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Intelligent Control in Core Electrical Systems: A Smart Energy Perspective

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Abstract

The quick development of smart energy technologies has changed how core electricity systems are controlled and managed. Intelligent control systems are very important for making these systems more reliable, efficient, and long-lasting. In this essay, we look at intelligent control uses in core electrical systems from the point of view of smart energy. One important use of clever control is demand-side management (DSM), which changes load patterns on the fly to make the best use of energy. DSM reduces energy costs, lowers high loads, and makes the grid more stable by using advanced formulas and real-time data analytics. Another important area is failure detection and analysis (FDD). To find and fix problems in electrical systems, intelligent control systems use machine learning and data-driven methods. Taking this preventative method makes the system more reliable and cuts down on downtime. Smart control is also an important part of integrating green energy because it makes it possible to use distributed energy resources (DERs) like solar panels and wind mills more efficiently. Intelligent systems make the best use of DERs by using prediction models and control techniques to make the connection to the grid as smooth as possible. This makes the most of green energy and has the least amount of effect on the environment. In addition, clever control makes the grid more reliable by letting it operate and fix itself. These systems can find and fix problems by looking at system data in real time, which makes sure that the power stays on. Intelligent control is a key part of current smart energy systems, and it opens up new ways to make core electricity systems more efficient, reliable, and long-lasting. To get the most out of smart energy systems, more study and development must be done in this area.

I. INTRODUCTION

The need to fight climate change and make sure there is enough energy for everyone is driving a huge shift toward sustainability in the world's energy scene. In this situation, smart energy technologies have become an important part of modern electricity systems, giving us new ways to make them more efficient, reliable, and environmentally friendly. Intelligent control, a concept that uses advanced algorithms, data analytics, and automation to make the operation and management of core electricity systems better, is at the heart of these improvements [1]. Traditionally, managing energy was done with organized facilities for production, transportation, and delivery, which included big power plants and power flow that only went in one direction. This controlled approach is being replaced by a more autonomous and flexible system. This is happening because there are more green energy sources, better energy storage technology, and more digital communication and control systems being used together. This [2] change brings about new problems and chances for making electricity systems work well and dependably, so new ideas based on smart control principles are needed. Needing to use less energy and

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save money is a big reason why intelligent control is being used more and more in core electricity systems. Demand-side management (DSM) has become an important way to reach this goal because it lets utilities and grid operators change how people use energy based on changes in supply and demand. DSM systems use advanced formulas and real-time data analytics to find chances for load moving, peak shaving, and demand response. This lowers energy costs, makes the grid more stable, and reduces peak loads. Furthermore, DSM lets end-users take an active role in energy management, giving them the power to make smart choices about how they use energy and then improve their energy use accordingly [3], [4].

