Recent Research Trends of Artificial Intelligence Applications in Power Electronics

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Abstract- The artificial intelligence (AI) is one of the most significant topics to obtain an optimal solution in various applications. Focusing on the AI applications to the power electronics, this paper presents their tendency and future trend systematically and exhaustively. In the process, IEEE Xplore is chosen for the paper investigation and the result is arranged chronologically. Furthermore, several considerable AI methods for the power electronics, such as the neural network, deep learning, genetic algorithm, particle swarm optimization, and multi-objective optimization, are explained. Several published papers with respect to AI applications to the power electronics in the renewable energy system are also introduced.

Keywords Artificial Intelligence (AI), Convolutional Neural Network (CNN), Evolutionary Multi-Objective Optimization (EMO), IEEE Xplore, Neural Network (NN), Power Electronics, Renewable Energy System.

1. Introduction

Recently, the research concerned with the Artificial Intelligence (AI) have been proceeded in the world. General Electric (GE), USA proposed Industrial Internet in 2012 [1]. The German government proposed Digital Germany 2015 (DG2015) in 2010 and Industry 4.0 in 2013. The Internet of Things (IoT) and AI have been recognized as key technologies to realize such a society. These technologies are tried implementing into the industry, service, etc. In the Industrial Internet, it is mentioned that these technologies are effective for the power generation, power conversion, and energy saving. It is noted that the AI application to the power electronics is not discussed.

The power electronics is the technical field related to the power conversion technology and motor drive technology using dc-ac inverters. Neither technology have remarkable AI applications. Due to this situation, Both AI engineers and power electronics engineers cannot understand how to apply AI to the power electronics.

The following six stages can be considered as the AI applications to the power electronics:

1) Device design
2) Circuit design
3) Control
4) System operation
5) Energy management
6) Engineering

When the current situation continues, the stage 4) to the stage 6) would be general AI applications to the power electronics, and the stage 1) to the stage 3) would be neglected. For the stage 6), the automation and failure prediction of equipment is achieved by the AI in the model-based manufacturing process, where the concept of Industry 4.0 is referred.

There are few academic papers about the stage 1) to the stage 3) mentioned below. In the stage 1), the IGBT gate drive was reported by the University of Tokyo and Kyushu Institute of Technology in 2017 [2]. In the stage 3), the switching power supply control for the hall effect thruster was only reported by F. Kurokawa et al. [3]-[9].

On the other hand, in the stage 4) and the stage 5), the operation of batteries and distributed power sources is important in the renewable energy system because the renewable energy sources generate power unstably. M. Vasirani et al. proposed the combination scheme of wind turbine generator (WTG) and electric vehicle (EV) to achieve the virtual power plant (VPP) and evaluated the system from the economic point according to the data of power from WTG, market price, and EV characteristics. Z. Zhao et al. and H. H. Abdeltawab et al. proposed the energy management optimization using the evolutionary computation (EC) and swarm intelligence (SI) as the AI applications to the system operation [10], [11]. These applications have been started. It can be predicted that AI would be utilized for taking advantage of the renewable energy and that many researchers would participate.

S. E. De Leon-Aldaco et al. [12], B. K. Bose et al. [13], G. Lei et al. [14], P. Qashqai et al. [15], S. Zhao et al. [16] have reported the papers reviewing the AI applications to the power electronics in such a situation. [13] introduces the expert system and neuro-fuzzy applied to the WTG. They are now early-stage methods. [15] explains general AI methods and introduces the papers focusing on the AI applications to the electric power field, including the power line and micro grid, and to the power electronics equipment, for instance, the power converters. Zhao et al. comprehensively reviews AI algorithms and applications from the viewpoint of life cycle [16]. The features of this paper are that AI functions are classified into the optimization, classification, regression, and clustering and three life cycle phases, the design, control, and maintenance, are focused on as AI applications. In [14], the design optimizations for the electric machines are reviewed. The design optimization method using EC or SI are introduced. Although [12] reviews the metaheuristics for the stochastic optimization of power quality and waveform, circuit design, and control parameter adjustment are reviewed, it is old.

These papers do not classify systematically and exhaustively the AI applications to the power electronics. Also, the investigations for the recent research in these papers are insufficient so that the trend of AI applications to the power electronics cannot be grasped.

