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Research Paper

Performance Improvement of Combined Wind Farms Using ANN-Based STATCOM and Grey Wolf Optimization-Based Tuning

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Abstract— *Changes in the electric supply can significantly affect electronic devices since they are very sensitive. Due to a nonlinear system with multiple interconnected and unpredictable demands in the smart grid, the electricity system is facing several issues, including power quality, reactive power management, and voltage drop. To address these problems, a static synchronous compensator (STATCOM) is frequently used to compensate and correct the voltage level at the power bus voltage. In this study, an Artificial Neural Network (ANN) and GWO based controlled STATCOM has been developed to replace the traditional PI based controller and enhance the overall STATCOM performance. The ANN controller is preferred due to its simplicity, adaptability, resilience, and ability to consider the non-linearities of the power grid. To train the classifier offline, data from the PI controller was utilized. The MATLAB/Simulink software was employed to assess the effectiveness of STATCOM on a 25 Km transmission line during increased load and three faults. The combined results of the PI and ANN controllers indicate that the ANN controller significantly improves STATCOM efficiency under different operating conditions. Moreover, the ANN controller outperforms the traditional PI controller in terms of results.*

Keywords—STATCOM, ANN, smart grid, grey wolf.

NOMENCLATURE

$\overrightarrow{N_P}$	$\overrightarrow{N_P}$ is the required best solution
C_p	C_p is the power coefficient
V_{dc}	V_{dc} is the compensation voltage from the wind farm side
V_{ds}	Direct axis of the stator
V_{out}	V_{out} is grid output
V_{qs}	Q axis of the stator
A	A is the area covered by the turbine blades
AI	Artificial intelligence
ANN	Artificial neural network
FACTS	Flexible AC transmission systems
MPC	Model predictive control
q	q is the air density
STATCOM	Static synchronous compensator
VSC	Voltage source converter

1. INTRODUCTION

The loads, generation outputs, and other crucial operating characteristics of the power system fluctuate continuously because it functions in a highly nonlinear environment [1]. The stability of the system depends on the type of disruption it may experience, and whether it lasts for a long or short time [2]. Machines associated with the system may be harmed, electrical equipment may heat up, and delicate equipment may malfunction. The system adapts to the shifting conditions as little disruptions in the nature of changes in load occur continuously. The overall system must be capable to function smoothly in this variety of conditions, required parameters and then meet the power requirements. It must also be able to withstand a number of severe disturbances, such as a transmission line short-circuit or the destruction of a large generator [3]. In the previous era, fixed or instantaneously switched sequence and synchronous condensers, reactors, and synchronous motors were commonly used to address several of these issues. The application of these traditional compensators is subject to some restrictions. Looking at the challenges was not successfully accomplished. The two main issues were delayed reaction and mechanical component wear and damage [4]. The demand for an alternative technology based on solid-state devices had increased due to the rapid expansion of power electronics deployment.

Flexible AC Transmission Systems (FACTS) controllers are power electronics devices that are used to control the flow of power in an AC power transmission system. They are typically used in high-voltage power transmission networks to enhance the controllability and stability of the system.

FACTS controllers can be classified into several types, including:

1) Shunt Controllers: These are connected in parallel with the transmission line and are used to regulate the voltage and improve the power factor of the system.
2) Series Controllers: These are connected in series with the transmission line and are used to regulate the line impedance and improve the power transfer capability of the system.
3) Combined Controllers: These are a combination of shunt and series controllers, and are used to improve both the voltage regulation and power transfer capability of the system.

Some of the commonly used FACTS controllers include different strategy to control the active power and reactive power of the system like TCSC and UPFC. They all perform the same function

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but in the different environment and conditions.

Overall, FACTS controllers offer many benefits, including improved system stability, increased power transfer capability, and enhanced voltage regulation. [5].

