of key aspects, such as control, diagnosis, and fault recovery, as well as communication systems focused directly on the operation of the electrical networks. Due to the relevance of knowledge concerning developments in these areas of Smart Grids, this paper presents a review of the research related to the control systems applied to Smart Grids and Micro Grids, both in supply and demand. Likewise, some control models relate to different processes, with a special focus on techniques related to Petri nets. The paper shows, among other outcomes, the advances in the control of smart grids, the types of generation and their influence on the design of transmission lines, integrated circuits applied based on sensors, communication technologies, and automation schemes in all levels of the electrical network. Finally, patents from 1950 to 2019 related to Smart Grid in energy systems are traced and presented.

Keywords: smart grids; renewable energy; control systems; Petri nets

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1. Introduction

Today, large urban centers and their population growth trends have resulted in an increased demand for basic resources such as water and energy for our current and future societies. This makes the need to supply primary resources in quantity and quality a priority, strengthening research and innovation into the development of new technologies that allow the private and public sectors to meet these needs [1]. This need to make the management of electrical energy more efficient has encouraged countries to develop research in traditional systems, starting from generation, distribution, and delivery to end-users. These developments have improved energy generation systems, including technologies associated with renewable energies, substations, distribution, transmission, and storage, among others. These developments caused the appearance of subsystems related to energy that were not essential before, but with the current demand, they will be necessary for the correct monitoring and control of the same networks, among which are the systems for measuring large volumes of data, comprehensive management, intelligent control, and expert systems. All of the above is based on the need to transform electrical networks into Smart Grids [2].

Worldwide, the trend is toward conducting pilots, implementing regulations, and designing Smart Grid models, seeking a diffusion of technology and greater research. Definitions, programs, pilots, and other initiatives are part of these strategies. For example, the Smart Grids European Technology Platform "EARPA" defines a Smart Grid as an "electrical network that can intelligently integrate the actions of all users connected to it; generators, consumers and those who integrate both; to efficiently deliver the supply of electricity in a sustainable, economic and safe way, which is integrated with turn by unconventional energies" [2].

On the other hand, the United States Department of Energy (DOE), in 2008 created the "Renewable and Distributed System Integration Program" to integrate the new concepts of smart grids and clean energies at all levels of the electric power chain [3]. In Latin America in 2010, the Inter-American Development Bank was the promoter of the creation of the Center for Energy Innovation, which promotes the development of clean and smart energy technologies [4]. This Innovation Center manages the exchange and dissemination of knowledge about energy for the region. The term "intelligent" in electrical networks has begun to appear in all scenarios, denoting multidisciplinary research concerning instrumentation, measurement and monitoring systems, information management, its response in real-time, and its monitoring system [5,6].

All these initiatives have forced countries to standardize the implementation of Smart Grid-based systems. For example, the United States has identified 75 regulations through the National Institute of Standards and Technology (NIST-ANSI) regarding Smart Grids [7]. Similarly, the European Union, through the European Committee for Standardization (ECS), identified 110 different standards and architectures that can be implemented in Smart Grids [8]. Under these principles of norms, standards, and research, it was evidenced that the control systems applied to the most-used Smart Grid and Micro Grid are the distributed control architecture managed employing layers (related but independent control systems) that cover supply and demand [9,10]. These systems not only involve the technical aspects, but also the management of risk and cost reduction through the optimization of operations, for example, in the district energy network and others [11].

This article aims to establish relationships between Smart Grids and their control models, mainly related to Petri nets, from their beginnings to current trends limited to new devices and developments that have led to registrations and licenses or patents.

2. Methodology

The study of Smart Grids is considered today to be a very important research field in the subjects of electrical networks, not only for environmental reasons or energy shortages but also for applying revolutionary non-linear control techniques, proposing ways of digitizing energy, and perhaps most importantly, improving accessibility and the right of all people to access it.

Figure 1 presents a flowchart that shows how the development of this document has been addressed over time. In this review, a follow-up of the patents related to the control systems applied to electrical energy and their relationships, especially with Petri nets, is carried out. The paper seeks to describe the relationship of Petri nets with Smart Grids, which is currently being investigated due to the need for a transition toward renewable energies.

This paper reviews the origins of the Smart Grid definition with some examples applied to the initial infrastructure. Section 3 presents concepts and theories based on the technologies implemented in Smart Grid projects and presents patents that were tracked to the company with projects applied to the energy sector. In Section 4, the most-used Smart Grid and electrical power-related control system techniques are established and sampled. Then, in Section 5, the observation that technologies and control systems are related to Petri nets (PNs) defines it as a control system with PNs. Likewise, patents obtained based on PNs for Smart Grid solutions with some applications and control systems are presented. Finally, Section 6 presents the conclusions of the work.

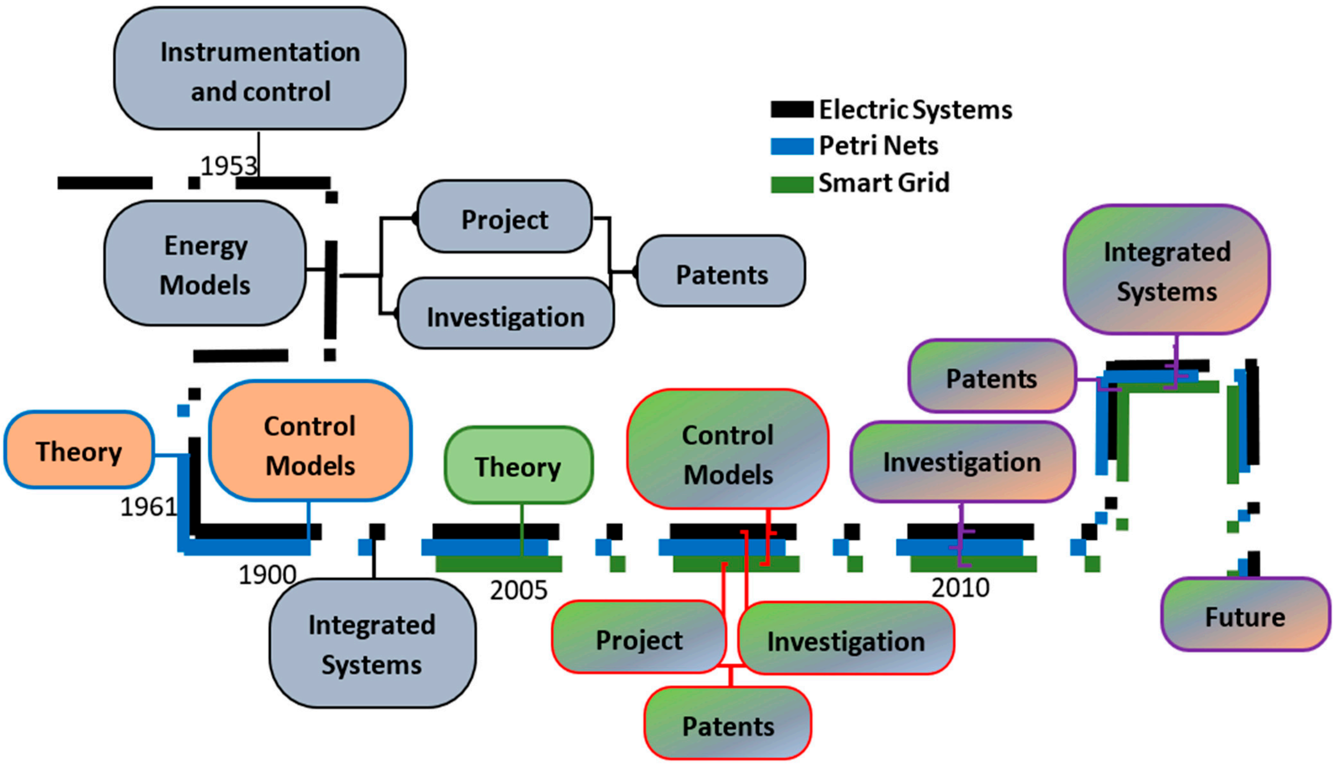

Figure 1. Flowchart to understand this review.