This paper presents the tendency and future trend of AI applications to the power electronics systematically and exhaustively. For the review and future prospect, the number of papers concerned with these applications is investigated and arranged chronologically using IEEE Xplore, which is one of the biggest data bases in the electric and electronics field.

The stages 2) to 5) of the AI applications to the power electronics will be reclassified in Section 2. Then, the types of AI, number of papers, and research fields for each AI applications are discussed. Section 2 reclassifies the stages 2) to 5) into the four stages i) to iv) to grasp the research trend of AI applications to the power electronics precisely. The stages i) to iv) indicate following applications: i) design of circuit, machine, and system; ii) control; iii) system operation; and iv) detection or prediction of degradation, failure, and abnormalities. Note that the stages 1) and 6) are omitted because of the following reasons: there is few papers in the stage 1), and the application is close to the industry in the stage 6). S. Zhao et al. classifies these applications into the design, control, and maintenance [16]. This paper, in addition, considers the operation, with which research concerned gains momentum, as a new classification. In [16], the operation is included in the control or maintenance. The investigation is carried out according to the following rules: the journal papers published by 2019 are the targets; their abstracts are searched using several keywords. The expert system and fuzzy system, which are old AI methods, are excepted since the aim of this paper is to investigate latest papers. Although the proceedings are not included and the total number of papers are small, the abstracts of strictly reviewed target papers have enough high reliability. The search results are verified by comparing with the body of papers. In Section 3, the types of AI, which can be applied to the power electronics, will be expressed. At last, Section 4 focuses on the AI application to the power electronics in the renewable energy system, which is one of the important current topics in the world, to solve the environmental issues.

It would be much appreciated if the results provided in this paper helps readers to start the AI research in the power electronics and leads to vitalization of this research field.

2. AI Applications to Power Electronics

The AI applications to the power electronics are reclassified into following fields:

i) Circuit, machine, and system design

ii) Control

iii) System operation

iv) Detection or prediction of degradation, failure, and abnormalities

The discussion will be proceeded based on this classification in this paper.

The paper investigation in each field is carried out by using IEEE Xplore Digital Library and focuses on the journal papers published until the end of 2019. Also, the way to search is to find the specified multiple keywords in the abstract. Thus, the search style is shown as follows: “Abstract”: keyword 1 AND “Abstract”: keyword 2 AND “Abstract”: keyword 3 AND … AND “Abstract”: keyword *N*.

2.1. Circuit, Machine, and System Design

The most basic AI applications to the power electronics are the design of circuit, machine, and system. They are divided into the following four optimizations: the first is the structure of circuit, machine, and system, the second is the parameter of circuit, structure, and system, the third is the model of circuit, structure, and system, the fourth is the normalization of design and parts and design procedure. EC and SI are effective methods for them. In addition, the combination of EC and neural network (NN) is effective for autonomous generation such as the circuit, machine, and system structures, circuit parameters, modeling, and so on.

The restriction setting in the circuit design is important and difficult. Due to this reason, partial developments would be proceeded. The system design and parameter optimization have similar difficulties, but it is relatively simple. Therefore, the AI can contribute effectively to them, and they have been developed before anything else. The papers concerned with the optimization of power line including the renewable energy system, which consists of emergency generator, photovoltaics, and batteries, has been reported. Some examples are introduced below.

According to [17] and [18], the NN and EC are applied to not only the power system but also the renewable energy system. They have been studied since around 2011. The EC or SI is also applied to the electric machine design [19]-[21].

The number of papers related to the motor design optimization using the genetic algorithm (GA) and particle swarm optimization (PSO), and its transition are shown in Fig. 1. The keywords in the search style are motor, design, optimization, and genetic algorithm for GA, while motor, design, optimization, and particle swarm optimization for PSO. The search results in this condition includes papers which is not subject to the search. The error rate of search is 0.1 (8/72) for the GA and is 0.25 (11/44) for the PSO. The search style is modified by adding “AND NOT controller” to remove the papers focusing on the motor control because the most of error is motor control optimization. As a result, the error rate of search, which indicates how many unexpected papers are included in the result, is reduced to 0.05 (three papers) for the GA and 0.08 (three papers) for the PSO. Eight papers including both methods, where the GA and PSO are combined or the comparison target, are reflected to both search results. The following discussion excludes the AI application to the motor control.