Static Synchronous Compensator (STATCOM) is a power-electronics-based device used in modern power systems for reactive power compensation, voltage control, and stability enhancement. It has been proven to be an efficient and cost-effective solution for mitigating power quality issues in the power system. With the increasing integration of renewable energy sources, the demand for STATCOMs has also increased. The STATCOMs not only improve the power system performance but also facilitate the integration of renewable energy sources by providing a stable grid connection. In recent years, several controlling techniques have been proposed for STATCOMs to enhance their performance.

The Voltage Source Inverter (VSI) control method is one often employed STATCOM control approach. This method uses a voltage source inverter on the STATCOM to produce a controlled AC voltage at the connecting point. In order to maintain the appropriate voltage levels and power factor, the control system of the VSI continuously monitors the grid voltage and current and modifies the output voltage of the inverter. In order to govern the reactive power exchange between the STATCOM and the grid, proportional-integral (PI) controllers are frequently used in this manner. The PI controllers generate control signals to modify the inverter output based on the error between the reference voltage and the actual grid voltage that is continuously calculated by the controllers.

One of the latest STATCOM controlling techniques is the Model Predictive Control (MPC) technique. The MPC technique uses a model of the system to predict the future behaviour of the system and optimize the control variables accordingly. In the case of STATCOM, the MPC technique is used to control the reactive power compensation, voltage regulation, and harmonic mitigation. The MPC technique has several advantages over conventional control techniques, including fast response, robustness, and adaptability to changes in the system parameters. The MPC technique has been successfully applied to the STATCOMs for improving the system performance.

Another latest controlling technique for STATCOM is the Artificial Intelligence (AI) technique. The AI-based controlling technique uses machine learning algorithms to learn the system behaviour and optimize the control variables accordingly. The AI-based controlling technique has several advantages over conventional control techniques, including adaptability to changes in the system parameters, high accuracy, and low computational time. The AI-based controlling technique has been successfully applied to the STATCOMs for improving the system performance.

In multi-STATCOM systems, the Droop Control approach is commonly used for load sharing and control coordination. This method produces a droop characteristic by giving each STATCOM a slightly varying setpoint voltage. The STATCOMs effectively share the reactive power burden by adjusting their output voltages in accordance to their droop slopes when the system suffers voltage variations. Utilizing several devices to distribute the control effort improves the system's stability and resilience.

In addition to the above-mentioned controlling techniques, several other controlling techniques have been proposed for STATCOMs, including Proportional Integral (PI) control, Fuzzy logic control, and Neural Network control. The PI control is a conventional control technique widely used in STATCOMs. The Fuzzy logic control is a rule-based control technique that uses linguistic variables to control the system. The Neural Network control is an AI-based control technique that uses a neural network to learn the system behaviour and optimize the control variables accordingly.

In conclusion, the controlling techniques for STATCOMs have been continuously evolving to improve the system performance. The latest controlling techniques, including MPC and AI-based techniques have shown promising results in improving the system performance. However, the selection of the controlling technique depends on the specific application and system requirements. Therefore, it is essential to consider the system requirements and select the appropriate controlling technique for the specific application.

A parallel FACTS element called a static synchronous control scheme (STATCOM) is frequently employed to maintain voltage stability.It can also be used to improve the stability of the power system by adding or eliminating reactive power from the network. It is entirely based on the voltage-source converter (VSC) for power electronics and may also provide active power when connected to a power source [4–6]. How precisely and rapidly erroneous signals are corrected determines how well STATCOM performs. Where effective STATCOM control can yield the highest compensatory impact [7]. A STATCOM is solutions that address by a Control scheme, which necessitates exact linear statistical models, which are difficult to develop and perform poorly when repeatedly exposed to discrete fluctuations, highly nonlinear, external disturbance, and other factors.

To, prevent the disadvantages listed above. New controllers with higher performance were required, and they were being developed [7]. Indeed, ANN strategies have been extremely beneficial in power electronics-based circuit for the maintenance of process stability over a relative wide range of conditions. A significant amount of work has recently been made to develop novel and unconventional control mechanisms that can frequently greatly improve or replace conventional control techniques. Table 1, shows the literature survey of some latest research paper.

