DC Microgrid: A Review

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Abstract

This paper mainly focuses on the applications of DC microgrid and energy management systems. Direct Current Microgrid is characterized by attractive features such as high efficiency, reduced cost and needless synchronization. The most common methods used for energy management of microgrid systems, namely the classical and artificial intelligence methods have also been discussed. Methodologies like ILC, LPM, from classical methods and fuzzy logic methods, and neural network methods from artificial intelligence methods have also been discussed in detail.

Keywords—microgrid, renewable energy, energy management system, feedback control system, energy scheduling, artificial intelligence method, classical method.

# Introduction

The microgrid consisted of renewable energy sources, an energy storage system, and controllable loads that can flexibly test different ideas related to microgrid operation and control while allowing considerable flexibility and reconfiguration capability [1]. After testing DC microgrid protection from various aspects such as DC fault current characteristics, grounding systems, fault detection methods, protective devices and fault location methods, it is concluded that DC microgrids are superior to AC microgrids in terms of reliability, efficiency and ease of control. integration of renewable energy sources and connection of DC loads [2]. A hybrid smart DC microgrid community system was completed using high time resolution data compared to a system optimized using lower speed time data to investigate the effect of time sampling of a renewable energy source [3]. A three-phase bi-directional PWM VSSC (ac-dc) is used to combine WT with DCMG which produces a constant DC voltage, but in case of any failure of this VSC, the DC boost converter is left to work to integrate the SPV to produce a constant DC voltage and the SOFC generation is also combined with this DCMG to maintain power balance in it [4]. Presenting a quantitative method for DC microgrid availability by identifying and calculating the minimum cut sets the probability of occurrence for converter topologies and different microgrid architectures [5].

Energy storage devices are typically used in renewable energy systems to increase system reliability. In a photovoltaic direct current microgrid (PVDCM), the system is designed to consist of a solar power system, a bus connected to a common bus through a boost converter, and a bidirectional buck/boost converter [6]. The behavior of physical compact, multi-terminal DC networks under electrical fault conditions can create demanding protection requirements, which represents a significant barrier to the wider adoption of DC power distribution for microgrid applications [7]. A distributed attack detection scheme for a DC MG system is presented, where the proposed detector detects all attacks only with the knowledge of the entire DC microgrid system, and by the eigenvalue assignment method, the proposed residual is separated from the load and neighboring voltage changes, also a nan optimization problem is provided to increase the attack detectability of the proposed observer [8]. The potential advantages of the DC system over the AC technology have made the DC microgrid a competent solution for anonymously increasing DC applications and load requirements [9]. Consisting of a half-bridge and center tap with terminal circuit, the converter provides power for low voltage high current applications. 650V gallium nitride (GaN) high electron mobility transistors (HEMTs) are used on the high voltage side to avoid the problems seen when using Si super junction mosfets in bidirectional phase-shift controlled power conversions, where the operating principle and power transfer characteristics are obtained based on analysis of the inductor current in the time domain [10].

A novel output-limited decentralized control algorithm for single-bus DC microgrids, where the control objective is to realize high-performance DC bus voltage control, user-defined load sharing, and circulating current minimization [11]. Design of a DC microgrid system for electricity supply considering load estimation scenarios with standard and high-efficiency appliances, where simulation shows that the proposed DC microgrid is a valid option for area electrification under each load and generation scenario [12]. A distributed cooperative control framework for multiple DC ESs in a DC microgrid presents a small signal analysis system, where the primary level implements droop control to coordinate the operations of multiple DC ESs, and the secondary control is based on a consensus algorithm. to regulate the DC bus reference voltage, including the balance of state of charge (SOC) between DC ESs. With this design, cooperative control can achieve the average DC bus voltage [13]. The converter switch snubber cannot be directly used for the SSCB snubber design, because the SSCB snubber puts more emphasis on its overvoltage suppression and fault current resistance instead of reducing the snubber loss, so it tries to create a snubber design method specialized in SSCB overvoltage suppression in bus fault interruption. and a targeted set of measurements is designed and applied to compare three RCD relief candidates: charge-discharge type, type I suppressor discharge, and type II suppressor discharge [14].