From 1990s to early 2000s, the GA was the mainstream in the motor design optimization. As a result of searching with the IEEE Explorer, no papers concerned about GA and PSO before 1990 are found. The PSO was utilized around 2010. Both GA and PSO are used in recent research. In 2011, the number of published papers reached its peak and decreased for two years right after the peak. Then, the peak came again in 2014. As the trend around former peak, the motor design optimization using analysis model was the mainstream. It was formulated as a single objective optimization problem and seemed to be laboratory level rather than the product development. The linear motor and permanent magnet (PM) motor were the research targets in these papers. On the other hand, around the latter peak, the electromagnetic field analysis, surrogate model, and topology optimization were proposed. Many papers proposed the formulation as the multi-objective optimization to strive the trade-off of cost and performance. Although the brushless motor was mostly chosen as a target because of the vehicle electrification, other motors utilized different applications were also the target. It seems that the object of these research were applications to the product development.

The fundamental discussion of system design and parameter optimization will be provided in the next chapter.

2.2. Control

It is important for the AI applications to the control in the power electronics to derive the model of control target. In this process, the k-nearest neighbour (k-NN), general linear model (GLM), support vector machine (SVM), and NN are utilized. Sometimes, these methods are combined with the EC and SI.

In this AI application, the AI mostly rather tunes the feedback controller in advance to easily correspond to various disturbances without learning than derives the complicated system model such as the non-linear model. The AI is only applied to the hall thruster engine control on the satellite [3]-[9] and the feedback signals estimation for a vector controlled induction motor drive [22].

From 2009 to 2012, F. Kurokawa et al. actively proposed the fast control using NN for the switching power supplies. These outcomes were summarized and published in [8], [9]. In [8], the tuning parts are divided finely, and there are many tuning parameters. Many parameters would lead to a reduction of reliability. Hence, it is not always effective to depend on the many parameters tuned by the AI and to make them necessary.

The number of papers related to the switching power supply control using the NN, and its transition are shown in Fig. 2. The keywords for searching are dc-dc converter, digital control, and neural network. The conference papers are included in the results because there are few journal papers. The search style is modified by adding “AND NOT “Abstract”: chopper” to be omitted the early papers concerned with the chopper. Consequently, the error rate of search is 0.1 (2/20). Almost papers searched here were published by F. Kurokawa et al. As a result, it becomes clear that the NN is utilized for the switching power supply control for the following purposes. The NN improves the efficiency and controller response of the dc-dc converter to dynamical system changes [23]. The NN also realizes a faster load transient response and superior soft start performance of the dc-dc converter [24]-[38]. In the PV system, the NN is used to identify the maximum power point [39], to improves the control performance of the dc bus voltage [40], and to improves the low-voltage ride through (LVRT) performance

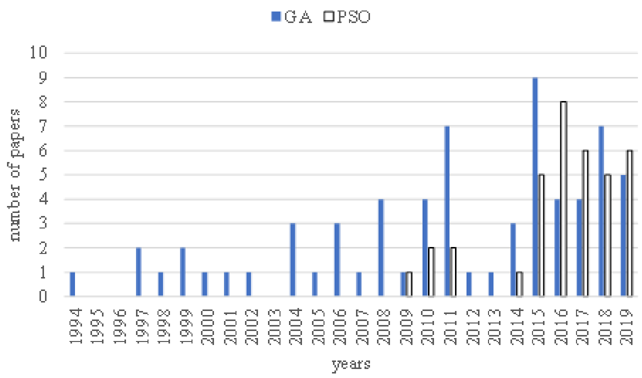

Fig. 1. Transition of papers with respect to motor design optimization using GA or PSO.

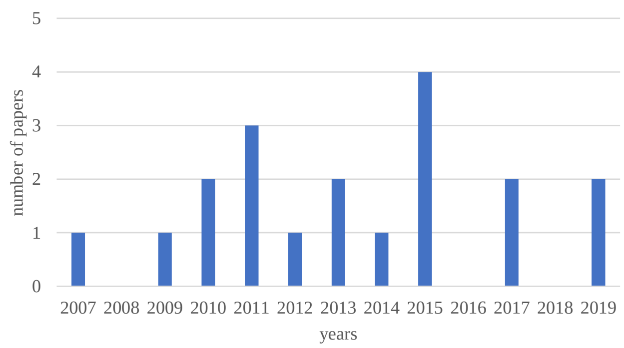

Fig. 2. Transition of papers with respect to switching power supply control using NN.