This paper presents a novel methodology as stated below:

- Modelling of the windfarm for Realtime input.
- Integrating ANN with GWO to improve the wind farm stability.
- Performing case study on 25 Km transmission line for stability analysis.

The remainder of this essay is structured as follows. The modelling and description of different component is stated in Section 2. The multi-objective GWO is explained in Section 3. The overview of wind turbine modelling and ANN-GWO operation is provided in Section 4, and the article summary is given in Section 5.

2. MODELLING AND DESCRIPTION OF DIFFERENT COMPONENT

This section provides a thorough overview of the functionality and controllability of STATCOM with regard to various components.

2.1. ANN model

The artificial neural networks (ANNs) mostly used worldwide are a type of machine learning algorithm designed/modelled after learning the human brain's structure and function. ANNs are designed to recognize complex patterns and relationships in data, making them an essential tool for various suitable applications, related to image recognition, natural language processing, and in deep process related to speech recognition.

An ANN is composed of multiple layers of artificial neurons that work together to process input data and generate output predictions. Each neuron receives input from other neurons or external sources, and based on a set of weighted connections and an activation function, it generates an output signal that is transmitted to other neurons in the next layer. Through a process called back propagation, the network adjusts the weights of the connections between neurons to improve its performance on a given task. Fig. 1 depicts a straightforward schematic picture of how an ANN works in general [14, 15].

Table 1. Literature survey comparison.

Reference	Technique used	Drawback
[8]	Model predictive controller	Overall stability is less
[9]	Autotuned weight factor	It's a complex and time taking technique
[10]	Model-free adaptive control	It impacts the efficiency under full load condition
[11]	Virtual inertia	Its still at the stage of verification
[12]	Using PID/PI control-based model prediction	Not effective during sudden instability
[13]	Fuzzy	Little slow and sluggish

Fig. 1 shows that the outcome is equal to the total of the input time the layer weights as shown in the following sentences [14, 15]:

$$Output = \sum Input * Weight. \quad (1)$$

So, from Eq. (1), its shows that the input is multiplied with the weight of each of the hidden layer neurons, and then the summation of all the hidden layer and input combination is done to get the final output.

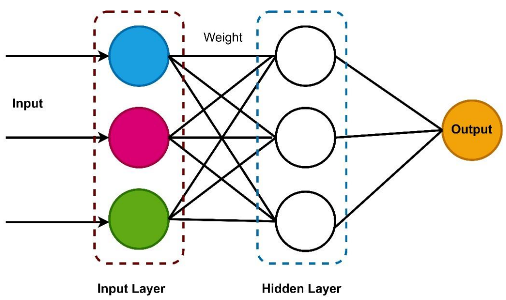

Fig. 1. ANN architecture.

2.2. STATCOM operating model

As shown in Fig. 2, one of the most important FACTS families, the Static Synchronous Compensator (STATCOM), which is more and more used in latest power systems, is decoupling capacitor to the system. It is a three-voltage system that can generate switching frequency as well as absorb it. When the scheme voltage (actual voltage at which load will work) is low, due to which the STATCOM generates reactive power (STATCOM capacitive). Reactive power is absorbed when the system voltage is high (STATCOM inductive). This system is comprised of the coupling transformer, taking measurements system, bidirectional converter device, control system, and a dc-link capacitor.

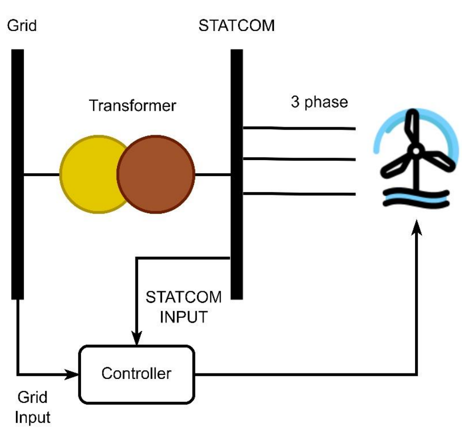

Fig. 2. Typical STATCOM connection.