This paper presents fuzzy control modeling, analysis, and design to achieve optimization of the power management system for a DC microgrid system. From the simulation results, the system reaches the equilibrium power and the battery SOC maintains the desired value to extend the battery life using control rules for the DC microgrid [15]. DC microgrid system possibilities and its viability were investigated. A complete design and analysis were proposed to effectively increase the energy conversion efficiency of a stand-alone solar PV system with a DC microgrid [16]. The conventional design method reported in the literature considers the nominal voltage of the supercapacitor when modeling and designing regulators. However, a supercapacitor unit can discharge up to 10% of its rated voltage due to self-discharge [17]. The resources are controlled using a decentralized droop-based controller. Various components of the system were modeled. A linearized system model is derived using a small signal approximation. the sensitivity of system poles to changes in cable resistance and inductance is identified. It is proven that the poles move further in the negative real plane with a decrease in inductance or an increase in resistance. The literature concluded that a DC system instead of a conventional AC system would improve operational efficiency and reliability [18]. A composite prescribed power control strategy is developed to stabilize a DC/DC boost converter supplying constant power loads. First, using the exact feedback linearization technique, the system of nonlinear uncertain DC converters is first transformed into the Brunov canonical form. Then, a nonlinear fault observer is used to evaluate the dynamic change of the load power, the accuracy of the output voltage regulated by forward compensation [19].

The suitability of the proposed high-gain, high-power DC-DC converter is demonstrated by experimental tests of the 60 V/1.1 kV, 3 kW converter; test results verify the inverter's suitability for DC distribution. A significant number of performance parameters of the proposed converter are compared with state-of-the-art converter topologies [20]. This paper presents a new robust controller based on linear programming based on Chebyshev's theorem as a robust control technique with respect to Kharitonov's theorem, which ensures the minimization of the total deviation from the desired performance in a closed-loop system, specified by a group of characteristic polynomials. The purpose of the proposed controller is to tightly regulate the DC bus voltage, which ensures the stability of the MG due to the effects of power fluctuations on the CPL [21]. It includes multi-layer hierarchical control schemes, coordinated control strategies, plug-and-play operations, stability and active damping aspects, as well as nonlinear control algorithms. Islanding detection, protection and control of microgrid clusters is also briefly summarized [22]. The optimization takes into account the forecast of PV electricity generation and load energy demand while satisfying constraints such as storage capacity, grid performance constraints, grid time prices, and grid peak times. The optimization, the efficiency of which is related to the prediction accuracy, is performed by mixed integer linear programming [23]. Recent literature has suggested that there is a trade-off between information and energy flow, and that intelligent, coordinated control of energy flow in a microgrid system can change the hardware requirements for energy storage. Two scenarios are considered; i) an example of a simple two stochastic source variable load renewable DC Microgrid and ii) a three-zone electric ship with a DC Microgrid and varying pulse load profiles [24].

First, the modeling and control of the DC microgrid is presented, and then the impacts of the resistive SFCL on the DC microgrid fault current and bus voltage drop are briefly analyzed. Using MATLAB, simulations are performed on various parameters of SFCL and the results confirm that the contributions of SFCL for DC microgrid include that: i) DC fault current is limited quickly and effectively. ii) The bus voltage drop is sufficiently compensated to ensure that the renewables reach fault-through operation. iii) The power transmission efficiency of the DC microgrid during a fault is suitably increased. Finally, a conceptual design of the resistive SFCL [25] is performed. This paper presents an analytical rationale for using a distributed voltage control scheme to stabilize the grid voltage over a wide range of operating conditions. Our simulations of a simple system with 2 PMUs connected to a power source show the stability of the proposed microgrid under power transients. The development of individual components of the microgrid system and the planned experiments described above will be used to demonstrate the stability of the microgrid during normal operation and recovery from failures [26]. The objective of this paper is to present the dynamic effect of CPL on a DC microgrid and how to implement a fault-tolerant multi-agent stabilization system to ensure grid stability. The main interest of the method is that it allows designing a stabilization system in such a way that it is able to ensure the stability of the network even in case of loss of one of the agents and in case of system reconfiguration. This is achieved by considering the stability issue as a constrained optimization problem [27].

Switching and impulse signals are used to model the dynamic DC microgrid system under DoS and FDI. A combined current and voltage fault is proposed and a switching secondary regulator is designed to deal with cyber attacks. Based on the method of stability analysis on hybrid systems, we establish a sufficient condition for the selection of control parameters in relation to the average delay time of an FDI attack and the normal communication speed in a DoS attack [28]. Microgrids can improve PV penetration efficiency, such as avoiding unwanted power injection and mitigating grid power fluctuations. Control refers to balancing performance with an energy management interface while respecting performance limits imposed by the grid and combining metadata and user requests [29]. The current control block consists of oscillatory current sharing and direct current sharing units. The main idea of ​​the proposed method is to share the oscillatory and DC components of the load current among the DG units based on their rated power by assigning the respective output impedance values ​​and droop coefficients to each DG unit [30]. The supervisory control, designed as a four-layer structure, takes into account the forecast of electricity generation and load power demand, storage capacity, network power limitation, time-of-use tariffs, optimizes energy costs, and solves instantaneous power balancing in the microgrid [31]. A suitable protection paradigm can only be achieved if it continuously requires a systematic consideration of DC topology, grid interconnection, grounding system, inverter operation and subsequent fault type and fault current behavior step by step [32].