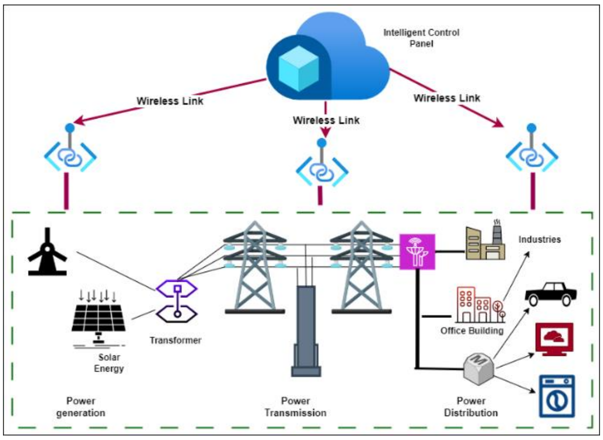

Figure 1: Intelligent Control in Core Electrical Systems

Intelligent control is also used for flaw detection and analysis (FDD), which [5] is a key part of making sure that electricity systems are reliable and strong. Modern power lines are getting more complicated and interconnected, which means that equipment breakdowns, outages, and other problems are more likely to happen. Machine learning, data-driven methods, and advanced monitoring technologies are used by FDD systems to track, analyze, and identify problems in real time. This allows for proactive repair and quick service restoration. By finding and fixing faults quickly, FDD systems reduce downtime, boost system stability, and make the grid work better overall. Intelligent control is also very important for making it easier to add alternative energy sources to the grid, which is a must if we want to be sustainable and cut down on greenhouse gas emissions. Renewable energy sources, like sun, wind, and hydropower power, aren't as stable and reliable as fossil fuel-based power plants because their power output changes over time [7]. To deal with these problems, intelligent control systems make the best use of distributed energy resources (DERs) and make sure that they work together with traditional power plants and energy storage systems. Intelligent systems use predictive modeling, planning, and control techniques to make it possible for green energy to be seamlessly added to the grid. This saves energy and has less of an effect on the environment. In addition, clever control makes the grid more [6] reliable by letting it operate and fix itself. In older power grids, decisions were mostly made by system managers and dispatchers who worked in a centralized control scheme. This centralized method is being replaced more and more by distributed control systems, which use advanced communication and control technologies to let local units work on their own. Intelligent control systems look at huge amounts of data from monitors, meters, and other grid assets all the time. This lets them make decisions on their own and adapt to changing conditions. These systems make the grid more resilient by finding and reducing problems at the local level. The intelligent control is a big change in how core electricity systems are managed and run. It opens up new ways to make them more efficient, reliable, and environmentally friendly. Smart control systems use complex formulas, data analysis, and automation to help utilities, grid workers, and end users save energy, find and fix problems, add green energy sources, and make the grid more reliable. To get the most out of smart energy systems and speed up the move to a more safe and reliable energy future, more research and development must be done in this area.

II. REVIEW OF LITERATURE

Adding smart control technologies to main power systems is a big change in how energy is controlled and used most efficiently. This part gives an outline of the relevant work in this area, focused on the main study areas and advances that have led to the creation and use of smart control systems in basic electrical systems.As an important area of study in intelligent control, demand-side management (DSM) focuses on finding the best ways to use energy to save money and keep the grid stable. A lot of research has come up with new formulas and methods for DSM, like load forecasts, optimization, and control [8] for example, came up with a new way to do real-time DSM that was based on deep reinforcement learning. This method saved more money and reduced peak load more than standard ones. [9]Also created a distributed optimization method for DSM in smart grids, which led to big changes in user comfort and energy economy. The results of these studies show how important advanced algorithms and optimization methods are for making DSM work better in core electrical systems.

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Smart control technologies have also helped with fault detection and analysis (FDD), which is another important area of study. A number of studies have looked into how to use machine learning and data to improve FDD, with the goal of making systems more reliable and lowering downtime. For instance, [10] suggested a deep learning-based method for fault detection in power systems that was very good at finding flaws quickly and accurately. [11]also created a data-driven method for FDD in smart grids that was better than standard methods at finding and fixing faults. These research projects show that clever control technologies might be able to make core electricity systems more reliable and resilient by finding and fixing problems more quickly.Researchers who study clever control have also looked into how to add green energy sources to the grid. Since green energy sources change and stop working at times, the grid needs good control methods to stay stable and reliable. A number of studies have suggested using complex control methods like model predictive control, fuzzy logic, and neural networks to connect green energy to the power grid. For instance, [12] suggested a model predictive control approach for the best merging of wind power into the grid. This led to big changes in the security of the grid and the use of green energy. Also, [13] created a fuzzy logic-based control strategy for optimum absorption of solar power into the grid. This made solar power production more reliable and efficient. It is clear from these studies that improved control methods are needed to make it possible for green energy sources to be effectively added to main power systems.

Researchers have also looked into grid resilience in the framework of intelligent control, with the goal of making it possible for systems to operate on their own and fix themselves. Distributed control, multi-agent systems, and self-healing algorithms are some of the new control structures and algorithms that have been suggested as ways to make the grid more resilient. As an example, [14] suggested a distributed control design for smart grids that could run on their own. This allowed the grid to respond to changing conditions and make it more resilient. Also, [15] created a multi-agent system for power systems to self-heal, which quickly restored service and made the system more reliable. These studies show how clever control technologies could help make the grid more reliable and make sure that core electricity systems always have power. Intelligent control systems have helped with important study areas like demand-side management, problem detection and analysis, integrating green energy, and making the grid more resilient. To get the most out of clever control technologies and speed up the move to a more sustainable and secure energy future, more research and development must be done in this area.

