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Review Article

Artificial Intelligence-based Control Techniques for HVDC Systems

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Abstract

The electrical energy industry depends, among other things, on the ability of networks to deal with uncertainties from several directions. Smart-grid systems in high-voltage direct current (HVDC) networks, being an application of artificial intelligence (AI), are a reliable way to achieve this goal as they solve complex problems in power system engineering using AI algorithms. Due to their distinctive characteristics, they are usually effective approaches for optimization problems. They have been successfully applied to HVDC systems. This paper presents a number of issues in HVDC transmission systems. It reviews AI applications such as HVDC transmission system controllers and power flow control within DC grids in multi-terminal HVDC systems. Advancements in HVDC systems enable better performance under varying conditions to obtain the optimal dynamic response in practical settings. However, they also pose difficulties in mathematical modeling as they are non-linear and complex. ANN-based controllers have replaced traditional PI controllers in the rectifier of the HVDC link. Moreover, the combination of ANN and fuzzy logic has proven to be a powerful strategy for controlling excessively non-linear loads. Future research can focus on developing AI algorithms for an advanced control scheme for UPFC devices. Also, there is a need for a comprehensive analysis of power fluctuations or steady-state errors that can be eliminated by the quick response of this control scheme. This survey was informed by the need to develop adaptive AI controllers to enhance the performance of HVDC systems based on their promising results in the control of power systems.

Keywords:

AI Algorithms;

HVDC Transmission System;

Power System Protection;

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1- Introduction

The study of artificial intelligence (AI) involves the methods used for developing systems that can make intelligent decisions. A part of the goal of creating these systems is to emulate elements of intelligent decision-making by simulating human thought and perception. A system emulates the intelligence and decision-making of humans. Power systems are subjected to various disturbances, including complex, non-linear changes in loads, generator outputs, and operating parameters. Depending on the initial operating conditions, load fluctuations can cause instability and loss of synchronization [1]. Power systems continuously experience minor fluctuations; it is assumed they have steady-state operation when faced with a particular disturbance. Systems are expected to maintain their synchronization by adjusting to changing conditions. The study on HVDC Systems in Smart Grids found that by employing effective reactive power compensators to control its bus voltage, the overall performance of the HVDC system can be improved [2].

A crucial factor of electric power networks that requires immediate attention is their increased power flow control. This can be significantly improved by enhancing existing transmission facilities with the use of automated transaction processing and decision support systems that are based on artificial intelligence [3]. The HVDC system employs solid-state controllers like flexible alternating-current transmission systems (FACTS) used to regulate power flow through

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transmission systems that are superior to those used in mechanically controlled transmission systems. STATCOMs, static synchronous series compensators (SSSC), and UPFCs are widely used FACTS controllers, which provide bulk power transfer, reduce delay angles, minimize the construction of additional transmission lines, and enable a reliable, economical exchange of power among neighbouring utilities [4]. FACTS devices offer more flexible solutions to network problems such as uneven power flow, transient and dynamic instability, oscillations, over voltages, and under voltages. Power electronics-based compensators help to maintain the bus voltage and the silicon-controlled rectifier (SCR), while devices such as SSSC and STATCOM aid in the compensation of reactive power in HVDC systems, maintaining their stability by acting on their generators and loads [5]. UPFCs not only optimize and improve the performance of HVDC systems in AC/DC settings but also control their transient stability.

2- HVDC Transmission System

There is an increasing interest in the use of artificial intelligence techniques, as they are capable of providing efficient, adaptive, and optimal solutions for applications in the high voltage direct current (HVDC) system, nonlinear driver design for generator excitation systems, and flexible alternating current transmission systems (FACTS). They propose some artificial intelligence techniques for HVDC systems in their study, Frequency Coordinated Control Strategy for an HVDC Sending-End System with Wind Power Integration Based on Fuzzy Logic Control [6], which combines expert systems, fuzzy logic, neural networks, and ANFIS.