[41]. Especially, the compensatory fuzzy neural network with an asymmetric membership function (CFNN-AMF) and the recurrent wavelet fuzzy neural network (RWFNN) are proposed as the modified NN in [40] and [41], respectively. The recurrent fuzzy neural network (RFNN) achieves the power smoothing control in the WTG system [42].

As the learning process is necessary in this field, a utilization to the applications where the limited learning range exists is expected. For instance, the hall thruster engine control mentioned above and electric machine design in [10] are listed.

The k-NN, GLM, SVM, and NN are applied to the optimization and automatic generation of dynamically changing control parameters. In this application, the limited learning range is the key to utilize these methods since a wide range learning brings its difficulty.

Although the controller optimization is generally strived after the circuit and system optimization, the results of controller optimization sometimes effect on the restriction and condition of circuit and system optimization. Therefore, there is some possibility of being required the circuit and system optimization again.

2.3. System Operation

The energy management optimization is listed as the AI application to the system operation. The EC and SI are suitable to this application as proposed in [11], [43].

As reported in [44], [45], the NN is applied to predict the output power of photovoltaics (PV) in the operation of micro grid including renewable energy sources. There are relatively many papers concerned with this topic.

For the PV output power prediction using NN, its number of papers and transition are described in Fig. 3. In the search style, photovoltaic, forecast, and neural network are chosen as the keywords for the NN. Also, photovoltaic, forecast, and deep learning (DL) are chosen as the keywords for the DL. The search results are compensated to omit the double count. The keywords in the search style for the compensation process are set to photovoltaic, forecast, neural network, and deep learning. The number of papers obtained by the compensation process is subtracted from the search result of NN and is added to the search result of DL. The error rate of search is 0.08 (3/38) here.

An interest in the renewable energy recently accelerates the publication of such papers. An amount of annual world's PV implementation and its transition published by the international energy agency (IEA) are shown in Fig. 4. From the comparison between Fig. 3 and Fig. 4, the paper publication had been started when the PV implementation exceeded 20 GW in 2011 and has been increasing when the PV implementation exceeded 100 GW in 2017. It can be said that there is obvious interrelation between Fig. 3 and Fig. 4. The PV implementation leads to the necessity of PV output power prediction. The mainstream has been orthodox multi-layer NN in this application. For the improvement of prediction accuracy, the DL will be applied mainly.

This optimization affects the restriction setting in the

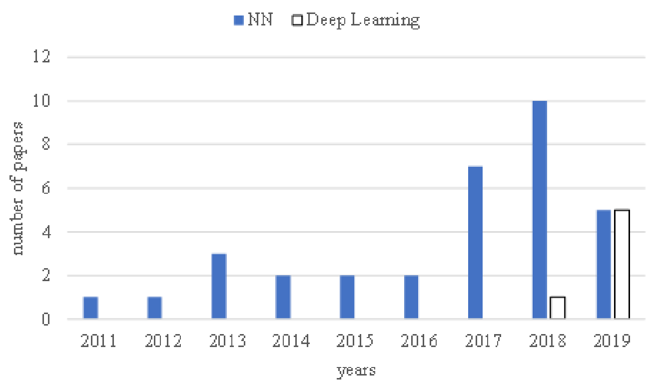

Fig. 3. Transition of papers with respect to PV output power prediction using NN.

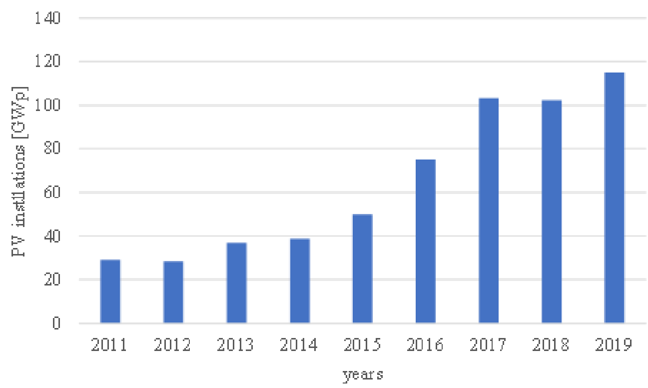

Fig. 4. Transition of annual world's PV installation.

circuit, machine, and system design and control. It is the same the other way around. This mutual effect should be considered when the AI is applied.