3. Smart Grids' Origins: Concepts and Theory

Studies have not been able to establish the origins of the first use of a Smart Grid, since it depends on the context used. For example, the term Smart Grid is part of different areas of engineering, including communications systems, programming systems, energy systems, advanced instrumentation, and the interaction of the different disciplines of electrical engineering where the concept of automated electrical networks is present.

Going back to the projects that include Smart Grids, there was the Telegestore project, implemented in Italy in 2000, which established for the first time the foundations of a Smart Grid as a project in automated energy and, although the concept as such does not appear in their research, it was one of the first projects that worked on this technology. This project consisted of installing and putting into operation smart meters on a large scale, connecting them through power-line communication (PLC), and sharing information with a central system [12].

On the other hand, the term Smart Grid in a scientific article that was focused on energy was used for the first time in 2005 in a paper called "Toward a Smart Grid", which was published in the IEEE Power and Energy Magazine and consisted of applying the flight technologies of an F-15 to its interconnected power systems. The main idea was to make the components of the power systems act as plug-and-play interconnections, and because of this, every component, substation, and power plant should have an intelligent processor. This article was the first to officially present the concept of smart energy grids [13].

The term of control in smart grids is believed to have been established when optimization techniques applied to power systems appeared in 1960; this was to optimize the cost in the design of the facilities, minimize losses in the operation, and reduce costs in the operation of generation plants and the design of transmission lines [14]. However, its application in projects first occurred in the 1980s, when electromechanical electricity meters appeared and its usefulness was demonstrated with the incorporation of integrated circuits and communication technologies, subsequently evolving into electronic energy meters [15].

This technology can be observed in patent US4240030A, in which the electric meter is equipped with special circuits and components that work in conjunction with an inserted magnetic card to regulate the supply of electricity to the system [16]. Likewise, in the United States, the first fully automated system for managing the load of electrical networks and its remote reading was developed using automatic meter reading (AMR) technology in 1985. This AMR technology evolved into advanced metering infrastructure (AMI), considered the intelligent sensor technology for smart grids [17].

Due to the importance of research and prototyping, the Smart Grid concept made its way into the production of innovative electrical devices that began to be licensed and patented around the world. For example, the first record of a device focused on automatically controlled energy was patent US2677789A, which presented a rectifier circuit controlled in an intelligent network in 1950 by the company English Electric Co [18]. Figure 2 shows the companies that have generated the most patents from 1950 to 2020, the percentage of patents for each company is related to the total number of patents published in that same year that were directly related to Smart Grid systems.

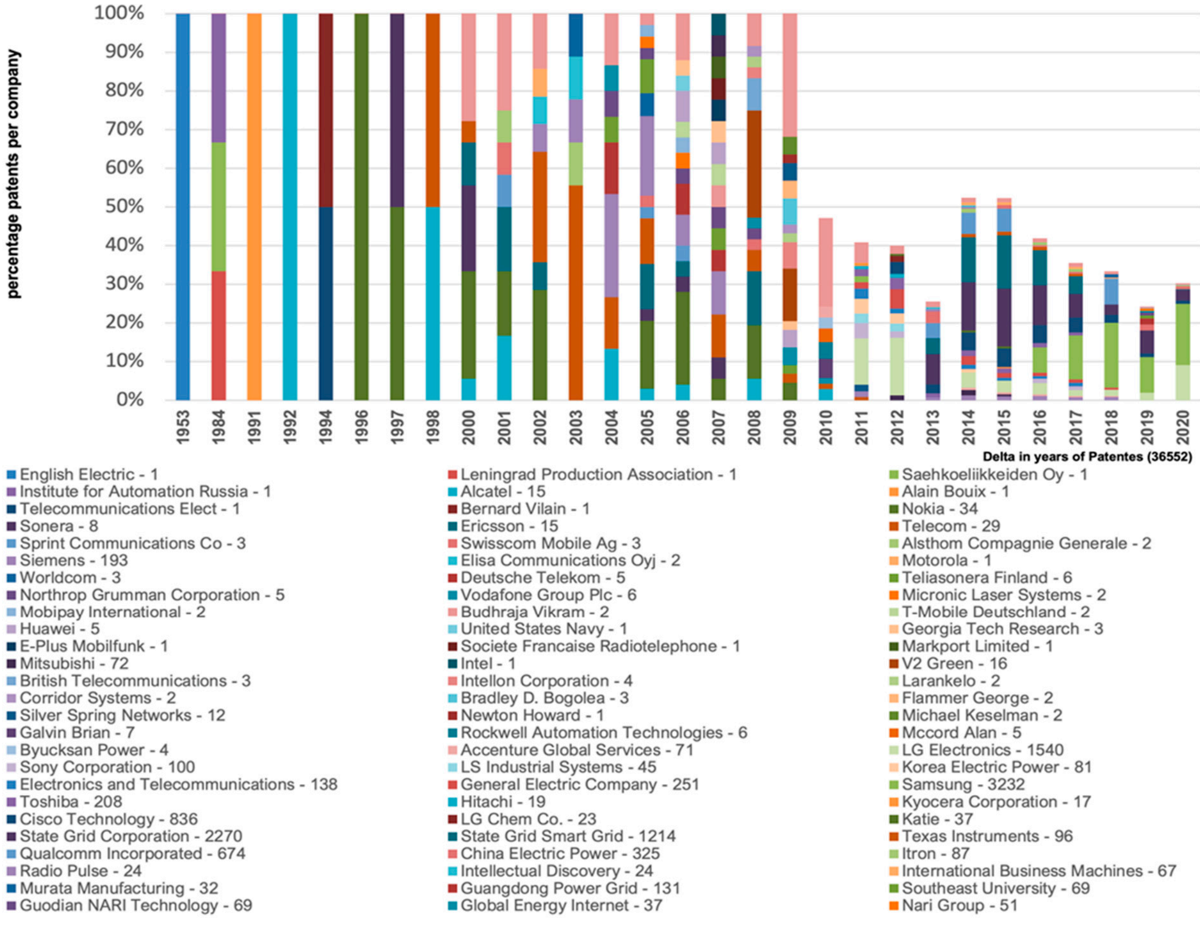

Figure 2. Percentage of patents related to Smart Grid in energy use.