A Static Synchronous Compensator (STATCOM) is a FACTS controller that is used to regulate the voltage of an AC power system. Its fundamental working principle is based on the injection of a controllable amount of reactive power after calculation into the power system, which can be used to compensate for voltage fluctuations and improve the overall stability and performance of the system. The STATCOM is essentially a voltage source converter (VSC) that is connected in shunt with the power system. It consists of a DC capacitor, a three-phase bridge converter, and a control system. The converter is able to produce a controllable AC voltage that is synchronized with the power system, and its output can be adjusted to provide the required reactive power support.

The control system of the STATCOM continuously monitors the voltage and current of the power system, and calculates the reactive power required to maintain the desired voltage level. The converter then injects the required reactive power into the system, which can help to mitigate voltage fluctuations and improve system stability. The STATCOM can also be used to provide other power system control functions, such as power factor correction, harmonics mitigation, and voltage regulation during system disturbances. Its ability to provide fast and accurate reactive power support makes it a valuable tool for improving the performance and reliability of modern power systems [8, 10, 12].

The following is the relationship between the basic fundamental element of the converter's ac output waveform and the amperage across the dc capacitor:

$$V_{out} = kV_{dc}. \quad (2)$$

Where V_{dc} is the compensation voltage from the wind farm side, and V_{out} is grid output. Where k is the parameter that is affected by the converter's setup, the frequency of switching pulses, and the converter parameters. The value obtained of the converter power supply, or V_{out}, which is dependent on V_{dc}, can be altered by varying the dc input voltage, which is managed to accomplish by switching the pitch angle of the inverters switching. The difference in voltage between the converter electrical supply and the ac power bus voltage determines whether reactive power flows from the network to the step - up transformer or directly from the dc link to the system [8].

2.3. Modelling of the wind turbine

All articles dealing with the topic of wind energy shared the mathematical modelling of induction generators (IG). It served as an introduction to the study's findings. According to [16–18], the IG model's direct and quadratic transformation ($d\check{}q$) transformation with regard to the synchronous frame is as follows:

$$V_{ds} = R_s I_{ds} + \phi_{ds}\partial - \phi_{qs}\omega_s, \quad (3)$$

$$V_{qs} = R_s I_{qs} + \phi_{qs}\partial + \phi_{qs}\omega_s. \quad (4)$$

In, similar manner the rotor side equation can be define by putting rotors values. The flux for rotor and stator and its dependency is shown in the Eq. (5).

$$[\phi_{ds,\,qs,\,dr,\,qr}]\,\alpha\,[\text{Inductance} + \text{mutual`inductance}]\,. \quad (5)$$

The output of wind turbines can be expressed as [19] and is a portion of the total power contained in the wind.

$$\text{Power} = \frac{1}{2}\rho A v^3 C_p. \quad (6)$$

where A is the area covered by the turbine blades, q is the air density, and C_p is the power coefficient, which depends on the tip speed.

3. GREY WOLF OPTIMIZATION FOR TUNING

The grey wolf is a kind of animal with exceptional hunting prowess and great leadership qualities. According to their capacity for leadership, a pack of wolves was separated into four groups [11]. Alpha always decides on routine activities like sleeping, hunting, and so forth. Betas are second in leadership and constantly assist Alpha in making decisions. They back Alpha without reservation. Delta, which consistently complies with commands from either Alpha or Beta, makes up the third group. The wolves who are old and unable to hunt make up Omega [12, 13]. GWO is based on wolves' enhanced capacity for hunting [20, 21]. In terms of hunting optimization, GWO is relatively comparable, but it differs slightly in terms of prey detection by identifying malicious wolves that may have an impact on its hunting efficiency by tricking the alpha and beta. In order to address this problem, this research introduces the innovative idea of GWO for tuning signal to STATCOM.