2.4. Detection or Prediction of Degradation, Failure, and Abnormality

It seems the AI applications to the detection or prediction of degradation, failure, and abnormalities are the most effective and quickly provides benefits.

At first, the acquired data should be modified for the learning process of AI. For instance, the k-NN, GLM, SVM, and NN are utilized for the regression analysis, which estimates a variable from the acquired data. The decision tree (DT), k-NN, naive Bayesian classifier (NBC), SVM, and NN are utilized for the classification.

Next, making clear the reason why the result is obtained in the feature extraction process is reasonable. The auto encoder (AE), whose hidden layer in NN can be utilized, is listed as an example.

These AI methods brings deriving the failure (prediction) model. When the system has dominant non-linearity, the AI should be applied. In such a case, the k-NN, GLM, SVM, and NN are chosen as a suitable method. Nowadays, the RL and deep AE are strived to be utilized for the failure diagnosis and detection of motors [46]-[48], and for the failure detection of switching power supplies [49], however, the number of publications concerned with this application is still few.

The AI is, of course, unnecessary when the conventional statistics and approximation can get a solution or equation expressing the phenomenon. The judgement that the AI is used or not and setting of restriction is the most important thig because these conditions affect a result.

3. AI Methods for Power Electronics

3.1. Overview

From the past publishes, it seems that AI methods listed in Section 2, which are the multi-layer NN, GA, and particle swarm optimization (PSO), are especially important for AI applications to the power electronics. It can be also said that recent trends of AI applications accelerate the application of DL. The multi-objective optimization would increase its importance to balance the specification, cost, and environmental load. Therefore, the multi-layer NN, GA, PSO, DL, and multi-objective optimization are introduced from the point of view of AI applications to the power electronics. Table 1 shows the advantages, disadvantages, and applications of each AI method to compare each other. The applications in Table 1 correspond to any of the four stages from i) to iv) shown in Section 2.

3.2. Detection or Prediction of Degradation, Failure, and Abnormality

The multi-layer NN has many nodes, which are dividedly included in multiple layers. The layers are divided into the input, hidden, and output layers. A non-linear activation function is utilized in the hidden and output layers. Nodes in a layer are connected to nodes in a next layer. Connections of nodes has a weight. A signal in the input layer is propagated to the output layer through multiple hidden layers in one direction.

The supervised learning is adopted as a multi-layer NN learning process for the model generation. The supervised learning is that a set of pair of input signal x and correct output

Table 1. Comparison of AI methods.

Type	Method	Advantages and disadvantages	Application
Neural Network	Multi-layer Neural Network	- Simple network configuration and learning algorithm - Concerns about overtraining	ii) [3]-[9], [22] iii) [45], [59] iv) [61]
	CNN	- High performance in image recognition - Relatively high learning cost	iii) [60] iv) [46]
	Auto-encoder	- Unsupervised learning is possible - Application is limited	iv) [47]-[49]
Intelligent Optimization Algorithms	GA	- Ability to deal with non-linear, non-differentiable, multimodal, combinatorial optimization - Concerns about initial convergence - Strong problem dependence	i) [17], [20], [21], [64] ii) [10] iii) [11], [62], [63]
	PSO	- Ability to deal with non-linear, non-differentiable - Concerns about initial convergence - Strong problem dependence	ii) [67] iii) [43], [65], [66]
	Ant Colony Optimization	- Ability to deal with non-linear, non-differentiable - Concerns about initial convergence - Strong problem dependence	i) [19]
	Multi-Objective Optimization	- Ability to deal with non-linear, non-differentiable, multimodal, combinatorial optimization - Concerns about initial convergence - Strong problem dependence - High calculation cost	i) [18] ii) [69] iii) [57], [68]

$t\{(x_j, t_j)\}(j = 1, 2, \cdots, M)$ is taken as supervised data, then, the weights W are modified to get the output close to t_j when x_j is inputted into the NN [50], [51].