Table 1: Summary of related work in Smart Energy system

Algorithm	Methodology	Key Finding	Scope	Application	Area
Deep Reinforcement Learning [16]	Real-time optimization	Outperformed traditional methods in cost savings and peak load reduction	Demand-side management (DSM)	Smart grids, Energy management systems	Energy Management
Distributed Optimization [17]	DSM in Smart Grids	Achieved significant improvements in energy efficiency and user comfort	Demand-side management (DSM)	Smart grids, Energy management systems	Energy Management
Deep Learning[18]	Fault diagnosis	Achieved high accuracy and efficiency in fault detection in power systems	Fault detection and diagnosis (FDD)	Power systems, Smart grids	Reliability, Fault Detection
Data-driven Approach [19]	FDD in Smart Grids	Improved fault detection and diagnosis capabilities compared to traditional methods	Fault detection and diagnosis (FDD)	Smart grids, Power systems	Reliability, Fault Detection
Model Predictive Control [20]	Wind power integration	Significantly improved grid stability and renewable energy utilization	Renewable energy integration	Wind power, Grid integration	Renewable Energy Integration
Fuzzy Logic Control [21]	Solar power integration	Enhanced efficiency and reliability of solar power generation	Renewable energy integration	Solar power, Grid integration	Renewable Energy Integration
Distributed Control [11]	Autonomous operation	Enabled adaptive response to changing operating conditions and improved grid resilience	Grid resilience	Smart grids, Power systems	Grid Resilience
Multi-Agent	Self-healing	Achieved rapid restoration of	Grid resilience	Power systems,	Grid Resilience

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System [12]		service and improved system reliability		Smart grids	
Reinforcement Learning [13]	Real-time control	Optimized energy consumption and reduced costs through dynamic load management	Demand-side management (DSM)	Energy management systems, Smart grids	Energy Management
Support Vector Machine [14]	Anomaly detection	Detected anomalies in power grid operation, enhancing system security and reliability	Anomaly detection	Power systems, Smart grids	Security, Anomaly Detection
Genetic Algorithm [10]	Optimization	Improved efficiency and reliability of power grid operation through optimal resource allocation	Optimization	Power systems, Energy management systems	Optimization
Artificial Neural Network [15]	Load forecasting	Enhanced accuracy of load forecasting, enabling more efficient demand-side management	Demand-side management (DSM)	Smart grids, Energy management systems	Energy Management
Particle Swarm Optimization [7]	Economic dispatch	Optimized economic dispatch of power generation, reducing operating costs and improving grid stability	Economic dispatch	Power systems, Energy management systems	Optimization
Kalman Filter [4]	State estimation	Improved accuracy of state estimation in power systems, enabling better control and operation	State estimation	Power systems, Smart grids	Control, State Estimation
Reinforcement Learning [3]	Energy storage control	Optimized energy storage operation, improving grid stability and reliability	Energy storage management	Energy storage systems, Smart grids	Energy Storage Management

III. METHODOLOGY

A. Data Collection and Analysis:

Data gathering is a very important part of the power distribution system experiment setup that needs to be carefully planned and carried out. Several important things need to be thought about to make sure that accurate and trustworthy data is collected.First, it's important to figure out exactly what factors and parameters need to be tracked and measured during the experiment. Levels of voltage, current flow, power factor, and other important electrical factors may be among these. In the power distribution system, sensors and meters that can correctly measure these factors should be chosen and put in key spots.Second, the way the data is collected should be set up to get both current and past info. You can keep an eye on the system's performance all the time with real-time data, and you can learn a lot about how it has behaved over time with past data. Data logging tools can be used to keep track of this data over time. To make sure that data from different sources is gathered and stored correctly, data syncing is also very important. To avoid data errors, this means making sure that all monitors and meters are in sync with the same time reference.Validating and checking the quality of the data is also an important part of collecting it. This means making sure the data is correct by looking for mistakes, outliers, and problems. Also, the data should be kept safely so that it doesn't get lost or changed.

B. Intelligent Control Implementation:

There are a few important steps and things to think about when putting intelligent control methods like machine learning algorithms or fuzzy logic systems into power distribution systems. These methods can help improve general stability, make systems run more efficiently, and make them work better.The first thing that needs to be done to use intelligent control is to choose the right method based on the power distribution system's needs and features. For instance, machine learning systems can look at old data and find patterns or trends that can be used to make decisions about the future. Fuzzy logic systems, on the other hand, can describe complicated, non-linear connections within the system so that control decisions can be made when information isn't clear.The next step is to make the control program once the method has been chosen. This includes coming up with the rules for how the smart control system should work. For machine learning algorithms, this could mean using past data to teach the

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computer how to make predictions. In the case of fuzzy logic systems, this could mean laying out the fuzzy sets, rules, and reasoning tools that will be used to make control choices.