A model of a nonlinear event-triggered DC microgrid system was developed. Using the average delay time method and the piecewise Lyapunov functional method, the asymptotic stability criterion of the resulting DC microgrid system was derived [33]. The purpose of the controller is to mitigate the effects of constant power load on the stability and performance of the DC microgrid system. In this work, the overall structure, operation and building blocks of the analyzed DC microgrid are first presented [34]. The analysis concluded that for the given loads, the best system design is composed of a 15.3 kW PV array, a 17 kW diesel generator, 57 kWh lead-acid batteries and a rated inverter. 6.93 kW; the total NPC of this system equals £56,264 [35]. In this paper, a robust circuit parameter design scheme for CLLC-DCT is proposed. With the proposed scheme, the proposed CLLC-DCT exhibits good power transfer and voltage regulation capability in a hybrid AC/DC microgrid, although its actual inductor/capacitor values ​​change with practical power and temperature [36]. Consumption management and power management rely on the control of different DC microgrid units. This paper presents an Islanded DCMG in which the PV system and the wind system are connected to the DC bus through a coupling device [37]. The distributed coordination control including containment-based voltage regulator and consensus-based current regulator is designed to offer a compromise control between voltage-bound regulation and current sharing, which is a highly flexible and reliable operation for islanded DC MG. A compromise concept is achieved by tuning the control weights between two controllers under different system conditions [38]. This document aims first to shed light on the practice

This paper aims to first shed light on the practical design aspects of DC MG technology regarding typical power hardware topologies and their suitability for various emerging smart grid applications. Furthermore, an overview of the current state of DC MG protection and grounding technology is presented [39]. This thesis describes the modeling, simulation and configuration of a Dual Loop Controller for the operation of Positive Performance Super Lift Luo (POESLLC) CCD Microgrid converters. Incorporating green energy sources makes DC microgrids exciting. Super lifting Luo converters are crucial for DC source connection in DC microgrids due to the low performance of these DC sources [40]. This paper presents a novel isolated bidirectional 400V to 12V DC-DC converter based on a modified phase-shift controlled double active bridge power stage. The proposed converter consists of a half-bridge and a center tap with an active clamp circuit, which has promising performance for low-voltage, high-current applications [41].

DC microgrids consist of multiple power electronic converter units connected in a network with sources and loads. They are commonly found in the power systems of electric ships, aircraft, etc. [42]. In this paper, the design of a low voltage (LV) DC microgrid protection system is proposed. A LV DC microgrid is used to interconnect distributed sources and sensitive electronic loads. In this contribution, the operating principles and technical data of DC LV protection devices, available even in the research phase [43], are presented. DC microgrids (MGs) have been gaining and DC microgrids (MGs) have been gaining steadily increasing interest in both academia and industry for the past few years. The advantages of DC distribution compared to its AC counterpart are well known [44]. The increased use of DC microgrid for critical applications has led to the need for advanced control design for stable system operation. Loads connected to a DC microgrid are controlled by power electronics and exhibit constant power load (CPL) behavior, which poses a serious challenge to stability as it increases nonlinearity and minimizes effective damping [45]. A DC microgrid (MG) system has several advantages over an AC system. Therefore, it has recently become the preferred architecture in many industrial applications. This paper proposes a systematic and simple design approach for an improved buffer state feedback controller that can stabilize DC MGs with multiple CPLs. The LMI conditions can be solved numerically using the YALMIP toolkit in MATLAB [46].