For some years now, energy research and innovation centers have had as their goal the implementation of a Smart Grid focused on guaranteeing reliability, flexibility, efficient use, availability, the integration of renewable energies, and reductions in the cost of energy, both for operators and users [19]. These investigations have defined the main characteristics that a Smart Grid should have as follows:

- Integration of sensors, actuators, measurement technologies, and automation schemes at all levels of the network (multipurpose communication platform) [20,21].
- Information systems, cyber security, and distributed intelligence (intelligent control techniques) [22].
- Integration of renewable energies and efficient transmission capacity of the network [23].
- Distributed generation and use of energy resources [24].

- Incorporation of efficient control equipment against failures and self-correction.
- Integration of users and smart electrical equipment, energy efficiency schemes, price signals, and monitoring of operations. Advanced home automation [25].
- Electric vehicles, load structures, storage capacity, and on-site generation [26,27].
- Research development of advanced technologies, such as high-temperature superconductors, mass storage systems, ultracapacitors, transformers, high-efficiency motors, equipment, and flexible alternating current transmission systems (FACTS).

Research related to Smart Grids in different countries has been related to achieving energy security and low carbon emissions. Australia, for example, is innovating commercial distribution management systems, integrating grid fault detection, power quality monitoring, and process automation [28]. In Canada, research is focused on the transmission transfer capacity of control systems, which thus provides voltage stability to the grid. In Ontario, for example, a reduction in peaks between 5% and 8% was achieved in the load profile of users [29]. In the United States, the Pacific project (Montana, Washington, Idaho, Oregon, and Wyoming) implemented a system of continuous Smart Grid coordination for public services [30]. Likewise, Houston implemented a measurement system with Smart Texas, which notifies if there is an interruption automatically through the internet and provides reports from the smart meters [31].

On the other hand, photovoltaic systems, charging stations, smart meters, heat pumps in the distribution network, and electric vehicles, among others, were integrated under the "London Low Carbon" program, which improved the efficiency of the energy and demand response [32]. In Asia, the "Jeju SG" project in South Korea shows photovoltaic solar energy technologies, wind energy, storage systems, distributed automation, electric vehicles, network monitoring, and telemetry in a dashboard-type system where the consumer can observe electricity rates in real-time, the type of generation source, the interaction with their loads (smart appliances), and the management of storage systems [31].

As an investment in telemetry systems, it is important to know the case of the Energy Regulatory Commission (ERC) in Ireland, which implemented approximately 9000 smart meters in homes and public and private sector companies in record time (Ecar Ireland project). Among other benefits, these systems allowed electric vehicle drivers to pay the electricity supplier in a fully automated way [33]. Likewise, the European IGREEN-Grid project used AMI (advanced metering infrastructures) on a large scale, consisting of installing renewable energy sources in the distribution networks with around 200,000 smart meters in the Madrid area without compromising the reliability and quality of supply [34].

Also, in the city of Santander, Spain, with the support of the European Energy Commission (Energy EU), the Smart Santander project was established in 2014, which comprises many Internet of Things devices implemented in various urban settings for the creation of a laboratory. Starting in 2017, tests have been carried out on the integration of new intelligent and efficient platforms, where devices based on the IoT transfer information initially in the home between the power plant and the end users, allowing the development of learning methods in the distribution [22].

Moving from the continent to Chongqing, China, the energy company's photovoltaic micro-grid presented problems of unknown line resistance, large load fluctuation, large control voltage error, and poor stability. To resolve this problem, Chongquig Jiaotong University designed a control algorithm with big data technology that helped achieve coordinated control of the micro-grid in the photovoltaic cell, the energy storage unit, and the DC–DC converter independently [35]. At Amity University, Jaipur, Rajasthan, India, on the city's smart grid, blockchain techniques were developed for strengthening the security, credibility, and integrity of decentralized transitive energy data. In addition, they support cybersecurity against attacks on the infrastructure of network equipment and sensors [36]. One of the main advantages of this technology is the reduction in energy exchange costs through the elimination of redundant mediators, among other areas of the commercialization of the energy sector [37].

As a summary, the following Figure 3 shows the percentage of research associated with different Smart Grid developments and technologies between 2009 and 2019. Table 1 shows a summary of the projects related to Smart Grids showing their merits and demerits for a better understanding.

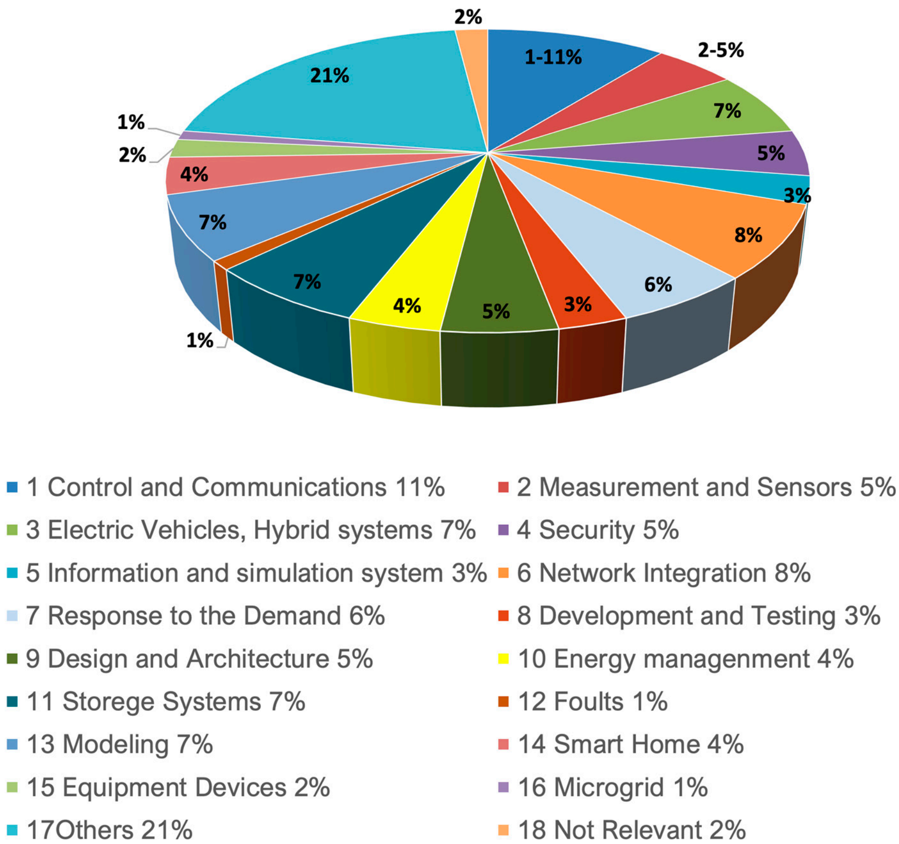

Figure 3. Technologies and developments related to Smart Grids [38].

Table 1. Summary of the projects related to smart grids.