The control program needs to be put into the power distribution system after it has been made. To do this, the code might need to be programmed into a microprocessor or a programmable logic controller (PLC) that is linked to the system. It's important to make sure the application is strong and can handle handling and controlling data in real time.The clever control system needs to be tried and proven to work after it has been put in place. In this case, the system is run in a controlled setting, and its performance is compared to either standard control methods or an average performance measure. To be called good, the system should show gains in stability, efficiency, or some other useful measure.Lastly, the smart control system needs to be kept an eye on and fixed when necessary. This means keeping an eye on its performance all the time and making changes as needed to make sure it works at its best. Depending on new information or changes in the system, it may also mean changing machine learning algorithms or making changes to fuzzy logic rules.

C. Variables and Controls

The type of clever control that is used is one of the most important individual factors. This variable can have advanced control methods like fuzzy logic systems, machine learning techniques, or more. Researchers can compare how well and efficiently different ways of improving the performance of the power distribution system work by changing the type of clever control method they use.The amount of interaction with smart grid technologies is another feature that can be changed on its own. This variable can include how linked and how the power delivery system works with other parts of the smart grid, like smart meters, energy storage systems, and green energy sources. Researchers can see how intelligent control affects the smart grid environment as a whole and how it affects intelligent control by changing the amount of interaction.The intelligent control algorithm's features, such as the learning rate or the number of fuzzy logic rules, may also be independent variables. So can outside factors, such as load demand, weather, and the structure of the system. Researchers can learn a lot about how well and when to use intelligent control in power distribution systems by changing these independent factors in a planned way and then measuring how those changes affect the system's performance.

IV. INTELLIGENT CONTROL TECHNIQUES IN CORE ELECTRICAL SYSTEMS

A. Core Electrical Systems

Core electrical systems are the basic parts and structures that hold electrical power delivery networks together. These systems are in charge of getting energy from power plants to people who use it, making sure that the supply is stable and efficient. To get the most out of core electricity systems, make them more efficient, and keep the power grid stable, you need to know how they work and what their parts do.Transformers are essential to electricity systems because they control voltage and send power to different parts of the system. Transformers raise or lower the power of electricity to make it easier to send over long distances and make sure that different kinds of tools and equipment can work with each other. Another important part of key electrical systems is the distribution lines that bring energy from transformers to substations and then to homes, businesses, and factories.

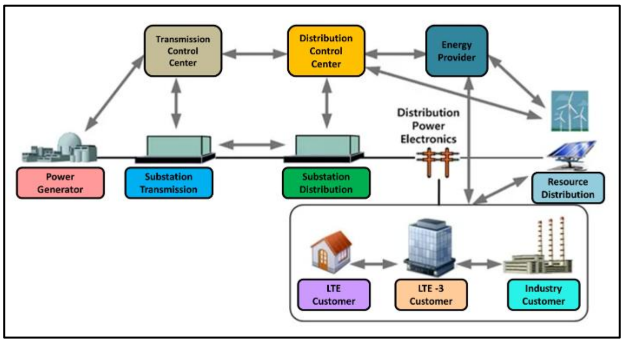

Figure 2: Overview of substation in core system

A substation is an important part of core electrical systems because it lowers the power so that it can be sent to nearby areas. Protection tools like circuit breakers and switches are also kept in substations. These are very important for keeping the electricity grid safe and stable. By cutting off bad parts of the grid, these devices help separate problems and keep power blackouts from affecting large areas.Control and switchgear systems are important parts of core electrical systems because they let you handle and control the flow of energy in the grid. Switchgear is made up of switches, fuses, and other parts that manage the flow of electricity. Control systems keep an eye on and coordinate the actions of different parts to make sure they work well and reliably.Smart grid technologies are being added to main power systems more and more to make them more reliable and efficient. Modern sensors, information networks, and control systems let these technologies keep an eye on and control the flow of power in real time. Adding smart grid technologies to key electricity systems makes them better able to adapt

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to changing demand trends, use green energy sources, and make the grid more stable overall.