Using a fuzzy logic approach, the performance of HVDC links with voltage source converters (VSCs) was evaluated based on the impact of fuzzy logic on the performance of HVDC links. A program was presented on electromagnetic transients (EMTP) that compares fuzzy logic with PIC-control in terms of its contents [7, 8]. A system controlled by fuzzy logic can perform faster in the event of a disturbance. It will enhance the efficiency of the system and make its components not to be faulty. As a result of the studies, Bauman et al. [9] developed an HVDC system using an adaptive network called a fuzzy input perceptron (FIP); the simulations showed that overshoot was eliminated and the peak current was reduced in situations involving ground faults. Also, Bernardes et al. [10] described an approach to fault classification in distribution systems that combines artificial neural networks (ANN) with fuzzy ARTMAP architectures. The network implemented an FL-based current controller for an HVDC power plant connected to a weak AC power system; the EMTP-RV simulation program was used to carry out simulation analyses [11]. According to Ananth et al. [12], the fuzzy controller was designed to control the voltage and power in an HVDC system based on a VSC system. As reported by Jeong et al. [13], the VSC HVDC frequency control strategy is used to implement the membership function via the neural networks. Neuro-fuzzy system optimization and effective features of the method were designed by Rohani et al. [14] for locating faults in VSC-HVDC power plants that utilize different methods of defuzzification and membership functions. Depending on the defuzzification methods, membership functions, and rules used for this controller, its performance varied among systems that implemented it. According to Ahmadi et al. [15], an optimized design of fuzzy-PID controllers is presented for the control of wind farms with HVDC lines.

When fuzzy-adaptive PI controllers are used on VSC-based HVDC transmission systems, the performance will be enhanced by fuzzy control. It has been proposed that fuzzy logic controllers (FLCs) can enhance the transient stability of the HVDC system [16, 17]. The study explored various operating modes for Frequency-Control Technologies for a VSC-HVDC [18]. An adaptive neuro-fuzzy controller was described by Meseret & Saikia [19] along with a conventional PID controller to mimic the effects of an HVDC link on the system frequency; its underlying mechanisms and implementation were studied using the new technology. Other researchers demonstrated that the fault detection and classification algorithm is based on a modified Clarke's transformation, while a model based on artificial neural networks (ANNs) improves fault detection and classification [20]. The effectiveness of ANN applications for fault detection on HVDC transmission lines is compared, and neural network-based fault detection techniques are presented by Nagar and Shah [21].

An ANN-based online current controller designed for the HVDC transmission line was evaluated for its performance by Khorashadi Zadeh [22]. ANNs have been developed to detect and diagnose faults in HVDC systems, while traveling waves-based methods have been used to estimate faults in HVDC systems [23–25]. In order to detect faults effectively and improve the dynamic stability of the HVDC systems, a fault identification system that supports all types of faults was designed by Muzzammel [26], Pradhan et al. [27], Zeng et al. [28], and Narayane et al. [29]. Researchers have conducted a study on the diagnosis of faults in HVDC transmission systems using wavelet transforms and neural networks, as well as the control conditions necessary for ensuring optimal performance in HVDC systems with dynamic stability [30].

Utilizing a neural network with radial basis function (RBF) in diagnosing faults in HVDC systems for large disturbances, Liu et al. [31], Zhang [32], and Roy [33] designed and developed a system that improves system productivity under dynamic operating conditions by utilizing feature extraction and artificial neural networks. The researchers replaced traditional fuzzy logic systems with a hybrid approach based on fuzzy wavelets and quantum neural networks. In addition, Ganjefar et al. [34] and Nayak et al. [35] proposed particle swarm optimization (PSO) as a method of improving the stability of the VSC HVDC system. In later works, adaptive control methods for monitoring large disturbances in systems and fault detection and protection methods were applied to this work. A hybrid approach to locating faults in VSC-HVDC systems utilizing optimal neuro-fuzzy systems is presented by Reeve and Sultan [36] and Zhang et al. [37]. Also, according to Muniappan [38] and Marreddy et al. [39], the use of fuzzy logic controllers has been shown to lead to improved HVDC transmission systems as well as increased reliability.

For relatively intelligent HVDC systems, a self-organized neuro-fuzzy algorithm was used to study the stability of a power system. Using the initiated adaptive neuro-fuzzy inference system, simulation results indicate that the system is highly effective in identifying defective protective equipment [40, 41]. In this study, an accurate system was developed to detect and locate faults in power transmission lines through the use of neuro-fuzzy approaches [42].