3.3. Deep Learning

By definition, the multiple layer NN which simply has more than four layers are called deep neural network (DNN). The machine learning method using DNN is the DL. The network called convolution NN (CNN) is widely and practically used for DNN. The CNN was proposed by Toronto University, who made an opportunity to be focused on the DL, and is mainly utilized for the character or object recognition. The DL realizes an automation of feature extraction, which was conventionally carried out manually, by the learning. Also, an immutable internal expression can be learned by the DL [52]. In the AI applications to the power electronics, the DL is applied to the PV output power prediction and failure detection of electric machines. Although huge amount of data acquisition is the issue, the DL would be spread to be applied widely.

3.4. Genetic Algorithms

There are many cases solving a continuous variable optimization in the power electronics. The GA has been adopted to solve such an optimization since relatively earlier time. The GA is a probabilistic multi-point search using a population and was regarded as an effective method for the problem having a non-linearity, multimodality, etc. The binary coded GA, which quantizes variables to express them in binary number and provides them a crossover or mutation, was utilized for early GA. Currently, the real coded GA, which expresses its solution in floating point and provides them a crossover or mutation taking a linearity of variables, is popular. The solutions themselves are kept as *n*-th order vector and build a population in the real coded GA. In the genetic operation, a master individual is chosen from a population and a slave individual is generated by the crossover, then, individuals to be left to the next generation are chosen from a master and slave individuals. A search is proceeded by this process repeatedly [53].

3.5. Particle Swarm Optimization

The PSO is one of the SIs and is a search imitating the process swarms of birds and insects find a feed. In a multidimensional space, this process is modeled by a particle swarm having a position and velocity. A position is evaluated by a fitness function and is updated by following process: each particle modifies its velocity while sharing its position to approach the best position in a swarm and former best position. These particles, forming a swarm, search in a space and derive the most optimal position there [54].

3.6. Multi-Objective Optimization

The evolutionary multi-objective optimization (EMO), which is extended version of GA, is widely used as the AI method for a multi-objective optimization. The non-dominated sorting genetic algorithm-II (NSGA-II) and strength pareto evolutionary algorithm-II (SPEA2) are the representative method and can effectively generate a population of approximated pareto solution [55], [56]. These are applied to many cases in the power electronics. In a multi-objective optimization, generally, it is desirable that a solution population which exists uniformly, and which is close to a proper pareto solution is obtained. However, it is pointed out that the EMO only itself cannot get such a solution population with high accuracy. Thus, the hybrid methods called the EMO with the local search (LS) and EMO then LS have been proposed [57], [58].

4. AI Applications to Power Electronics in Renewable Energy System

AI applications to the power electronics in the renewable energy system are investigated using the article search system of the International Journal of Renewable Energy Research (IJRER), which is a specialized academic society in the field of renewable energy. The search target year is from 2016 to 2020, the search target is abstract, and the keywords are "Neural Network", "Deep Learning", "Genetic Algorithm", "PSO", and "Multi-objective Optimization". As a result, 23 papers of NN, no paper of DL, 15 papers of GA, 22 papers of PSO, and 11 papers of MO are found. Note that the papers which does not treat the keyword as the main method are excluded after checking their abstracts. For instance, some papers introduce the keyword as a comparison method.

The main applications of NN are PV solar radiation forecast [59], power quality control [60], wind turbine [61], etc.

In [59], an artificial NN (ANN) is applied to predict solar radiation using meteorological satellite data and the proposed method is evaluated. For training and testing of NNs, NASA's geostationary satellite database is referred and geographic and meteorological data from 28 sites over the last 22 years are used. Geographical parameters (latitude, longitude, altitude) and meteorological data (temperature, sunshine duration, relative humidity, precipitation) are used as input data, and average solar radiation is used as network output. The correlation coefficient between the output of the model and the measured value of solar radiation exceeds 0.95, indicating that the model is highly effective.

A new algorithm for monitoring, mitigating, and classifying power quality failures using Multivariate Singular Spectrum Analysis (MSSA), Wavelet Packet Decomposition (WPD), and a one-dimensional convolutional neural network (1-D-CNN) is proposed in [60]. MSSA and WPD are decomposed into four levels to extract statistical features such as energy, entropy, standard deviation, root mean square, skewness, and kurtosis. The optimum feature extraction method is selected from the viewpoint of feature extraction accuracy and calculation complexity. The selected features are processed by the 1-D-CNN to classify power quality disturbances. The proposed method indicates the best classification accuracy compared with the conventional method.

