Research Article

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Power quality enhancement of solar–wind grid connected system employing genetic-based ANFIS controller

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Abstract: The demand for electricity globally has led to the search for renewable energy resources for power generation and attaining it in an eco-friendly manner. The solar photovoltaic systems and wind-based generators of power are regarded as primary resources of renewable energy and are called Distributed Generation units as they are scattered in nature. These are operated with bidirectional converters by providing auxiliary services at grid side and load side in either mode of microgrid operation. Besides, the DC power generation units’ integration gets converted into AC system by means of inverters. These types of systems not only increase voltage and current harmonics and power frequency deviations but also drive the distribution system to risky operating zone. This emphasizes the stipulation of advanced control schemes for microgrid architecture. Consequently, power electronic converters introduce harmonics in the system and affect system performance. To report these expanded issues, the authors recognized an advanced custom power device entitled Distributed Power Flow Controller (DPFC). In this study, the proposed system on solar–wind-based hybrid energy approach has been examined primarily through the strategy of DPFC mechanism. Later, the system has been examined with Genetic Algorithm (GA)-based fuzzy logic controller and GA-based adaptive neuro fuzzy inference system controller for shunt control of context built with DPFC mechanism. Furthermore, the validated results are verified using MATLAB/Simulink software.

Keywords: power quality, solar–wind system, fuzzy logic controller, distributed power flow controller, adaptive neuro fuzzy inference system

1 Introduction

The swift escalation of power electronic equipment and its appliances has vividly altered the distinctiveness in the distribution system. The redundant, serious power-quality problems are created in recent distribution network due to power electronic device-based nonlinear components. The categorization of power-quality issues is shown in Figure 1. Fascinatingly, it is renowned that the same power electronic devices have the capability to shield utility grid and load from power-quality problems [1–3]. The Flexible AC Transmission System (FACTS) device and Custom Power Device are considered as the vital compensation devices to be installed in the power system for the finest management of reactive and active power flow. With the advancement in FACTS, several innovative concepts are turning the power system into a more reliable and flexible one and providing better control over power flow without altering the generation schedule.

A novel means of Distributed Power Flow Controller (DPFC) which facilitates a modernized approach of improving functionality in the power system network through Unified Power Flow Controller (UPFC) has been developed in this paper. The DC link doesn’t exist between the converters in DPFC for power exchange functionality as in UPFC. Wherein, the controller of DPFC context, builds with component of the third frequency harmonics developed among the trading within dynamic strategy of power converters network design. Besides, the proposed scheme offers exceptional performance to prevail over current as well as voltage distortions. Furthermore, the developed approach with the simulation model was established using MATLAB/Simulink software and verified through control technique performance [4].
In view of the aforementioned discussion, the proposed system under dynamic procedures is represented under Section 2. Several control strategies under DPFC incorporating with Genetic-based fuzzy logic controller (FLC) and Genetic-based adaptive neuro fuzzy inference system (ANFIS) are explained in Section 3. Detailed assessment of the proposed system has been simulated and the results are shown under Section 4. Section 5 concludes with the discussions and suggestions.

2 Proposed dynamic approach

Figure 2 depicts the suggested dynamic system block diagram. Whenever a fault occurs in the system Point of Common Coupling that enables the output reflection within the power gained from the grid system. Thus, the device integrated into the development of the customized topology with labeled DPFC is shown under different loaded conditions. The research study uses DPFC and Genetic-FLC and Genetic-ANFIS for converter regulation.

2.1 Concept of wind energy conversion system

Wind turbines, permanent magnet synchronous generators (PMSGs), and power electronic converters are the primary parts of a wind energy conversion system.

2.1.1 Mathematical model for wind turbine

Wind turbines transform the kinetic energy of wind into mechanical power [5]. Wind turbine power is expressed as:

Figure 1: Concerned issues classified in power quality context.

Figure 2: General structure of proposed PV–wind hybrid scheme.
\[ P_m = \frac{1}{2} \rho C_p A_v V_w^3 , \quad (1) \]

\[ C_p(\lambda, \beta) = 0.73 \left( \frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2 \right) e^{\frac{18.4}{\lambda_i}} , \quad (2) \]

where

\[ \lambda_i = \frac{1}{\lambda - 0.02\beta - 0.003} , \quad (3) \]

\[ \text{TSR}(\lambda) = \frac{\omega_e R_s}{V_w} . \quad (4) \]

Assume that constant rotor pitch angle and power coefficient \( C_p = 0.59 \) (Betz’s law). However, realistically, the generation of performance coefficients \( C_p \) ranges from 0.2 to 0.4, respectively. Figure 3 shows the schematic representation of wind turbine using MATLAB/Simulink.

### 2.1.2 Mathematical model for PMSG

The dynamic model of PMSG is developed under quadrature of 90° on \( d \)-axis and \( q \)-axis concerning rotation inclined within the reference of 2-phase synchronous frame as developed (Figure 4).