B. Role of Intelligent Control in Smart Energy Management

Intelligent control is an important part of smart energy management because it makes energy systems run more efficiently, reliably, and over time. Smart energy management uses new tools and control methods to make the production, transfer, and use of energy more efficient. Smart energy management is made possible by intelligent control techniques like machine learning algorithms, fuzzy logic systems, and advanced optimization methods. These techniques have many benefits, such as:

- Demand Response: Smart control lets flexible pricing and demand response programs work, so people who use energy can change how much they use based on current prices or grid conditions. This helps keep supply and demand in balance, lowers high loads, and makes the grid more stable generally.
- Integration of Energy Storage: Smart control makes it easier to connect energy storage systems like batteries and pumped water storage to the power grid. These systems can store extra energy when demand is low and release it when demand is high. This cuts down on the need for expensive peaker plants and makes the grid more reliable.
- Green Energy Integration: Smart control helps handle the changing and unsure nature of green energy sources like wind and sun power. Intelligent control lets more green energy be used while keeping the grid stable by predicting production and making grid operations run more smoothly.
- Grid Optimization: Smart controls constantly look at data from monitors and smart meters to make decisions in real time that improve how the grid works. This includes controlling the power, balancing the load, and finding faults, which makes the system more efficient and reliable.
- Microgrid Management: Microgrids are small energy systems that can work on their own or connect to the main grid. To manage them, you need intelligent control. Intelligent control makes the best use of energy flows, organizes scattered energy resources, and makes sure that microgrids work reliably.
- Energy Efficiency: Intelligent control helps find ways to save energy and make buildings, factories, and transportation use energy more efficiently. This means that less energy is wasted and the cost of energy is lower generally.

C. Intelligent Techniques

1. Machine Learning:

The field of artificial intelligence called machine learning is all about making programs that can learn from data and use that data to make guesses or choices. guided learning, unsupervised learning, and reinforcement learning are some of the different types of machine learning methods.

- Supervised Learning: In this type of learning, the algorithm is taught on a named dataset, which means that each data point is linked to a title or result. The program learns to connect the right input data to the right output by making a loss function as small as possible. In smart energy management, supervised learning is often used for tasks like predicting energy demand or finding strange patterns in energy use that involve classification and regression.
- Unsupervised Learning: In this type of learning, the algorithm is taught on a dataset that has not been labeled, and it is up to the algorithm to find patterns or structure in the dataset on its own. Unsupervised learning can be used to group data points that are similar together or make the data less complex. Unsupervised learning can be used for load monitoring or finding trends in how much energy is used in smart energy management.
- Reinforcement Learning: In this type of machine learning, an agent learns how to make choices by dealing with its surroundings and getting awards or punishments for what it does. Over time, the agent learns how to get the most out of all the tactics it tries. You can use reinforcement learning to handle energy to do things like make a smart grid work better or control energy storage systems.

2. Neural Networks:

Neural networks are a type of machine learning model that is based on how the brain is built and how it works. They are made up of layers of nodes, or neurons, that are all linked to each other. Each neuron takes in information, uses an activation function to process it, and then sends the result to the next layer of neurons. Networks of neurons can learn complicated patterns and connections in data. This makes them great for jobs like speech and picture recognition, natural language processing, and control systems.

- Feedforward Neural Networks: The most basic type of neural network is a feedforward neural

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network, in which data moves from input to output in a single direction. As part of smart energy management, they are often used for jobs like predicting energy usage or finding the best way to use energy.

- Recurrent Neural Networks (RNNs): RNNs are types of neural networks that have links that make loops, which keeps data alive over time. Because of this, they work well for jobs that need to deal with sequential data, like natural language processing or time series forecasts. RNNs can be used in smart energy management to guess how much energy will be used in the future by looking at data from the past.
- CNN: CNNs, or convolutional neural networks, are special kinds of neural networks that are made to work with grid-like data, like sensor data or pictures. They are known for using convolutional layers, which take in data and use filters to pull out traits. CNNs are often used in smart energy management to do picture recognition jobs, like looking at heat photos to find problems with electrical equipment.