3- Artificial Intelligent Control of HVDC System

A flexible AC transmission system, often known by the acronym FACTS, can control the flow of power from the transmitting end to the receiving end of the system. There are three primary FACTS devices - SSSC, STATCOM, and UPFC. According to Adnan & Alsammak [43], the most important types of FACTS development technologies can be applied to future power systems. The author presented a detailed discussion of a new power line fault detection method that uses DWT [44]. Based on an MMC-HVDC line fault source, the hybrid HVDC breaker proved to be a reliable method for transient fault detection [45]. A Monte Carlo simulation was performed to assess the effectiveness of a fuzzy inference system incorporating adaptive networks for locating transmission line faults [46].

By combining both ANFIS and Hilbert Space, the authors presented an innovative approach to protecting the microgrid, which can be used for power transmission systems as well as for numerous other applications on the HVDC grid [47]. A hybrid multi-infeed HVDC system was proposed by Eyenubo & Oshevire [48] utilizing VSC-HVDC in order to improve short-circuit ratios. A series of studies have been conducted on the integration of VSCs with HVDCs, as well as a performance evaluation and analysis of SSSCs, to enhance the power grid [49, 50].

Some studies have also designed and installed hardware updates on STATCOM and UPFC to study closed-loop dynamics [51, 52]. The results of the experimental tests performed on an additive self-tuning (ST) control scheme are presented for a static synchronous series compensator that exhibits rapid responses under all conditions [53, 54]. A fuzzy optimal controller based on the STATCOM algorithm was used to simulate oscillations in series-compensated transmission systems [55]. The use of STATCOM was utilized by Gyugyi et al. [56] to determine the suitable reactive power flow by using a solid-state approach to rebalance the distribution voltages.

Fuzzy-based STATCOM has been used to evaluate voltage stability in a heavily loaded HVDC system [57]. Based on the results of a model and simulation analysis, fuzzy control of static VAR compensators was developed by Chang & Qizhi [58]. Also, Lehn & Iravani [59] and Karlecik-Maier [60] described the changes to a PWM-STATCOMS system caused by faults and imbalances in distribution networks due to a STATCOM that was connected to an electrical power grid. It presents the voltage variation measured at STATCOM outputs. This voltage variation is used for reactive power compensation and to improve power quality in response to voltage fluctuations [61]. Also, Li et al. [62] and Wang et al. [63] illustrated how to identify faults on transmission lines in the VSC-HVDC grid, as well as how to develop mathematical models for the steady-state transient stability of devices. Parizzi et al. [64] and Liaqat [65] provided an overview of power quality problems, issues related to international standards, and how power influences the HVDC transmission system.

The performance of a fuzzy logic-based H-bridge STATCOM controller based on transient simulations has been investigated [66]. It thoroughly modeled a robust control for D-STATCOM to obtain voltage stability; it had previously demonstrated excellent performance and was developed in order to achieve voltage stability [67]. Present the concept of Virtual Synchronous Machine (VSM). It is used as a controller for PV-STATCOM, in which the solar inverter is used for maximum power point tracking as part of the PV system [68]. Thakre & Kumar [69] and Gupta et al. [70] used STATCOM to do an analysis of the operation and control of drop voltage on the distribution network under normal and contingency conditions to reduce the total power losses associated with voltage fluctuations on the distribution network.

It has been demonstrated [71–74] that digital controllers can enhance the performance of a PWM AC–DC converter among interconnected power systems. An HVDC system that employs voltage source converters at unbalanced voltage has also been proposed to overcome some of the disadvantages of existing UPFCs and provide dynamic control of power flow across transmission lines. An effective method of identifying faults in voltage source converters has been developed by modeling and analyzing the VSC-FACTS controller [75, 76].

The control parameters of VSC stations have been optimized using PSO since VSCs are nonlinear components of M-HVDC networks [77]. It has been proposed that neural networks can manage damping in uniform energy flow control units in order to mitigate low-frequency oscillations in power systems [78]. The improved power performance of a renewable energy-based power system through grid optimization using a unified power quality conditioner (UPQC) with fuzzy logic controller (FLC) method is based on the results of the study [79]. Fuzzy logic is used in UPFC controllers to control the shunts and series converters through the implementation of control converters [80].

The remainder of this paper is structured as follows: In Section 4, the methodology proposed for applications in HVAC systems is described in detail. In Section 5, the characteristics of the proposed methodology, ANN, are discussed, as well as its advantages and disadvantages. In Section 6, the various areas where ANN is applied are presented. Section 7 presents how the model is developed and applied. The last section, Discussion and Conclusion, gives a general overview of the functions of HVDC, its drawbacks, and how the application of ANN could lead to its developments.