In [61], the model based on an ANN is proposed for data mining of gearbox temperature and vibration measurements, and its performance is compared with other similar approaches. Vibration analysis is ineffective for failure diagnosis even when an ANN is used. On the other hand, the ANN model of gearbox temperature is useful for early failure diagnosis. The proposed method is tested on a dataset of wind farms in southern Italy and indicate its usefulness in actual wind turbine failure diagnosis.

The main applications of the GA are distribution networks [62], renewable energy operation optimization [63], PV circuits [64], etc.

An improved GA is applied to the optimal operational strategy for WTG based distributed generation and battery energy storage systems (BESS) in distribution networks in [62]. The charge and discharge schedule of BESS minimizes energy loss under network operational constraints such as node voltage, feeder current, and node power balance. Simulations using a standard 33-bus distribution network indicate that the proposed method can reduce energy loss and keep the node voltage magnitude of all buses in the distribution system within acceptable limits. Also, an effect of power fluctuation from the WTG is mitigated by the proposed method.

The energy management and optimization methods based on a GA in the hybrid renewable energy systems (HRES) is proposed in [63]. The proposed method determines the optimal share of power generation from each power source to minimize energy costs and emissions and prolong battery life. It has been tested on an HRES system consisting of PV, WTG, and batteries. In the test, various operating conditions such as temperature, irradiance, wind speed, and battery condition are considered. A mathematical model of system components is introduced. The results obtained from simulations and experiments are compared under various operating conditions such as actual temperature, irradiance, wind speed, and 24-hour load profile to confirm the validity of proposed method.

In [64], the electrical array reconstruction of the Total-Cross-Tied (TCT) array using a GA is proposed to address the multiple peak point occurrence of PV characteristics due to partial shading in PV systems. The physical location of the PV modules in the TCT array is fixed and their electrical connections change depending on the level of irradiance. The proposed method is tested on a 6x6 size array under various shading conditions. Compared with existing reconstruction methods, the proposed method reduces multiple peak points of PV characteristics and improves the output power of PV systems.

A PSO is mainly applied to the renewable energy operation optimization [65], microgrid [66], wind turbine generators [67], etc.

In [65], a PSO is applied to the optimal scheduling method for home appliances connected to stand-alone renewable energy systems (PV, WTGs, batteries, diesel generators). In the simulation, two cases are compared: the one is with the home appliance scheduling planed by the proposed method and the other is without any scheduling. The simulation results indicate that an optimal scheduling of home appliances saves fuel consumption of diesel generators and reduces system energy costs by optimizing battery energy use and maximizing renewable energy use.

In [66], the hybrid particle swarm optimization with sine cosine acceleration coefficients (H-PSO-SCAC) is utilized to address the unit commitment (UC) issue of a microgrid. The microgrid in the case study consists of one WTG, one PV, and three diesel generators. The aim of proposed method is to minimize diesel generator fuel costs and power transaction costs under load distribution constraints and microgrid power generation unit constraints. It is verified by the simulation that proposed method is more effective in terms of robustness than PSO and GA.

The PSO supported dual matrix converter for a doubly fed induction generator (DFIG) driven by a variable speed wind turbine system is proposed in [67]. A dual matrix converter system is used. The one matrix converter controls the DFIG and the other controls the load on the induction motor. By using a PSO-based switching strategy, the harmonic component of the matrix converter is significantly reduced. A prototype of the matrix converter system is implemented, and the control performance of the proposed method is evaluated.

The main applications of multi-objective optimization (MO) are the distributed generator [68], energy management [57], and wind turbine control [69].

The MO is applied to the operational management which allocates the distributed generators, adjusts their size, and reconfigures networks in [68]. An evolutionary algorithm based on SPEA2 which minimizes active power loss, annual operating costs (installation, maintenance, and active power loss costs) is proposed here. In addition, the voltage profile of power systems is improved. The simulation result indicates effectiveness of proposed method in an IEEE 33 bus test system with multiple distributed generators.