3. Fuzzy Logic:

Fuzzy logic is a way of thinking about math that copies the confusion and lack of accuracy that people have when they think. Fuzzy logic lets you have levels of truth, which are shown by numbers between 0 and 1. This is different from classical logic, which only has two options: true or false. In situations where it's hard to give exact numbers, fuzzy logic comes in handy. One example is smart energy management.

- Fuzzy sets: In fuzzy logic, fuzzy sets are used to show ideas that aren't clear or aren't well-defined. A fuzzy set has a membership function that tells each item in the set what level of membership it has. To give you an example, a fuzzy set for "high temperature" might have items from 0 to 1, where 0 means "not high" and 1 means "very high."
- Fuzzy Inference Systems: Fuzzy reasoning built on fuzzy rules uses fuzzy inference systems to decide what to do. Three key parts make up a fuzzy reasoning system: fuzzyfication, rule evaluation, and defuzzification. Fuzzyification turns the input data into fuzzy sets, rule evaluation uses fuzzy rules to figure out how much the output fuzzy sets belong to each other, and defuzzification turns the fuzzy output back into a clear value.
- Smart Energy Management: Fuzzy logic is used in smart energy management to do things like find faults, predict load, and optimize energy use. For instance, a fuzzy logic controller can change how the building's HVAC systems work based on fuzzy rules that take into account things like the number of people in the building, the temperature and humidity outside, and so on.

V. APPLICATIONS OF INTELLIGENT CONTROL IN SMART ENERGY SYSTEMS

A. Demand Response and Load Management:

Demand response is an important part of smart energy systems because it lets people change how much energy they use based on grid data. Smart control is an important part of demand response because it coordinates and improves the actions of many different systems and devices to lower high demand and keep the grid balanced. For example, heaters, lighting systems, and machines can be programmed to use less energy during busy times or when prices are high. Demand response programs can work better, be more reliable, and adapt to changing grid conditions if they use clever control.

Another important use of clever control in smart energy systems is load management. Smart control programs can look at past data, weather forecasts, and other things to guess how loads will change in the future and make sure that different parts of the energy system work at their best. Scheduling the use of demand-side resources, energy storage systems, and engines can help keep costs low, emissions low, and the system as a whole more efficient. Energy systems can better adapt to changes in supply and demand when they use clever control for load management. This makes the grid more stable and robust.

B. Energy Storage and Integration with the Grid:

Energy storage is a key part of smart energy systems because it lets you store extra energy and use it when you need it. Energy storage systems need to be managed well so that they are charged and drained at the right times to get the most out of their efficiency and dependability. Intelligent control programs can look at real-time data from the grid, weather forecasts, and other sources to find the best way for energy storage systems to work. This makes the grid more stable and cuts costs.

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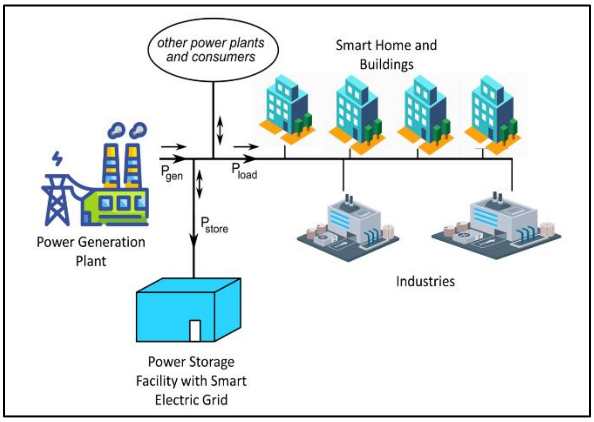

Figure 3: Illustration of Energy Storage and Integration with the Grid

Another important way that clever control is used in smart energy systems is for grid interaction. Energy systems can better add green energy sources like solar and wind power to the grid by using more complex control methods. Intelligent control can help handle the unpredictable and changing nature of green energy sources, making sure they are connected to the grid in a way that keeps things stable and reliable. Using smart control for grid integration can help energy systems use more green energy sources, lower their pollution, and work more efficiently overall.

C. Renewable Energy Integration:

Adding renewable energy is a big problem for smart energy systems because renewable energy sources aren't always available. Intelligent control is a key part of adding green energy sources to the grid because it handles how variable and unsure they are.