4- Proposed Methodology

This work is a case study. It is written in a narrative style, where the object of the study is described in depth via textural analysis. The case being focused on in this work is the proposed methodology, ANN, used for HVDC. ANN replaced the traveling wave theory as the method for estimating fault locations in HVDC systems. In this traveling wave theory, the time of propagation of the traveling wave head from the fault point to the point of observation indicates the distance of the fault. This theory has some limitations, as follows:

- In this method, the fault location depends directly on capturing the traveling wave heads. A compromise in capturing the travelling wave heads will result in a failure. Most of the time, the transient wave signals are too weak to detect, resulting in a fault location not being detected.
- In fault location, the speed of the wave and the time it takes to travel to the location of observation are key factors, but the transmission line parameters determine the speed of the wave.
- Generally, the traveling wave theory is influenced by interference in a signal. If that interference somehow overshadows the effect of the wave head, the location of the fault cannot be determined.

The above drawbacks of the traveling wave theory have made the Artificial Neural Networks have gained an increased reputation with their recent advancements in the field of Electrical Engineering. This is due to their robustness, which is unaffected by a number of parameters such as the speed of the traveling wave, fault type, and interference level. The diagram of ANN is shown in Figure 1.

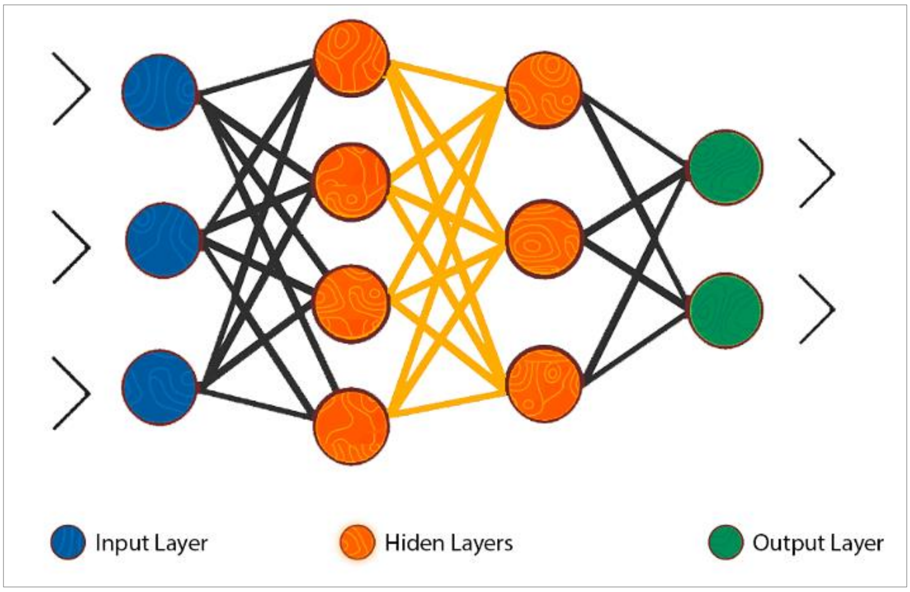

Figure 1. Diagram of the proposed ANN

5- Techniques of Artificial Neural Networks

The proposed methodology ANN has the following characteristics:

- Classification: ANN can be trained to classify a pattern or data set by utilizing a predefined classification system.
- Prediction: It has the ability to come up with an output that is expected based on the input. It is trained to predict the output based on the input.
- Clustering: The neural networks are used to identify some features of the data that can be used to classify them into different categories without having any prior knowledge of these features.
- Association: When a network is trained to recognize certain patterns, it will associate a noise pattern presented to it with the closest pattern in its memory.

There are some advantages and disadvantages of using neural networks, as outlined in Table 1.

Table 1. A Comparison of the Advantages and Disadvantages of Neural Networks

Neural Network Advantages	Neural Networks' drawbacks
Neural networks can perform the tasks of a linear program.	Generally, for a neural network to work properly, it needs to be trained
Neural networks are capable of performing any task without any problems	Neural networks with large sizes require a lot of processing time
The parallel nature of this system will allow it to continue even if some of its elements fail	Its architecture is different from that of a micro-processor

6- A Survey of ANN to Data-Integrative Applications

ANN can be applied in various types of data, some of which are listed in Table 2.