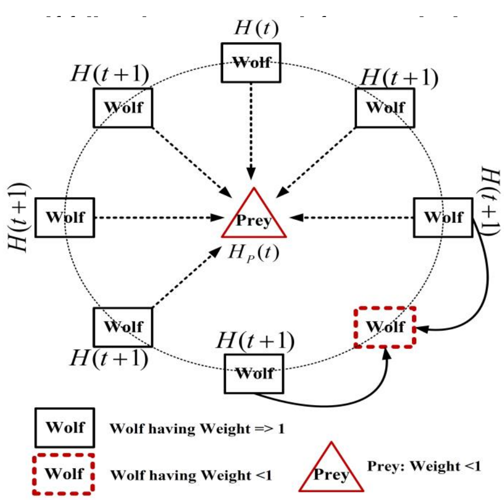

Fig. 3. GWO for STATCOM.

Fig. 3, shows GWO for the STATCOM values.

For tuning the STATCOM parameters, the GWO uses the optimal solution using equation:

$$\overrightarrow{N}(t+1)\Big|^{n_z(t+1)-n_m(t+1)} = \overrightarrow{N_P}(t) + \overrightarrow{V_A} * \overrightarrow{V_D}. \quad (7)$$

Here t represents number of iterations, $\overrightarrow{N_P}$ is the required best solution, $\overrightarrow{V_A}$ is co-efficient vector, n_z is total number of sensors parameters monitored, n_m is number of parameters away from optimal solution, and $\overrightarrow{N}$ is highly trusted node. In Eq. (8), $\overrightarrow{V_D}$ an be define as follows:

$$\overrightarrow{V_D} = \left|\overrightarrow{C} * \overrightarrow{H_p}(t) - \overrightarrow{H}(t)\right|. \quad (8)$$

Vectors $\vec{V_A}$ and $\vec{C}$ can be calculated using Eqs. (9) and (10).

$$\vec{V_A} = 2\,\vec{V_A} * \vec{r} - \vec{a}, \quad (9)$$

$$\vec{C} = 2\,\vec{r_2}\,. \quad (10)$$

Where, during the course of each iteration, the component of r and r_2 linearly falls from 2 to 0 and are random vectors in the range [0, 1]. To achieve the optimal result, alpha, beta, and delta decisions are chosen in the GWO technique. The position is updated and used for the following best solution after each iteration [22, 23]. The best fit and control parameters is obtained using Eqs. (7) to (10) for STATCOM operations.

The flow chart of the overall operation is shown in the Fig. 4. The proposed methodology consists of two stages. The first stage is using ANN for best solution and stage two is using grey wolf optimization to tune the STATCOM parameters to get OPF solutions.

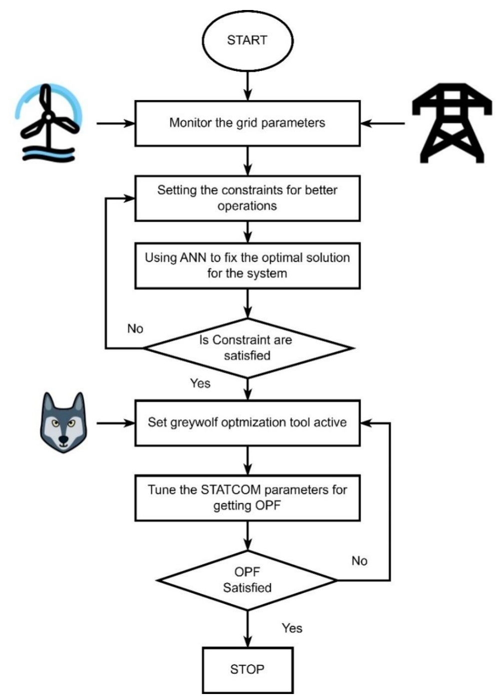

Fig. 4. Flowchart for proposed methodology.

4. RESULT AND DISCUSSION

In the proposed paper, the OPF problem was solved by FACT's devices using the newly designed meta-heuristic GWO method, which was inspired by nature. The GWO algorithm, which was introduced by Mirjali in 2014, was motivated by the hunting habits of Grey Wolves. To assess the efficacy of the proposed algorithm, we use the IEEE-14 Bus Test system to optimise the OPF problem.