The mathematical formulation of PMSG in synchronous reference frame is indicated by Eqs. (5)–(7). Assume that the generator’s reference frame speed is \( \omega_e [5] \).

\[ V_{gd} = R_s i_{gd} + L_s \frac{di_{gd}}{dt} - \omega_e L_s i_{gq} , \quad (5) \]

\[ V_{gq} = R_s i_{gq} + L_s \frac{di_{gq}}{dt} + \omega_e (L_s i_{gd} + \lambda_m) . \quad (6) \]

Electromagnetic torque is given as

\[ T_e = \frac{3}{2} \frac{p}{2} \lambda_m i_{gq} . \quad (7) \]

### 2.2 Solar photovoltaic (PV) system

A PV solar module’s equivalent circuit is shown in Figure 5. It harnesses solar energy to produce electricity. The ideal PV cell is signified with source of current linked in parallel with diode [6].

In accordance with Kirchhoff’s current law,
2.3 DPFC

DPFC is a derivative of UPFC in this research study [7–12]. Similar to UPFC, DPFC can influence all system variables. DPFC replaces shunt and series converters’ common DC links. With the aid of third harmonic component, active power switch over occurs between a shunt and a series converter. The DPFC’s series converter uses distributed FACTS [13]. In addition to cheap cost, DPFC offers good dependability owing to the series converters’ redundancy. Figure 6 represents DPFC internal circuitries.

3 DPFC control strategies

DPFC management systems help to reduce power-quality concerns including sag, swell, and harmonics. The controllers must be able to identify and investigate system issues as well as correct for voltage and current harmonics. Their negative harmonic currents create inverter gate pulses. In this study, DPFC that uses Genetic-based FLC and Genetic-based ANFIS is used to alleviate power quality concerns that includes sags, swells, and harmonics. Genetic Algorithm (GA) is implemented to determine the optimal values of DC voltage of the shunt controller of DPFC. Then, these optimal values are applied for fuzzy and ANFIS controllers. The system’s performance is monitored using MATLAB/Simulink.

3.1 Implementation of DPFC integrated to Genetic-FLC

Application of GA enables the tuning effect oriented into the implementation of FLC under certain system format. Further, the optimization of membership functions (MFs) initiated into Rule Base and Database for the FLC system developed by Lee and Takagi applying triangular-shaped MFs within the GA-based binary coding. Moreover, the manual design or automation with GA is associated with the design developed under FLC that tunes with the system of Knowledge-Base employing scenarios of training sets [14]. Estimation within FLC can be capable of input and output sets under limitation of accuracy developed further with the tuning scenario under GA implementation. GA-based optimization can be explained by a technique controlled on a step-by-step basis. The solution begins with individual analysis and subsequent results [14–16]. With the study developed, the population can be analyzed with the GA-based binary code under random creation of execution. Furthermore, the mapping under the linear system can be obtained with the values of variables under input and output for individual string. Later, the deviation on absolute value can be predicted with the scenarios calculated in fitness analysis. The resulting population will be included into the deployment of GA strings, where it will undergo additional modification due to reproduction, crossover, and mutation [14]. The proposed GA-FLC is shown in Figure 9. The triangular Modular Function of Figure 6: Internal circuit of DPFC.
FLC is given by Eq. (10) [17,18]. The development of the process of fuzzification and defuzzification can be performed for the functions of triangular membership purposes (Figure 7).

\[
\mu(x) = \max \left[ \min \left( \frac{x - x_1}{x_2 - x_1}, \frac{x_3 - x}{x_3 - x_2} \right), 0 \right].
\]

(10)

3.2 Implementation of DPFC integrated to genetic-ANFIS

The graphical representation of the TS-FLC model, shown in Figure 8, is similar to the ANFIS system framework. The advantages of FLC and adaptive neural networks are combined in this approach. Nodes of different shapes are used to represent the various layers of the network. A square node indicates an adaptive node, while a circular node indicates a fixed node. Fuzzy inference systems have many of the same components as ANFIS. The ANFIS framework consists of five interconnected layers [19,20].

Layer 1:

This layer contains the X1 and X2 inputs. These are known as MFs. The most common shapes are triangular MF and bell shaped. The first layer’s outputs serve as a basis to the second layer.

Layer 2:

This layer 2 is considered as the Membership Layer. It determines the MF weights. The xi inputs from the previous layer are recognized and merged with respective

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**Figure 7**: Flow chart of the proposed GA-FLC.
Figure 8: ANFIS structure.

Figure 9: Voltage waveforms at certain load value under GA-based FLC.

Figure 10: Current waveforms at certain load value under GA-based FLC.
Figure 11: Power waveforms at certain load value under GA-based FLC.

Figure 12: Spectrum analysis of load voltage harmonics at $t = 0.2$ s through GA-based FLC (under sag condition).

Figure 13: Spectrum analysis of load voltage harmonics at $t = 0.6$ s through GA-based FLC system (under swell condition).
weights. The results obtained are MFs for portraying the fuzzy set theory of the corresponding parameters. It should be stated that layer 2 possesses \( nK \) nodes, each of which results in the MF estimate under \( i \)th antecedent of the \( j \)th rule given by
\[
y^{(2)}_{ij} = \mu A_i \cdot x(i),
\]
where \( A \) is a matrix that defines a partition of space \( x_i \).
\( \mu A_i \cdot x(i) \) is frequently chosen as a generalized MF outlined through the following equation:
\[
\mu A_i \cdot x(i) = \mu(x_i, c_i^j, b_i^j, d_i^j).
\]

It is significant that the parameters in the preceding equation were indeed made reference as the premise parameters.