Table 2. Neural Networks and Their Applications

Architecture	Application	Activation function
Neural networks with deep learning	Intelligent search algorithms; it is used for pattern recognition, fraud detection, medical research, drug discovery etc.	Functions of logistical operations
Neural network with modular components	Recognition of targets, for classification, prediction, optimization, filtering etc.	Sigmoid-Tan-Signid model
Using multi-layer perceptrons	It is used to classify health care data and for medical diagnosis	Sigmoid-Tan-Signid model
Algorithm for supervised classification	Portfolio of management services, weathering detection, customer discovery, stock price prediction etc.	Sigmoid-Tan-Signid model
Functions of the radial basis	Control and modelling of a process, for pattern recognition, signal processing,, system identification etc.	Using a radial basis of calculation
Convolutional neural networks (CNNs)	Recognition of voice and images, image processing, classification, segmentation	Functions of logistical operations
Using support vector machines	Credit rating system, it is used for handwriting recognition, face detection, gene classification, email classification	Functions of logistical operations
Algorithm for back-propagation	It is used for forecasting process, image and speech recognition	Functions of logistical operations

7- Designing A Neural Network Model

7-1- Input Variables Selection

The first step in ANN modeling is to select the input variables, which is one of the most important steps. Model performance is heavily influenced by the accuracy of this parameter. In the analysis of the input variables, two important factors must be considered: significance and independence. Alanis et al. [81] presented several approaches to evaluating input and output parameter similarity. Data visibility or knowledge is measured using ad hoc analytical methods that are based on interrelationships and collective agreements [82]. An optimization method typically involves filtering and dimensionality reduction. When it comes to dimension reduction, the input is spun or clustered, and the filtering process is performed based on partial correlations or agreement information [77, 83].

7-2- Model Type Selection

The performance of an ANN architecture is also strongly influenced by the type of model employed. There are many types of neural networks, including feed-forward, perceptrons, multilayer perceptrons, convolutional neural networks, radial basis function neural networks, recurrent neural networks, LSTMs, and modular neural networks. The information in a feed-forward neural network flows only in one direction, from the input layer to the output layer. Multilayer perceptrons are the most common structure for feed-forward neural networks. A feedback loop layer is used to direct data from the input to the output and then re-direct it back to the input. In order to achieve optimal data prediction, it is generally recommended that a hybrid method such as Genetic Algorithm Aided Artificial Neural Networks (GANN) or ANFIS-RNN be used [84, 85].

7-3- The Training of the Data

Based on the physical base domain knowledge, the data will be divided into two types of classification methods: supervised and unsupervised. Ad-hoc methods will be considered unsupervised. Generally, these data are used as a basis for dividing the data randomly, while the trial-and-error method is used for the supervised division of the data, utilizing genetic algorithms and optimization techniques [86].

7-4- The Normalization of Data

As part of the normalization process, data is restructured in a relational database to avoid duplicate data. This is a very crucial step when working with the neural model, which is an extremely powerful tool when using the learning function. There are a variety of training methods that can be used to obtain standard and perfect results, among which gradient descent, Jacobian matrix, Levenberg-Marquardt (LM), and quasi-Newtonian backpropagation are some of the methods that are employed. However, stochastic methods can also be used to calibrate the model, though Bayesian methods are more commonly used in this regard [87].

7-5- An Evaluation of the ANN Network Models

A statistical evaluation method is necessary in order to evaluate the performance of the model after training, including measurements of correlation coefficients (R), coefficients of determination (R2), mean squared errors (MSEs), mean absolute errors (MAEs), percentage errors, and root mean square errors (RMSEs).These methods allow us to determine the difference between measured and predicted models as a consequence. There are various statistical techniques that are commonly used when testing a model for replicative validity. These techniques can be used for correlation analysis, nova analysis, goodness evaluation, regression evaluation, and model tests to determine whether the data match the original real system. In general, modeling refers to the correlation between input and output data, whereas generalization refers to the capability of the model to be examined by predictive validation to gain insight into the potential of the model over and above the range of data that is used in calibrating [88].