The technical parameters are stated in the Table 2. Will simulate the model for two cases as stated below:

- Case 1: STATCOM operation under normal condition
- Case 2: STATCOM operation under trip condition

Ratings and parameters of the STATCOM used for the system is given in the Table 3. The control parameter of the STATCOM is stated in Table 4.

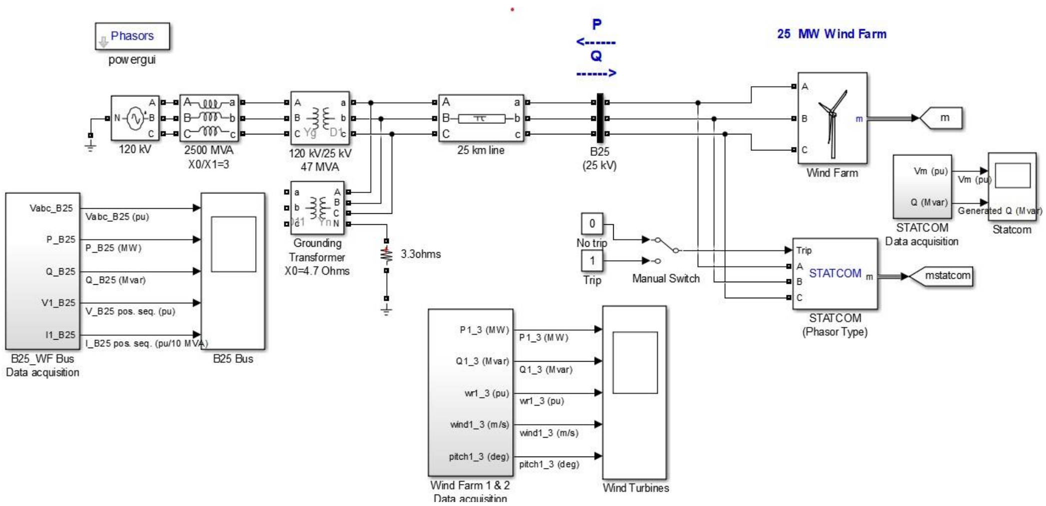

Fig. 5. Simulink.

Table 2. Technical parameters of the model.

Parameters	Values
Wind Farm	25 MW
Transmission Line	25 Km
Type of Transmission Line Model	Pi Type
Wind Farm Bus	25 kV
Grid	125 kV
ANN Neuron	40
No. of grey wolf	50

Table 3. STATCOM parameters.

Parameters	Values
Nominal Voltage	25 kV
Frequency	60 Hz
Converter Rating	3 kVA
DC Link Voltage	4000

4.1. STATCOM operation under normal condition

In this case the load is vary and then the operation of the STATCOM is verified. Fig. 5, shows the data actualization from wind farm bus during normal operation of varying load. To tackle the load change the wind turbine 1 & 2 activate their operations as shown in the Fig. 6. In similar manner, Fig. 7 shows the operation of STATCOM using proposed methodology.

4.2. STATCOM operation under trip condition

condition During trip operations at time 13 and 15 second the operation gets effected due to trip in the system which can be either fault or sudden huge load change. Still the simulation shows that the grid is stable and operation is maintained. This shows that the proposed methodology is useful.

Now Table 5 shows the accuracy and efficiency of the system. Finally, the discussion is stated in the next subsection.

Table 4. Control parameters.

Parameters	Values
Reference voltage (PU/S)	10
Droop (PU)	0.03
Voltage Gain (Kp & Ki)	5 & 1000

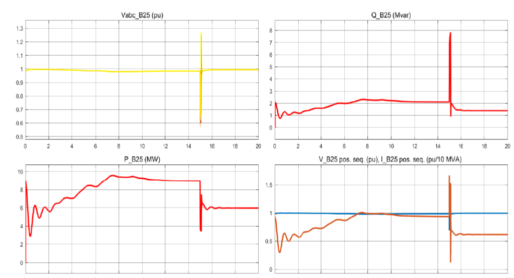

Fig. 6. Wind farm bus details.