In [67], the EMO is utilized to a renewable energy management in large-scale medical facilities. As a case study, in a system combining PV with emergency generators (EGs), a MO issue that seeks the configuration and operation of EGs is introduced. The minimization of power costs during normal operation by cutting power peaks and minimization of fuel consumption during emergencies are objectives of optimization. A two-stage EMO which combines the multi-start with the local search function is proposed. The proposed method realizes a diverse and highly accurate search for solution sets. The proposed method is applied to the case study and evaluated, and the results indicate that a highly accurate solution set can be obtained.

In [69], multi-objective PSO (MOPSO) addresses the control parameter adjustment in load voltage control of a stand-alone wind turbine connected to a battery. The parameters of PI controller that controls the bidirectional converter through the duty cycle control can be tuned by MOPSO so that the DC link voltage can be maintained according to the reference value. A steady-state error and maximum overshoot are used as objective functions for the MO. The proposed method is tested in the simulation under a strong wind condition whose speed changes slowly. The simulation results reveal that the DC voltage can be kept constant at 400 V and the proposed method is effective.

5. Conclusion

This paper classifies the AI applications to the power electronics into four fields: i) Circuit, machine, and system design, ii) control, iii) system operation, and iv) detection or prediction of degradation, failure, and abnormalities. After categorizing, the AI methods which can be applied to these four fields are introduced. The overview of features and current situations about these four fields are given, and the papers concerned with the AI applications to the power electronics are introduced. Furthermore, the trend of study is analyzed by investigating published papers of IEEE Xplore data base. The following AI methods utilized in these AI applications are briefly explained, that is, the multilayered neural network, deep learning, genetic algorithm, particle swarm optimization, and multi-objective optimization. The AI applications to the power electronics in the renewable energy system attracting attention as a solution of the worldwide important environmental issue are introduced.

The conclusion of this paper is listed below:

a) The optimizations using the evolutionary computation and swarm intelligence are actively studied in the AI applications to the circuit, machine, and system design. This tendency would continue. For the circuit design, the partial development would be proceeded due to the importance and difficulty of the condition setting. The system design is relatively easy to set the condition so that the AI application is effective as well as the parameter optimization and is the prospects of progress.

b) In the AI applications to the control, it is expected that digital control using the neural network would be developed. However, the examples are still few, and the innovation is expected. The implementation of the AI would be started on the application which has the limited learning range because the learning process is mandatory for the AI applications to the control.

c) The energy management optimization is popularly studied in the AI applications to the system operation. Recently, the study about the output power prediction of renewable energy sources has been increasing. It is expected from now that the hybrid configuration which consists of several AIs would strive for achieving the automation of the system design with the high prediction accuracy.

d) Conventionally, there is few papers about the AI applications to the detection or prediction of degradation, failure, and abnormalities. The failure diagnosis for motors and failure detection for switching power supplies are strived in recent years, and further development is expected.

e) According to AI applications to power electronics in the renewable energy system, following three topics are actively studied: the photovoltaics solar radiation prediction using a neural network; microgrid, distribution network and renewable energy operation optimization using a genetic algorithm and particle swarm optimization; and distributed generator and energy management using multi-objective optimization. In the future, it is expected that the latest technologies such as deep learning mentioned in c) will be applied.

The discussion in this paper is composed by the search result of IEEE transactions and IJRER. When we focus on international conferences and other journals, it seems that AI applications to the power electronics are being presented actively [70]-[76]. From this situation, this research field is an important topic and further development is expected from now on.

In the near future, the power supply systems will include many various switching power supplies and rely on renewable energy sources. This situation will lead to a complexity of the power supply systems. In such a power supply system, a develop of the circuit, machine, and system design and system operation would be difficult without the AI because the design and operation policy would be changed to the following: all devices in the power supply system achieve the best operation for the entire system. It is important for each switching power supply connected to the AC or DC buses that they should avoid disturbing the balance of entire system rather than the locally best performance with the high feedback gain design and its operation. For instance, such a design would cause an oscillation in the power supply system. Therefore, it seems to be reasonable the AI takes such a complex design and control on itself. Hereafter, it is expected that power electronics engineers refer this paper and applies the AI to a lot of scenes of power electronics.

Finally, authors thank to the data base IEEE Xplore which we used for our investigation in this paper. It would be appreciated from our experience of investigation if the key word which can be to the point is set more properly being conscious of a search. Especially, it is desired that researchers can separate the proposed method/algorithm and comparison targets easily.

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