7-6- Division of the Data

A neural network is a machine learning algorithm that utilizes a large number of datasets in order to produce a result. In general, datasets can be classified into three main categories: training, testing, and validation. In order to obtain the optimal structure and avoid overfitting, it is necessary to evaluate the unknown connection weight based on the training dataset. The general performance of the trained model will be evaluated at the conclusion of the training effort after it has been trained to work with a validation set.

7-7- Selection of the Model Structure

An optimal structure for NN is determined based on the number of nodes and layers in the model. An optimal structure will reduce prediction errors or optimize forecasts of NN. The NN structure with the fewest number of hidden neurons is chosen based on trial and error in order to make them perform the best. When it comes to putting neurons in a hidden layer, there is no specific rule. However, the hidden neurons of an ANN structure can be calculated using some basic guidelines. Several techniques can be used to determine network neural structure. A number of methods can be employed to determine the neural structure. Classified techniques can be used to obtain efficient ANN models using the recurrent neural network approach. This method can also be applied to determine the optimal ANN model.

8- Discussion and Conclusions

In order to provide a better understanding of how power can be handled by AI inside power systems and how these much-improved technologies have developed over the past few years, this case study examines all the work that has been done lately in the research of AI-based advances and applications to HVDC power systems in order to see how the vast improvement has had a significant impact on the application of this technology in the power sector. Studies have shown that HVDC transmission has numerous advantages compared to a conventional AC transmission system. These are listed below:

- An HVDC transmission system consists of only two conductors, it is simple to construct, it provides a higher power carrying capacity per conductor, and line losses are much lower than in AC transmission systems.
- It has possible low reacting cable losses because of low conductor resistance in DC asynchronous interconnection.
- The precise control of DC links enhances the stability of power flow, making them more reliable.
- It is more cost-effective since HVDC has a higher power carrying capacity than AC power.
- The line can be controlled easily in terms of the amount of power being transmitted on it.
- The skin effect in HVDC systems is not as prevalent as it is in AC systems.
- The current density in HVDC transmission can be higher than that in AC transmission.
- It has long-distance transmission of power from large electrical energy sources.
- It transmits power through large water bodies of about 30 Km or more.
- AC cable transmission for very long distances is made possible using compensating stations to nullify cable capacitance.
- Quick change in direction and control is possible.
- Bidirectional power flow is possible with HVDC systems.
- HVDC transmission is economical for distances over 600 km in comparison to expensive AC power transmission.

Also, the HVDC transmission has some disadvantages, which are listed as follows:

- The higher cost of electronic stations converter used with expensive HVDC lines.
- Rectifiers and inverters in converter stations require a huge magnitude of reactive power.

The converter in the AC-DC segment of the HVDC system generates harmonics, which cause interference when injected into the AC system. The filters are employed on both the AC and DC sections to eliminate interference caused by harmonics, which complicates the system incurring higher cost. The harmonics are suppressed using capacitors and reactors.

In order to ensure that AC-DC systems are protected, strict surveillance of system signals, and a notification system for disturbances are required. HVDC systems must make immediate decisions in the range of micro to milliseconds. The optimal behavior of the systems is dependent on the knowledge of and rapid detection of faults. Considering the fact that large HVDC systems are integrated with main transmission lines, it is essential to detect, classify, and eliminate faults as quickly as possible.

Developments in HVDC technology were made possible because of the tremendous advancements in power electronics components and artificial intelligence approaches like fuzzy, ANN, etc. The stability of the HVDC system had been demonstrated using many artificial intelligence methods, like FL, ANN, ANFIS, etc. It was further observed that enhancement of the stability of the HVDC system with FACTS devices is a new area of research. An overview of the various AI techniques and their applications in the HVDC system is given in this paper.

Since the global power transmission industry today faces many challenges, such as complex, non-linear changes in loads, generator outputs, and operating parameters (to name a few), the advent of AI-based methods to make smart decisions is the ideal solution for optimizing HVDC systems. This study, by summarizing the current state of research in this field, is not only relevant but also contributes by helping researchers and industrialists with key information required for further work on the subject.

9- Declarations

9-1- Data Availability Statement

Data sharing is not applicable to this article.

9-2- Funding

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9-3- Acknowledgements

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9-4- Institutional Review Board Statement

Not applicable.

9-5- Informed Consent Statement

Not applicable.

9-6- Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the author.

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