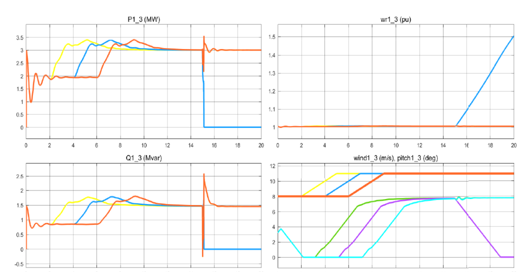

Fig. 7. Wind farm unit 1 & 2 activity during load change.

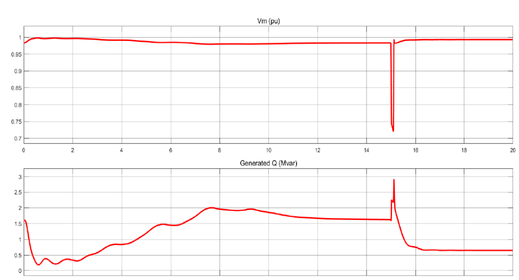

Fig. 8. STACOM operation using proposed methodology.

4.3. Discussion

In the STATCOM's control circuit, the ANN-grey wolf controller has taken the position of the PI controller. This contributed to the

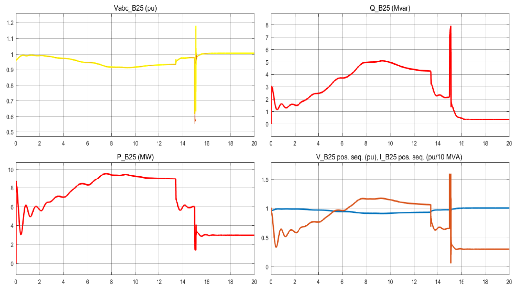

Fig. 9. Condition during trip operation.

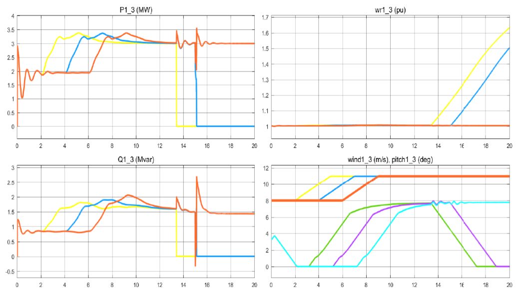

Fig. 10. Wind farm unit 1 & 2 activity during trip operation.

authors of the study goal of making comparisons the efficacy of the PI-controlled based STATCOM and the ANN-grey wolf-controlled based STATCOM [24, 25]. To be clear, the ANN-purpose grey wolf's was to improve the system's stability throughout a wide operating range while delivering a quick and dynamic reaction. Figs. 6-9 displays the final outcome. The results clearly show that the ANN based system was able to increase the stability of the connected power system by raising the voltage on the STATCOM-connected weak buses.

Comparison is down with PI and PID controller in the Fig. 10.

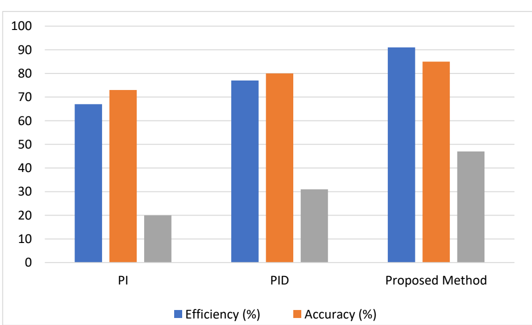

Fig. 11. Comparison with existing techniques.

For stability analysis we have done Nyquist criteria to check the overall stability of the system as per the conditions. The Nyquist diagram in Fig. 11 shows the stability and capability of the proposed methodology. In the similar, manner the system first order response is shown in the Fig. 12. The response shows that the system is stable at the extreme condition of the fluctuations dynamics in the system.