Low-voltage, low-energy direct current microgrids based on solar photovoltaic (PV) are becoming very popular in non-electrified areas of developing countries due to a) lower initial costs compared to grid alternatives and b) the limited energy needs of rural residents. In this work, we develop a framework for optimal planning and design of low-energy, low-voltage DC microgrids with minimal initial cost [47]. This paper is a nonlinear adaptive feedback controller designed to control the DC bus common voltage for different components in a DC microgrid under different operating conditions [48]. The main goal of this research was to create a semi-automatic object image analysis (OBIA) methodology for landslide localization. We used specific combinations of these information layers to generate objects by applying segmentation at multiple resolutions in a sequence of feature selection and object classification steps [49]. Novel DC microgrids, which feature simple and efficient integration with renewable energy sources and energy storage elements, are attracting increasing attention in industrial applications [50]. A fuel cell is a promising resource in an autonomous DC microgrid. Hybridization of a fuel cell with a battery is commonly implemented to overcome the slow dynamics of the fuel cell. Then the battery compensates for the high-frequency fluctuation and the fuel cell provides consistent steady-state performance [51]. This work presents a performance study of a DC microgrid when a voltage drop technique is used to regulate the grid voltage and control the load sharing between different sources. A small DC microgrid model containing microsources and loads was implemented in the Simulink/Matlab environment [52]. It is known that the behavior of constant power loads is a potential cause of instability of DC microgrids. This issue is dealt with by the DC microgrid stabilizer proposed in this article [53]. In this paper, we present a feedback control scheme for a hybrid alternating current (AC)/direct current (DC) microgrid bidirectional link converter. The output voltage and current are measured, which allows us to design an appropriate power flow control [54]. In this paper, islanding mode droop control is implemented. In this study, a parallel circuit containing three DC/DC converters (two Boost and one Buck) was designed, which were connected to a resistive load and a constant power load through a multipole switch [55].

More than 1.3 billion people worldwide, mainly in Africa and Southeast Asia, do not have access to electricity. Electrification of these remote rural regions through national power grids is largely unviable due to i) high infrastructure costs and ii) limited power generation capacity in many countries. Therefore, low-power, low-voltage solar photovoltaic (PV) DC microgrids are becoming very popular in these regions [56].

This article presents an overview of the latest advances in DC distribution systems. Due to the significantly increasing interest that DC power systems are gaining recently, researchers have explored several issues that need to be considered during this transition interval from current conventional power systems to modern smart grids including DC microgrids [57]. In this paper, we introduce the concept of ubiquitous biofeedback serious games (UBSG), a family of games that integrate biofeedback processes into their operation. They rely on physiological inputs collected from the player via biological sensors to control gameplay [58].

In this paper, we introduce the concept of ubiquitous biofeedback serious games (UBSG), a family of games that integrate biofeedback processes into their operation. They rely on physiological inputs collected from the player via biological sensors to control gameplay [59].

The direct current (DC) microgrid has attractive features such as high efficiency, reduced cost, and the necessity of synchronization. Control and operation of the DC microgrid is gaining importance with the high penetration of distributed energy sources. Therefore, the development of an advanced platform for testing DC microgrid control and operation is attracting more and more attention nowadays [60].

This paper presents microgrid distributed energy resources (DER) for a rural stand-alone system. It consists of a solar photovoltaic (solar PV) system, a battery energy storage system (BESS) and a wind turbine coupled to a permanent magnet synchronous generator (WT-PMSG). DERs are controlled by maximum power tracking (MPPT) based proportional-integral (PI) controllers for both maximum power tracking and error feedback compensation [61].

This paper focuses on the design of a controller to obtain microgrid voltage stability. Two controllers [PI and fuzzy logic PI (FL-PI)] are designed to analyze the voltage stability of the DC microgrid. Real-time simulation result [62].

This paper presents the modeling and simulation of an autonomous DC microgrid in the Matlab Simulink environment. The proposed microgrid system consists of a wind turbine, a solar PV array and DC loads [63].

This work presents a performance study of a DC microgrid when a voltage drop technique is used to regulate the grid voltage and control the load sharing between different sources. A small DC microgrid model containing micro sources and loads was implemented in the Simulink/Matlab environment [64]. DC microgrids, which feature simple and efficient integration with renewable energy sources and energy storage elements, are attracting increasing attention in industrial applications. In this article, a two-way Z-source circuit breaker with an O-shaped impedance network (abbreviated O-Z-source circuit breaker) is proposed, which will guarantee the reliable operation of DC microgrids. With a simplified structure, the O-Z source circuit breaker enables bidirectional power flow with fewer components compared to conventional Z source circuit breakers [65].

This paper investigates the design of a centralized nonlinear controller based on integral terminal and fast integral terminal sliding mode control for a hybrid AC/DC microgrid including a renewable distributed generator as the primary source, a fuel cell (FC) as the secondary source, and a battery. ultracapacitor as hybrid energy storage system (HESS) [66].