Project	Method	Merit	Demerit
Tele-manager. Italy, 2000.	This project consisted of installing and operating large-scale smart meters, connected through power-line communication (PLC) and sharing information with a central system.	One of the first projects to automate information and communication systems.	It was not determined if it really was an intelligent network: there was no record of whether it had any control model.
Implementation of Smart Grid Technologies in an F-15 aircraft in its interconnected power systems. 2005.	F-15 aircraft power systems that act as smart grids with plug-and-play interconnected with an independent smart processor per process.	First project to introduce the concept of smart grids and, although it is a single machine, it is analyzed as independent processes interacting with each other.	It remained simply the first project that used the concept of Smart Grids.
Management of the load of electrical networks and its automatic reading of meters. United States, 1985.	Implementation of AMI (advanced metering infrastructure) technology, considered as smart sensor technology for smart grids.	One of the first projects to use instrumentation with automated remote readings in electrical networks.	It focused only on instrumentation and its benefits but is not associated with remote response methods for control systems.

Table 1. *Cont.*

Project	Method	Merit	Demerit
Commercial distribution management systems. Australia, 2010.	Innovation in commercial distribution management systems, integrating network failure detection, power quality monitoring, and process automation.	Integration of intelligent networks based on information management, to have a comprehensive control model in fault detection.	There is no mention of the integration of networks of renewable energy sources.
Transmission transfer control systems. Canada, 2010.	Focuses on the transmission transfer capability of control systems to provide voltage stability to the grid. Achieved maximum reduction between 5% and 8% with network load issues.	Results of the control and stability systems in the network are found.	The integration of renewable energies in the processes is missing.
Smart Santander Project. Spain, 2014	Installation of Internet of Things devices in various urban environments for the creation of a laboratory. Integration testing.	The transfer of information between the central point and the end users. Marketing automation.	It is not known if there is integration in the charge for renewable energy generation.
Integration of smart grids for public services. USA, 2015.	Implementation of a continuous coordination system for smart grids for public services. Installation of a measurement system with Smart Texas, which automatically notifies if there is an interruption through the internet and provides reports from smart meters.	Integration of information systems and communications with AI control systems. Report in real-time on the web.	It is unknown if there is integration of renewable energies in the project.
London Low Carbon. London, 2016.	Integration with photovoltaic systems, charging stations, smart meters, heat pumps in the distribution network, and electric vehicles, among others. Integration with information and control management systems, which reported improvements in energy efficiency and demand response.	The integration of renewable energy generation systems in an electrical network is known. Completely autonomous system.	None.
"Jeju SG" project. South Korea, 2016	Integration of photovoltaic solar energy technologies, wind energy, storage systems, distributed automation, electric vehicles, network monitoring, and telemetry, in a board-type system.	Smart Grid automatic control system in real time.	None.
Energy Regulatory Commission (ERC) of Ireland, 2018.	Implementation of 9000 smart meters in homes and public and private sector companies.	The provider can pay for electricity in a fully automated way for electric vehicles. Integration of renewable energies.	None.

4. Smart Grid Control Systems

The development of control techniques in smart grids has its origins mainly in the need to mitigate network failures and changes in power quality. The foregoing is due to economic concerns and the environmental impacts of energy issues in terms of sustainable development [39–41]. Smart Grids have also contributed to the development and integration of renewable energies into the distributed system since this type of generation source presents intermittent output [42]. These intermittency characteristics of renewable sources and the stochastic behavior of demand make these networks complex systems with types of non-linear control that must be robustly modeled, analyzed, tested, and implemented when considering their operation, safety, reliability, and maintenance [43]. The above shows that the best ally of renewable energy sources is Smart Grids.

According to the Department of Mechanical and Aerospace Engineering of the University of Syracuse in the United States [44], the control theories implemented in most Smart Grids can be grouped into four categories, which are discussed in the following sections.

4.1. Rule-Based Control (RBC)

Also known as autonomous control, based on static command control strategies RBCs are not capable of making any adaptive decisions, and, in most uses, algorithms are based on fuzzy logic. Their implementation is simple and flexible compared to other control strategies [45]. To improve decision-making in an adaptive way and in a stable state, a metaheuristic or homeostatic algorithm is implemented [46,47]. Figure 4 shows an example of the programmable temperature control systems (PTC) in North America, where their automatic adjustment is based on rules associated with high demand, intervening in the adjustments of these meters based on times when users do not make changes [48].

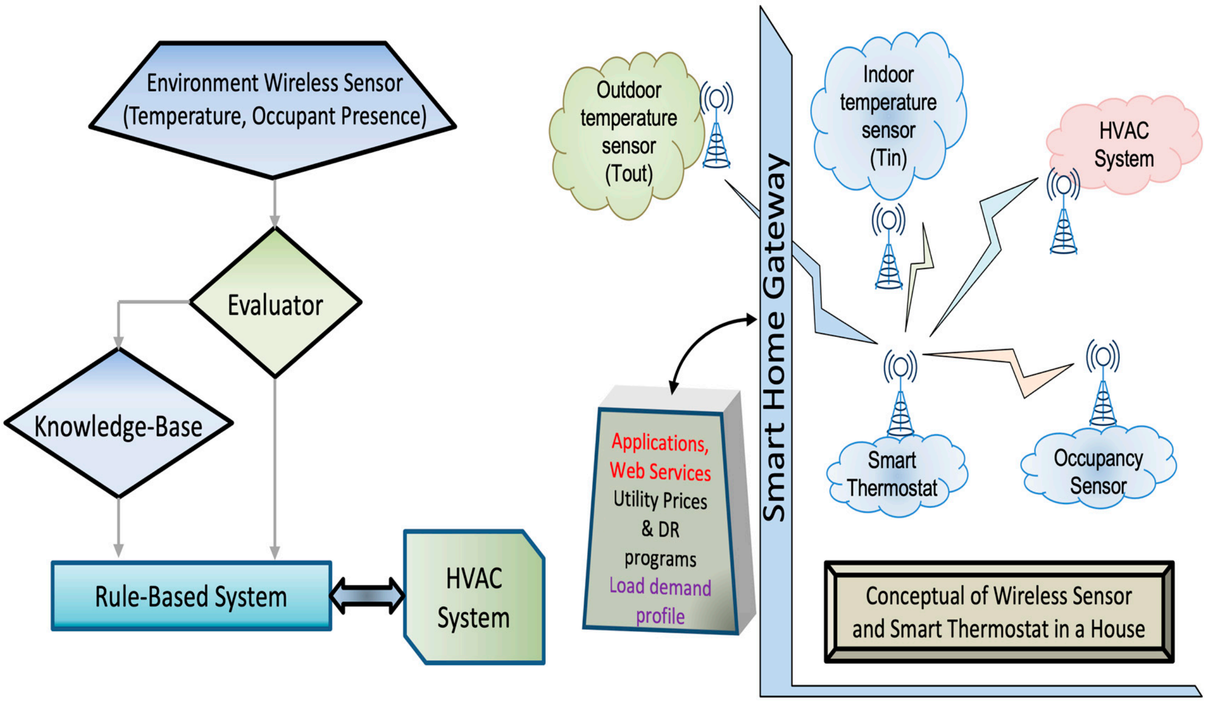

Figure 4. Rules-based control systems and wireless sensors [48].