**Layer 3:**

This is referred to as the “Rule Layer.” The number of layers is assumed to be the same as the number of fuzzy rules. On this basis, fuzzy rule matching and activation levels are calculated for each rule. Each node computes its own set of normalized weights to use throughout the network. The aggregation operator for layer 3 is the product \( t \)-norm, which has \( K \) fuzzy neurons. Nodes are linked to a rule, and each neuron’s output determines how the \( j \)th rule is being followed by [21,22].
\[
y^{(3)}_j = \prod_{i=1}^n \mu A_i \cdot (x_i) \text{ for } j = 1, 2, \ldots, K.
\]

**Layer 4:**

Layer 4 exemplifies as the defuzzification layer. Fuzzy rules are used to derive the outputs for \( y \) in this layer. Fuzzy Singletons yield another set of Neuro-Fuzzy parameters. Weighted connections between Rule Layer and defuzzification layer reveal these parameters. Neurons in this layer are responsible for restoring things to their normal state. The resulting numbers are referred to as “normalized firing strengths,” along with which they are stated into the following equation:
\[
y^{(4)}_j = \frac{y^{(3)}_j}{\sum_{k=1}^n y^{(3)}_k} \text{ for } j = 1, 2, \ldots, K.
\]
Layer 5:
This is the network’s Output Layer. This layer takes input from Layer 4 outputs. This layer sums up inputs and transforms the results of Fuzzy classification into a more precise form. In this layer, each node’s output is provided by the other nodes.

\[ y_j^{(5)} = y_j^{(4)} f_j(x) \text{ for } j = 1, 2, \ldots, K, \]  

where \( f_j(x) \) signifies \( j \)th node for Layer 5 network.

Summation of the outcomes is attained for the proper development of network output, which is formulated based on the following equation:

\[ y_j^{(5)} = \sum_{j=1}^{K} y_j^{(4)} , \]  

4 Simulation outcomes and discussions

This study describes the functioning of DPFC method utilizing GA-FLC and GA-ANFIS. These are designed in MATLAB/Simulink. Initially, a novel approach of PV/wind-based hybrid configuration has been initiated under grid integration of the GA-FLC system. Furthermore, a device was developed for DPFC integrated under GA-ANFIS for applying into fusion strategy of hybridization.

Nevertheless, the result developed by simulation validation is set on DPFC over several controllers under loading points. On other hand, various instances have been calculated for the issues generated to monitor the power quality initiated in the particular load condition.

Figure 16: Waveform of power at load point with GA-based ANFIS.

Figure 17: Spectrum analysis of load voltage harmonics with GA-based ANFIS at \( t = 0.2 \) s (under sag condition).
4.1 Simulation outcomes on system developed with PV/wind hybrid system under integration of GA-FLC

The following are the simulation results of proposed system with GA-FLC based DPFC. Figures 9 and 10 depict the waveforms for voltage and current under various points of load condition. Figure 11 depicts the generation of power under loading condition within the creation of power-quality issues of sag and swell developed among the instances of 0.2–0.4 s along with 0.6–0.8 s, respectively. Figures 12 and 13 depict the spectrum analysis of load harmonics for voltage as a parameter under sag and swell harmonics at t = 0.2 and 0.6 s within the total harmonic distortion (THD) of 0.64 and 0.60, respectively.

4.2 Simulation outcomes on system developed with PV–wind hybrid structure integrated to GA-ANFIS

Figures 14 and 15 show the device designed on DPFC integrated to GA-based ANFIS that compensates for sag and swell to analyze network disruptions. Figure 16 shows the load’s active power, i.e., till t = 0.5 s for 150 and 200 kW power capabilities. The spectrum analysis inside the load voltage acquired under specific ranges at t = 0.2 s with % THD of 0.03 and at t = 0.6 s with % THD of 0.03 is shown in Figures 17 and 18.

4.3 Comparative assessment

Table 1 compares the levels of harmonic distortion produced through different compensatory approaches. Also, it shows that DPFC with Genetic-based ANFIS reduces voltage sags and swells better than DPFC with Genetic-based FLC under different situations.

5 Conclusion

This article examined a DPFC device to reduce voltage sags and swells. DPFC allows a structure that differs from UPFC in impacting system characteristics. DPFC has shunt, central, and series topologies. The PV–wind Hybrid system studies dynamic sag and swell approximation under stress. The DPFC device tested for FLC and ANFIS controllers connected to the GA method. Harmonic content is measured in 0.6 s. Simulations show that GA-ANFIS outperforms GA-FLC in compensation and harmonic distortion. Capsule Network [23–25] can improve controller implementation for power-quality increase.
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Informed consent: Informed consent was obtained from all individuals included in this study.

Ethical approval: The conducted research is not related to either human or animals use.

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References