This project involves the design of a low voltage DC microgrid system for rural electrification in South Africa. Solar energy is freely available and environmentally friendly, and is considered a promising energy source due to its availability and topological advantages for local electricity generation [67].

In DC microgrids, constant power loads (CPL) reduce the effective damping of the DC-DC converter and can cause destabilizing effects on the DC-DC converter. To overcome such CPL issues and ensure the large-signal stability of DC-DC converters in DC microgrids, some forward terms are added to a two-loop V-I drop-based controller for a large-signal DC-DC converter [68].

In this paper, a novel energy storage system (ESS) voltage regulator in DC microgrids (DCMG) is proposed to enhance DC bus voltage stability. First, a mathematical model of the DC-MG in state form is developed [69].

A hierarchical control framework comprising primary, secondary, and tertiary levels has become the standard solution for microgrid (MG) control, where the tertiary is responsible for managing the power flow between microgrid clusters. This paper presents the design of a tertiary-level predictive function controller (PFC) for DC microgrid (DCMG) clusters [70].

Microgrid EMS is a multipurpose system that addresses technical, economic and environmental issues. The main goals of EMS are to optimize operation, energy planning, and system reliability in both grid-connected mode and island mode [71].

Different energy management strategies have been proposed in the literature [71] to achieve an optimal and efficient operation of microgrids. The most common methods used for the energy management of microgrid systems can be categorized into two major categories as follows:

a) Classical methods

b) Artificial intelligence methods

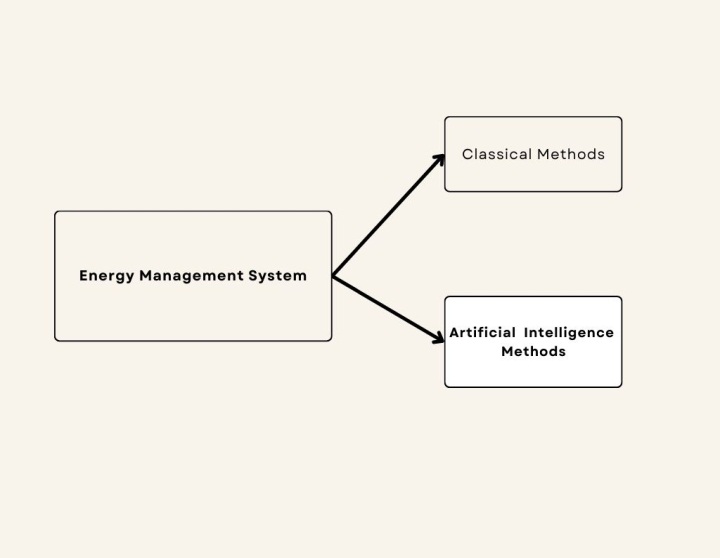
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Fig. 1: Classification of energy management system.

**a) Classical Methods:**

1. ***Iterative Language Control***

ILC is a control methodology that is particularly suitable for dynamic systems whose control tasks are performed in a finite time interval and are constantly repeated. The key idea behind ILC is to take available system information from past and current runs and generate control input for the next run.

1. ***Linear Programming Methods***

A linear programming (LP) method is presented for calculations of safety dispatch and emergency management on large energy systems. The method is reliable, fast, flexible, easy to program and requires little computer storage. The linear programming method is used to minimize the total cost of energy consumed and the net cost in steam-condensing systems. The LP technique will determine the optimal values ​​of process design variables to achieve minimum cost.

1. ***Mixed***[***integer linear programming***](https://www.sciencedirect.com/topics/computer-science/integer-linear-programming)***(MILP)***

It is a state-of-the-art mathematical framework for optimizing energy systems. The ability to solve relatively large problems that involve temporal and spatial discretization is particularly important for planning the transition to a system where inseparable energy sources are key. Here, one of the main challenges is to realistically describe the technologies and system boundaries: on the one hand, linear modeling and on the other hand, the number of variables that the system can handle requires a trade-off between the level of detail and computational time.

1. ***Model predictive control (MPC)***

It is an advanced process control method that is used to control a process while meeting a set of constraints. It has been used in the process industry in chemical plants and oil refineries since the 1980s.