4.2. Optimal Control (RBC)

The objective of this type of control is to solve an optimization problem and implement its result. Optimization problems are generally solved in the context of a complex systems control scheme, such as model-based predictive control (MPC) [49]. The principle of control is to optimize (minimize or maximize) one or more target variables, varying their decision values while satisfying a set of constraints. In the case of the Smart Grid in Figure 5, the conventional approach is to minimize the cost of the operation, which includes different components (fuel, storage, maintenance, policies, cycles, demand, and supply, among others) [50]. An application of this control has been developed at the Tamil Nadu Institute of Technology and Sciences, India, where a predictive control model called the trust was implemented in the wireless sensor nodes to observe them as energy supply and demand nodes and thus obtain more adequate metrics. The proposed trust model validates compensation failures and data loss failures in smart meters [51].

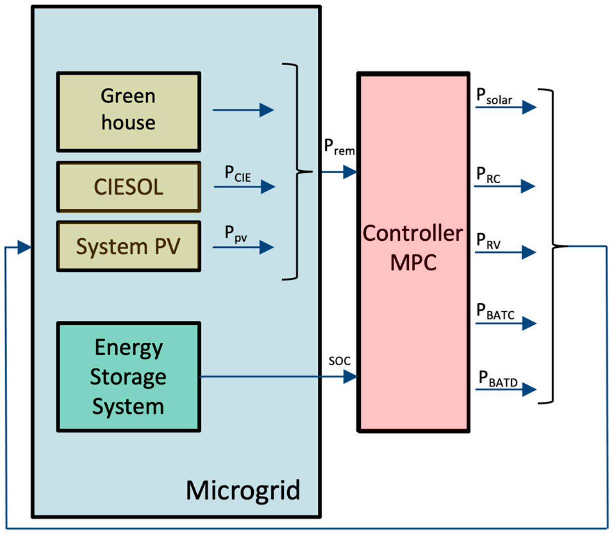

Figure 5. MPC controller in a micro-network [47].

4.3. Agent-Based Modeling (ABM) Control

Agent-based modeling control systems are intelligent systems consisting of a collection of agents that interact with each other in such a way that the entire system learns and evolves. The term "agent" refers to a computer system capable of performing autonomous actions, which can be divided into different agents, including: controller, central coordination, load, network entry and exit, planner, management, market, regulation, and others [52,53]. These agents communicate with each other to perform coordinated actions, perform complex calculations, and make decisions. These models are more focused on energy management.

They can be used in situations where a fully formulated optimization problem would be impractically complex or where a model of the complete system cannot be known. They are tolerant of errors due to their decentralized control scheme [54,55].

Research carried out at Beihang University in Beijing, China, presents agent-based control as a solution to failures when they are associated with the dynamic load balancing of the smart grid. The agent-based algorithm optimizes groups of nodes called herds based on load compensation using communication architectures [56]. A similar system for distribution network restoration in future smart grids can be seen in [57], where the self-repair capacity of future networks will be a must.

4.4. Model-Based Predictive Control (MPC)

Model-based predictive control is a control strategy based entirely on the dynamic model of the system. In general, it is a linear model that takes as input the current state of the system and external disturbances and generates a future state [58]. The resulting state is optimized in a prediction horizon of N + 1, and the now-current state (N + 1) with the current and predicted disturbances is introduced into the model, as in Figure 6. The MPC has the advantage of having an account of the future state of the system and future disturbances when making control decisions for the current next step; thus, one can anticipate future events and act on that prior knowledge in the present. An advantage of the predictive control of the model is that it is only as good as the model that is placed in it [59,60].

This type of model is being applied in commercial buildings in Hong Kong for the management of the demand for air conditioners and its relationship with the supply of energy through the Smart Grid. The main objective is to maximize the power reduction based on a predictive profile of the electrical networks as well as maintain the air temperature inside the building. The MPC controller determines the demand control outputs based on the building's thermal response model [61].

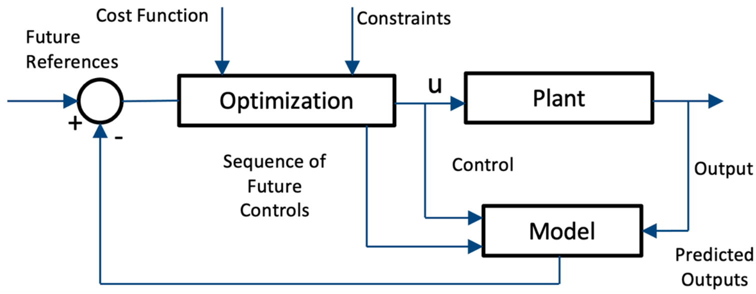

Figure 6. Model of a predictive control [62].

4.5. Control Based on Discrete Event Models (CMEDS)

This type of control is based on asynchronous dynamic systems, which evolve according to the occurrence of events [63]. Its behavior can be described as sequences of events forming a language and thus establishing a process that can be coupled to a supervisor, and this can force the processes to be recurrent. It is present where the Petri nets are perfectly coupled by the supervised control manager, as seen in Figure 7. This type of control was applied in Detroit in the United States by the Department of Electrical and Computer Engineering at Wayne University. Its objective was to avoid overload tripping of circuit breakers through the distribution or output of the overload in the network with the maximum possible power transfer [64].

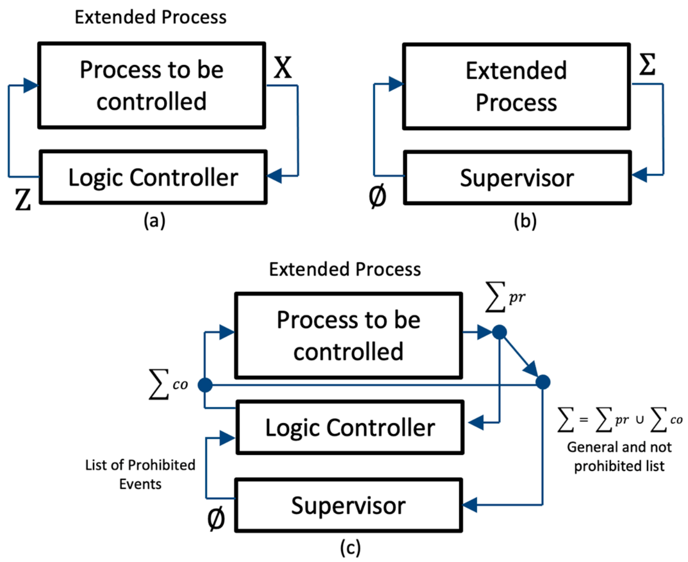

Figure 7. Supervised control. (**a**) The extended process. (**b**) The supervisor's scheme. (**c**) The supervised control scheme [65].

Supervised systems are managed via Petri nets since they establish programmable logic rules and define events restricted by actions. These Petri nets have penetrated control systems for failure analysis, financial systems, energy, storage systems, automation systems, and telecommunications through their different forms, such as timed, hybrid, and stochastic Petri nets, combined with other control methods or colored [66,67].

These models can be combined by different techniques, which can be from the same PN family but from different sources, such as Bayesian Petri nets and stochastic Petri nets. In this case, one of them can act as the supervisory PN, which controls the events, and the other PN can generate the model through an algorithm for process control. In addition, a combination of hybrid models can be presented. These can be PNs with a discrete or continuous control model. An applied example of the combination of PN techniques is the modeling of urban traffic systems in the city of Turin, Italy, which uses real-time control strategies. The hybrid model uses timed colored Petri nets (TCPNs; Figure 7, section (b) of reference [68]) as a system control of entrances and exits in the intersections; these TCPNs establish the possible stopping times, numbers of vehicles, and flow directions, while the vehicular flow on the road has been modeled through a stochastic discrete-time model (Figure 7). Hybrid model validation has shown that relevant traffic dynamics have been considered, but the real-time computational cost is of low latency and time-saving, making it suitable for real-case applications. The above, due to the simulation, can be performed in parallel for the hybrid model [68].