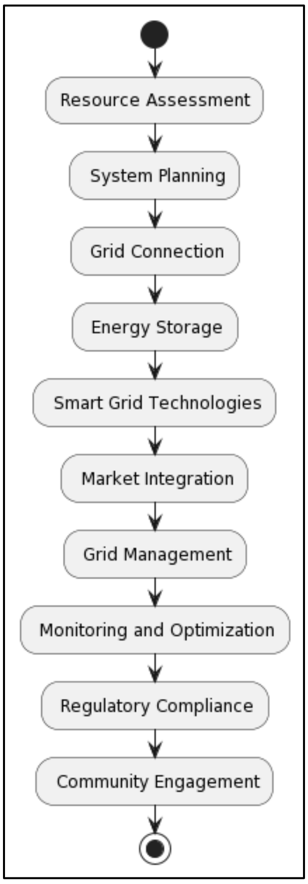

Figure 4: Process flow for Renewable Energy Integration in smart energy

This can include predicting how much renewable energy will be made, making sure that renewable energy systems work as well as they can, and making sure that other parts of the grid work together with renewable energy sources. Using smart controls to incorporate green energy sources can help energy systems use more of these sources, lower their pollution, and make the whole system more reliable.

D. Smart Metering and Monitoring:

Smart metering and monitoring are important parts of smart energy systems because they give real-time information about how much energy is being used, how much is being generated, and the state of the grid. To get the most out of this info and make the grid work better, intelligent guidance is needed to look at it and take action on it. Smart meters can tell people how much energy they are using in real time, so they can choose when and how to use energy more efficiently. Smart meter data can also be analyzed by intelligent control programs to find problems, predict future energy use, and find the best ways to use energy. Energy systems can be more efficient, save money, and make the grid more reliable by using clever control for smart tracking and billing.

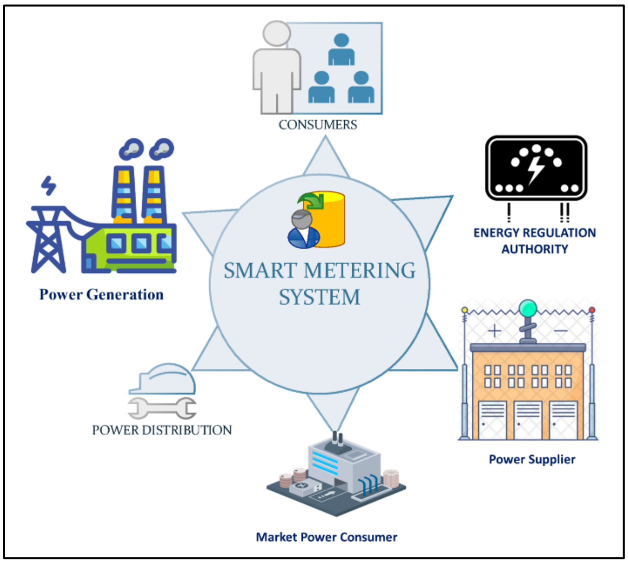

Figure 5: Overview of optimization in smart metering system in smart energy

VI. CONCLUSION

Intelligent control is one of the most important technologies for turning basic electricity systems into smart energy managers. Intelligent control techniques, like machine learning, neural networks, and fuzzy logic, can make energy systems more reliable, efficient, and long-lasting in ways that have never been seen before. Core electricity systems can improve their efficiency, use green energy sources, and adapt quickly to changes in supply and demand by using these technologies.Demand response and load management techniques can be used with intelligent control, which is one of its main benefits. Energy systems can change how people use energy in real time by using complex formulas. This lowers high demand and makes the grid more stable generally. This is good for both grid owners and customers because it gives them more information about how much energy they use, which leads to more efficient and environmentally friendly practices.It is also very important for adding green energy sources to the grid that they have clever control. Intelligent control helps make sure a steady and consistent energy supply by taking care of the changes and unknowns that come with using green energy. It is important to do this if we want to move toward a low-carbon energy economy and use less fossil fuels.Smart control also makes it possible to handle energy storage systems, grid integration technologies, and smart billing solutions well. When put together with smart control, these technologies make up the core of smart energy systems. They make it possible for a more reliable, efficient, and long-lasting energy infrastructure. The intelligent control is one of the most important technologies that is changing the way core electricity systems work so that they are better, more efficient, and last longer. When we use clever control, our energy systems can reach their full potential. This will help make the world better and more sustainable.

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