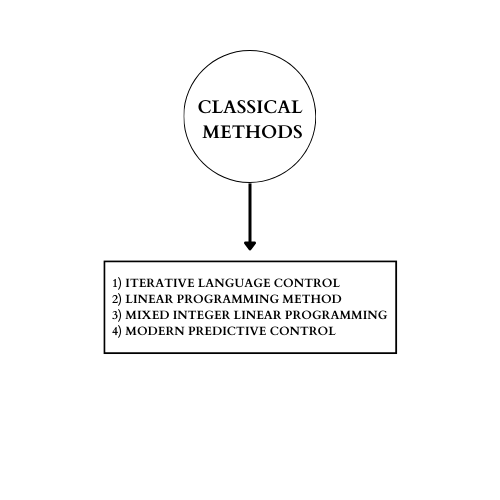
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Fig. 2: Different types of classical methods.

**b) Artificial Intelligence Methods:**

1. ***Fuzzy Logic Method***

fuzzy modeling of each input variable is converted to a fuzzy variable using a process called fuzzification. Basically, fuzzification converts numeric input values ​​into linguistic variables. The second process uses fuzzy sets to categorize each input value.

1. ***Neural Network Method***

The standard method for training neural networks is the stochastic gradient descent (SGD) method. The problem with gradient descent is that to determine a new approximation of the weight vector, it is necessary to calculate the gradient from each element of the sample, which can slow down the algorithm considerably.

1. ***Evolutionary Algorithms***

Evolutionary algorithms in real problems. Similar to swarm intelligence algorithms [6], the main reason is the growing demand for intelligent optimization methods in many business and engineering activities. EAs are particularly suitable for optimization, planning, scheduling, design, and control problems.

1. ***Multi-Agent System***

MAS can be viewed as a collection of

autonomous and intelligent entities called agents, evolving in

an environment they can perceive and act on. This environment

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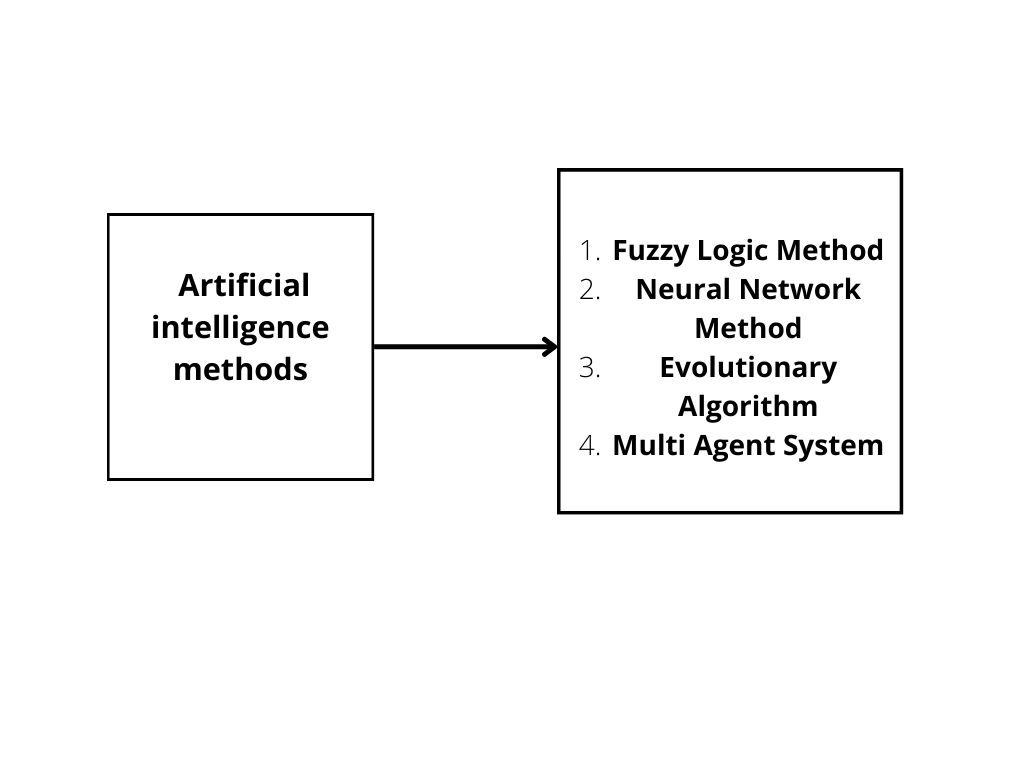


Fig. 3: Different types of artificial intelligence methods.

# Conclusion

##### In comparison with the conventionally used AC microgrid and hybrid AC/DC microgrid, the DC type has so many compensations in terms of system reliability, efficiency, and cost-effectiveness. However, different aspects, like protection systems, control tactics, architecture design, and stabilization techniques need a lot of research effort. This paper has reviewed several cases regarding DC microgrids in various applications.

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