5. Smart Technological Developments with Petri Nets in Control Systems

Petri nets were created in 1962 by Carl Adam Petri in his doctoral work "Kommunikation mit Automaten" as a graphical and mathematical modeling tool that can be applied in many systems, based on bipartite graphs [69]. Petri nets are used for systems with concurrent, asynchronous, distributed, parallel, non-deterministic, and/or stochastic characteristics that process information. Numerous research has been developed that has strengthened the theory, and today they are the fundamental tool for modeling and simulating dynamic systems of discrete events [70]. The applications that use Petri nets and their types are diverse, present in areas such as automation processes, fault diagnosis, telecommunications, and logistics systems, as shown in the previous section. For example, in [71], a colored Petri net is implemented for the diagnosis of intermittent failures in semiconductor devices, while in [72], the same type of CPN is used in the sustainable logistics of a company for the green purchasing process. Some of these applications have evolved into important developments in software and hardware that have culminated in innovation and development processes, and therefore in registrations, patents, and utility models.

One example is the case of the software developed by Aarhus University initially for CPNTools research and that today is used for modeling, mainly in telecommunication systems [73]. The research and development of the PNs have also allowed the main automation technology companies in the world a whole range of programmable logic controllers for industrial use with efficient platforms for the modeling of processes, such as the Grafcet and the Gemma [74,75]. Both emerging technologies and Industry 4.0 have taken an important step toward the development of PNs, directing their futures toward the current needs of computer systems with artificial intelligence [76].

The history of Petri nets in the development of software and hardware for prototypes is very important because it has spurred progress and great changes in the telecommunication, automation, and electrical networks industries. Below, Figure 8 shows a Sankey diagram, where the patents related to R+D+i processes are grouped into technology sectors associated with Petri nets according to the period. For example, in the energy line, there is talk of patents in fault control but focused on energy, or the development of modeling software but focused on energy systems. Finally, there are patents on models to streamline public transport; likewise, other areas can be seen where the Petri net research has culminated in important developments for the industry. It is important to highlight from Figure 9, that all those that did not have a classification were grouped into the generalized Petri nets group.

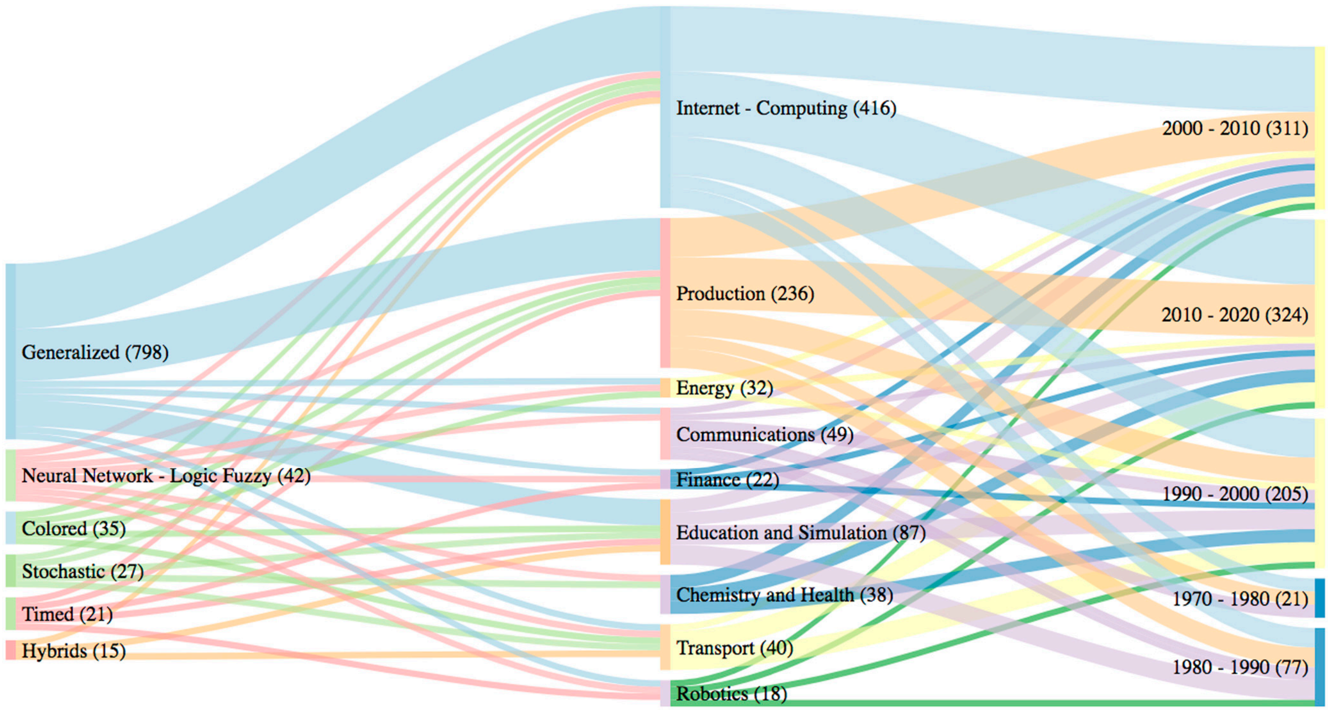

Figure 8. Related patents (PN type–technology development sector–Period).

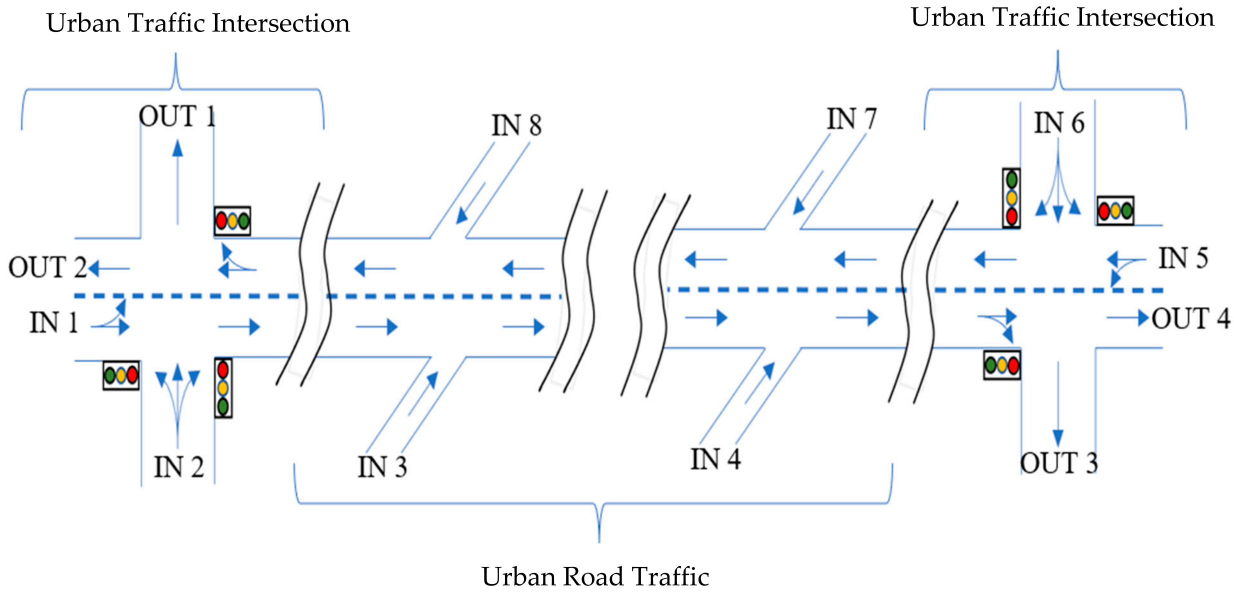

Figure 9. Urban area used in the evaluation of the hybrid model [68].