Table 5. Accuracy and efficiency of the system.

Parameters	Values
Total simulation	20
Passed	17
Fail	3
Accuracy	85%
Efficiency	91%

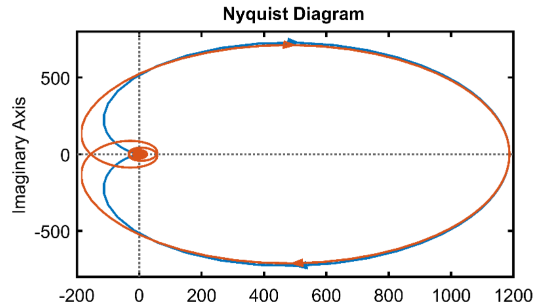

Fig. 12. Nyquist plot of the methodology for the case study.

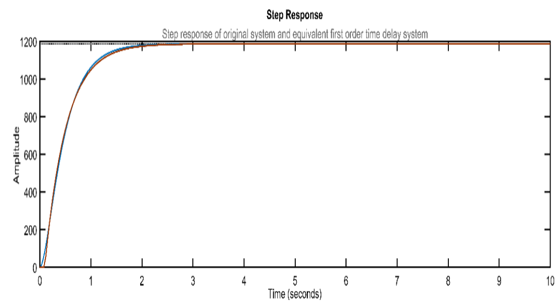

Fig. 13. System first order response.

5. CONCLUSION AND FUTURE WORK

A Static Synchronous Compensator (STATCOM) can be optimized using Artificial Neural Networks (ANN) and (GWO) algorithm. This approach involves training an ANN to predict the optimal STATCOM settings based on input parameters, and then using the GWO algorithm to find the optimal values for the input parameters. The first step in this process is to collect data on the power system, including voltage and current measurements, and identify the input parameters that can be used to adjust the STATCOM settings. These input parameters may include the magnitude and phase angle of the STATCOM output voltage, the DC voltage of the converter, and the frequency of the output voltage. Next, an ANN is trained using the collected data, with the input parameters as inputs and the desired system performance as outputs. The ANN is trained using a supervised learning approach, with the desired system performance as the target output. The trained ANN can then be used to predict the optimal STATCOM settings for a given set of input parameters. Finally, the GWO algorithm is used to find the optimal values for the input parameters, which can be used to adjust the STATCOM settings accordingly. The GWO algorithm is a meta-heuristic optimization algorithm that is inspired by the social behaviour of Grey Wolves in nature. It is capable of finding optimal solutions to complex optimization problems, and has been successfully applied to various engineering and scientific applications. By combining the predictive power of ANN with the optimization capability of the GWO algorithm, the STATCOM can be optimized to provide the best possible performance under a wide range of operating conditions. In this paper this approach help to improve the stability and reliability of modern power systems by attending more than 90% efficiency, and is becoming increasingly important as renewable energy sources are integrated into the grid.

Despite the significant advances in the field of STATCOM controlling techniques, there is still room for improvement. Future work in this area can focus on the following aspects:

1) Multi-objective optimization: Most of the current STATCOM controlling techniques are designed to optimize a single objective, such as voltage regulation or reactive power compensation. However, the power system operation involves multiple objectives, such as voltage stability, power factor correction, and harmonic mitigation. Therefore, future work can focus on developing multi-objective optimization techniques for STATCOMs that can simultaneously optimize multiple objectives.
2) Robustness analysis: The STATCOMs operate in a dynamic environment where the system parameters and operating conditions are continuously changing. Therefore, it is essential to analyze the robustness of the STATCOM controlling techniques against variations in the system parameters and operating conditions. Future work can focus on developing robust control techniques that can provide stable and reliable operation of STATCOMs under varying operating conditions.

In conclusion, future work in the area of STATCOM controlling techniques can focus on developing multi-objective optimization techniques, robustness analysis, real-time implementation, integration with renewable energy sources, and power-electronics-based devices interoperability. These advances can significantly improve the performance and reliability of STATCOMs in power systems.

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