Some of the investigations into technological developments show the PNs as support for control theories [77] as seen in Table 2. Reviewing the research that evolved into these technological developments, it is observed that in most of the research in the places of the PNs, other control theories are managed, which are then led to predefined events through transitions. Likewise, in other developments, great algorithmic and control development is observed in the transitions of the PNs. One of the most interesting developments is the use of applications based on distributed control [78]. Next, some of the most important technological developments are related to PNs in the integration or execution of control models in a Smart Grid and Micro Grid.

Table 2. Patents related to Petri nets.

Number of Patent	Date	Description
EP0704778A1	30 September 1994	Method for the distribution of electrical energy using diffuse Petri nets in electrical power generation systems from steam [79].
CN102680817B	28 April 2012	Fault diagnosis method in a power transformer based on fuzzy Petri nets [80].
CN103001328B	19 November 2012	Method for diagnosing faults in smart substations using Petri nets [81].
CN103020713A	19 November 2012	Intelligent substation fault diagnosis method combining topology and logic with relay protection [82].
CN103278328B	16 May 2013	Method for diagnosing faults in a wind turbine generator based on a fuzzy Petri net [83].
CN103308824A	31 May 2013	Fault diagnosis method in a power system based on a probabilistic Petri net [84].
CN104182613B	25 July 2014	Construction method of the fault diagnosis model in a ship's electric power plant, based on Petri nets [85].
CN104268375B	10 September 2014	Petri net-based ship electrical power station fault diagnosis method [86].
CN105990834B	15 February 2015	Fault diagnosis and evaluation procedure of the battery energy storage station [87].
CN105470932A	28 August 2015	Protection simulation method in a power transmission line with object-oriented Petri nets [88].
CN105548815A	14 January 2016	Method for detecting faults in the electrical network based on Petri nets with maximum probability decoding [89].
AU2016100316A4	23 March 2016	Model of a system to control energy transmission [90].
US10103569B2	23 March 2016	Model for controlling a power transmission system [91].
CN105894213B	27 April 2016	Method for a multi-agent-based power grid fault diagnosis system supported on Petri nets [92].
CN106443341B	29 September 2016	Method for a smart grid system to diagnose faults [93].
CN106908132A	20 January 2017	Improved Petri net-based strain gauge load cell failure detection method [94].
CN107729620A	20 September 2017	Integrated software for a methodology for forecasting energy consumption based on colored Petri nets [95].
CN107656176B	9 November 2017	Electrical network fault diagnosis method based on a Petri–Bayesian network [96].
CN107769202A	28 November 2017	Reliability evaluation method of the distribution network based on fuzzy Petri net [97].
CN110018390A	15 March 2019	Hierarchical method of fault diagnosis in an electrical network based on fuzzy Petri nets using the integral variable weight method [98].
CN109884473A	29 March 2019	Electrical energy review system and method based on Petri nets [99].
CN110348114A	9 July 2019	Non-precise fault recognition method for the reconstruction of the information on the state of integrity of the electrical network based on Petri nets [100].
CN110470951A	18 August 2019	Active power distribution network method to diagnose faults based on information from PMU and Petri net [101].

5.1. Automatic Control Model in Substations Interconnected with a Smart Grid

The application of PNs in the design, monitoring, and automatic control of distributed generation (DG) models on the substations for their transmission has focused on solving problems of bidirectional power flows that change the operating conditions of the system [102]. In this case, the solution presented is that the PNs for DG models associate the switching sequences of reconnection, disconnection of low voltage loads and restoration, energy transport, and faults, among others. These operations are usually carried out using autonomous devices; however, in these cases, Petri nets are used only to specify the control of the information flow between the devices. The control itself oversees expert systems, such as evolutionary algorithms, neural networks, and fuzzy logic, among others, which involve concurrent multitasking architectures through the administration of PNs. The IEC 61850 standard established unified criteria for automatic control functions with Petri nets, seeking that current research establishes a convergence between these powerful tools [103]. As an example, patent US10103569B2 shows a group of circuits that detect the presence of demand changes, disconnection faults, substations, and out-of-range processes. This patent facilitates information and data processing [91].

5.2. Automatic Control Model in Substations Interconnected with a Smart Grid

This model is focused on the supply of unconventional energy that interacts with the Smart Grid, for example, from non-renewable sources. In this case, energy generation is calculated using mathematical models based on daily availability. This allows the gap between energy production capacity and energy demands over 24 h to be calculated. The problems of these interconnection models are related to the control and supervision of the distribution of electrical energy, which can give rise to stability and quality problems in the networks.

This is due to a greater extent to: energy storage, intermittent generation, unexpected demand, network overload, voltage quality, or non-compliant energy returns to the network. To ensure a continuous supply, energy must be managed according to the model proposed in Figure 10. This is achieved by designing the interconnection system based on demand, generation, and the needs of the renewable energy system [104]. For this, operating rules are established for the use of unconventional electrical energy, among them the priority of generation over the grid as well as the sale of surplus energy to the national grid. This operating strategy is based on an iterative evolutionary algorithm to control and manage power flows using Petri nets as a management system for control in its nodes and its execution in its transitions [105]. The viability of this model is determined through an economic analysis of the cost of energy [106].

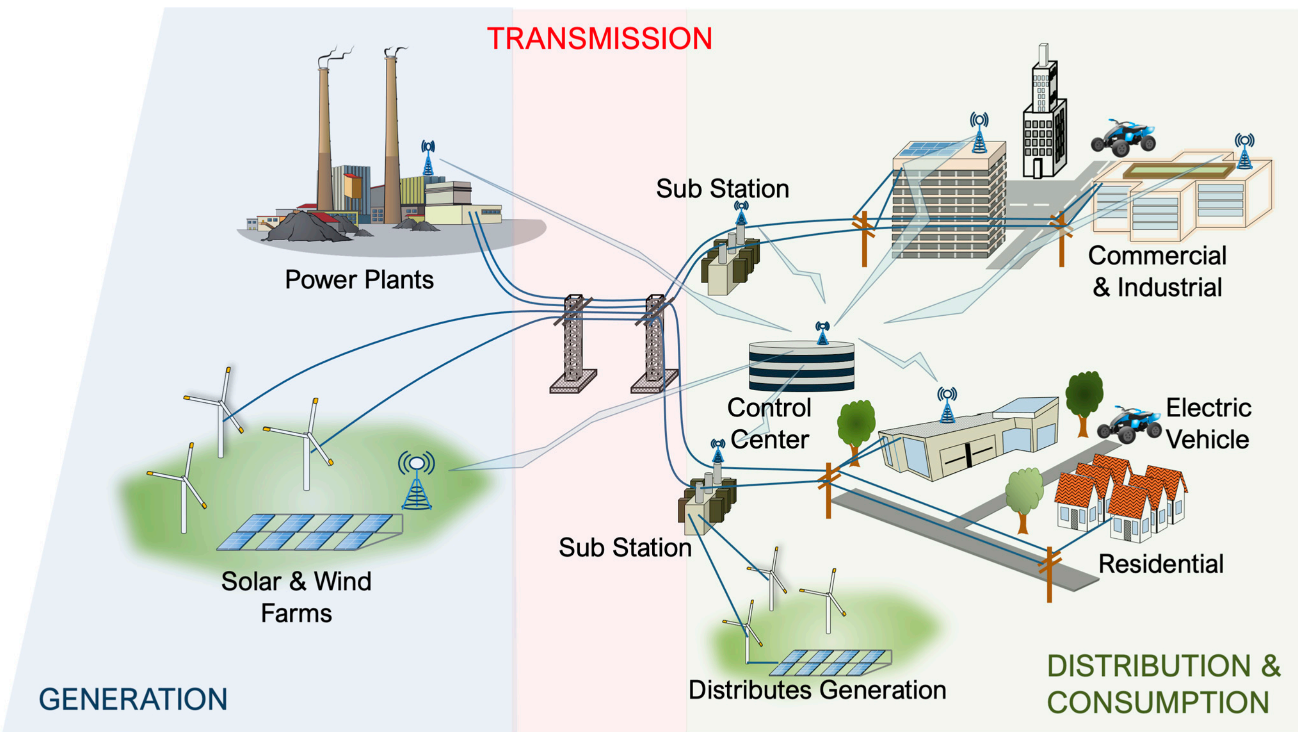

Figure 10. Intelligent interconnection model "Distributed Smart Grid" [107].

5.3. Adaptive Control Model Using AAHPNES Expert

The Hierarchical Autonomous Adaptive Expert System with Petri Nets (AAHPNES) is based on models of expert judgments on if–then rules supported in fuzzy logic. This system uses a Petri network for logical-mathematical operations based on the maximum and minimum allowed. This models as follows [108].

- Each antecedent proposal is seen as a place of entry.
- Each consequent proposal is modeled as a starting point.
- The logical operator under these conditions is represented in the transition.

This AAHPNES model is implemented in the SCADA-type power distribution system, which executes the reconfiguration function of the automatic power supply management of public services (UMA-FRF). This UMA-FRF system, after a failure, automatically restores electrical power to affected customers at load points, reconfiguring the network topology for distribution. The result of the simulation shows a performance in decision-making of 94% assertive in critical situations, which would have been proposed by experts [108].

6. Conclusions

The Smart Grids future is still incipient, and its research is still in the early stages due to the complexity of the generation, transmission, and distribution chains (GTD) and to several current technologies and developments, especially in the fields of control, communication systems, and fault diagnosis. In this paper, it was observed that the technologies that are available require a great investment in money, time in R+D+i, and continuous testing; evidence of this is the registration of patents in recent years by technology companies in Smart Grids, which are primarily focused on energy sustainability and environmental conservation and preservation. A defined research future of Smart Grids is very difficult to predict, but research suggests a focus on the development of technologies and innovations in line with the dynamics of cities and urban centers that have more and more households, industries, and companies, which demand, in some cases, up to 70% of the energy demand of the countries and show a tendency to rise.

This paper also shows the applications of the different technologies found and the most relevant currently, as well as the importance of these in the energy processes of generation and demand, information management, and the application of renewable energies and decentralized systems, among others, showing the advantages and disadvantages of these systems and their possible applications in the new energy models applied to the energy demands of today's urban and industrial centers.

Finally, the paper presents a follow-up of Smart Grid-related technologies, their relationship with Petri net models, and their management for control systems. It was considered in the paper to carry out a study of technological surveillance that shows a base of developments related to smart grids and a technological correlation with models based on Petri nets. From this relationship, thirty-two patented developments were found that use embedded models of PNs in their hardware, of which twenty-three are detailed in this review.

7. Future Research

Some other recent developments have occurred in the field of Smart Grid approaches. For example, developments in the protection of communications in Smart Grids based on cybersecurity techniques for false data detection [109]. Another very interesting example is the application of smart grids in the search for energy efficiency in smart cities [110]. On the other hand, the demand for electric vehicles in cities is beginning to be an inconvenience for the electrical networks; this issue should correspond to research on energy management and the demand response of these scenarios in the search to strengthen the sustainable transportation systems of the cities [111]. Finally, immersed in the fourth industrial revolution, technologies such as sensor networks are fundamental tools for collecting data in cities and in electrical networks to predict failures, carry out remote surveillance, and control energy in homes to be closer to the end user in Smart Grid management [112].

In addition, the future of Petri nets within smart grids presents various ways of working, including control systems and their modeling. Several of these feature combinations of robust controls, such as neural networks and fuzzy logic, among others. It is currently being investigated how the Petri nets manage the feedback of the controls or generate the model through the logical Petri net (LPN) tool [113–116]. Another investigation is the fault systems, which are the most studied via the Petri nets, and in this document, it is established that the logical control Petri net (CLPN) in fault detection has been under constant study, mainly when a fault occurs for which solution data have not been obtained since the control does not respond adequately [117–119]. One more way through which Petri nets are investigated is through monitoring, demand, efficiency, and quality systems; there are few studies where they focus mainly on the efficiency of the process or satisfy the demand, looking for a multitask combination where Petri nets are under investigation and the topic is recent [114,120]. Many universities and institutes are focusing their research on developing technologies on how to build strong, reliable, secure, and highly efficient Smart Grids. However, the big challenge is related to the energy demand of obtaining a superior Smart Grid [121].

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Abbreviations

EARPA (European Automotive Research Partners Association). DOE (Department of Energy. United States). NIST (National Institute of Standards and Technology). ANSI (American National Standards Institute). ECS (European Committee Standards). PNs (Petri Nets). PLC (Power Line Communication). IEEE (Institute of Electrical and Electronics Engineers). AMR (Automated Meter Reading). AMI (Advanced Metering Infrastructure). FACTS (Flexible Alternate Current Transmission Systems). ERC (Energy Regulatory Commission). RBC (Rule Based Control). PTC (Programmable Temperature Control). MPC (Model Predictive Control). ABM (Agent Based Model). CMEDS (Control Models Event Discrete Systems). CPNs (Colored Petri Nets). GRAFCET (Graphed Functional de Commanded tape Transition). DG (Distributed Generation). IEC (International Electrotechnical Commission). AAHPNES (Autonomous Adaptive Hierarchical Petri Nets Expert System). SCADA (Supervisory Control and Data Acquisition). UMA (Unit Management Automatic). GTD (Generation, Transmission and Distribution). R+D+I (Research + Development + Innovation).

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