Voltage Dip Mitigation in Wind Farms by UPQC Based on Cuckoo Search Neuro Fuzzy Controller

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Abstract—This paper presents, cuckoo search algorithm (CSA) based neuro fuzzy controller (NFC) to improve the performance of unified power quality conditioner (UPQC) for voltage sag mitigation in wind farms. CSA is used for optimizing the output of neural network so the classification output of the neural network is enhanced. CSA is an optimization algorithm which inspired by the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of other host birds. The inputs of the networks are error and change of error voltage signals of wind farm which calculated by compare with the reference signal. Next, the output of network i.e. compensated voltage is optimized by CSA. From the output of CSA, an optimum rule base fuzzy inference system is developed voltage dip mitigation in wind farm based squirrel cage induction generator (SCIG). The proposed CSA-NFC based UPQC is implemented in MATLAB. The performance of proposed UPQC is compared with traditional UPQC, NFC-UPQC, GA-NFC-UPQC, and adaptive GA-NFC-UPQC.

Keywords— UPQC; Wind Farm; voltage dip; NFC; cuckoo search

I. INTRODUCTION

For working out all power quality associated problems, unified power quality conditioner (UPQC) is one of the most well-known devices that are used [1], [2], [3]. To pay damages the unbalance of both source voltages and load currents [3], it formulates apply of series and shunt active power filters (APF). Concurrently, the UPQC is one of the primary custom power devices (CPD), which has the capability to work out both the current and voltage related problems [4]. The series APF counteracts the voltage-based distortions, whereas the shunt APF eradicates the current-based alterations [4]. For harmonic obliteration and simultaneous compensation of voltage and current, UPQC is frequently used and accordingly, it improves the power quality offered for other harmonic sensitive loads such as wind energy conversion system based squirrel-cage induction generators (WECS-SCIG) [5].

In recent years, dramatically increasing the penetration of wind farms in electrical power system, caused the importance behavior of wind turbines under grid faults and low voltage conditions or other disturbances. Faults or low voltage in the grid cause voltage sag at the point of common coupling (PCC). Voltage sag and other voltage disturbances will decrease the electrical torque of SCIG; consequently, the active power of WECS-SCIG will be reduced. Whereas, the mismatch between mechanical and electrical power make increasing the speed of rotor of SCIG. By increasing of rotor speed, the wind farm absorb more reactive power that can cause more depression in voltage magnitude [5]. After clearing the fault, if the rotor speed does not over its critical speed, SCIG can get the stability equilibrium point. Otherwise, if the wind generators unable to withstand against faults, it must be disconnected from the grid and it may cause a cascading voltage collapse and the breakdown of voltage of the rest of wind farm generators [5]. In order to overcome of these mentioned drawbacks, it is necessary to compensate the voltage sag with a fast dynamic response technique.

In this paper the Spanish grid code is used to improve the stability of WECS-SCIG facing the fault conditions.

Fig. 1 defines the area of voltage sag at the PCC that should be borne by wind farms [5].
In Fig.1, shaded area demonstrated that wind farm must be stay connected during the voltage sag under this requirements. Additionally, wind farm must injected maximum current for voltage sag recovery during the fault. For example, wind farm must be stay connected during a voltage sag (with 80% depth) at PCC for 500 msec. This requirements leads to investigated more about mitigation of voltage sag with a fast dynamic response technique.

Some literatures studied methods of control of UPQC [6-10]. The UPQC that executes quadrature sort of voltage injection in sequence is named as UPQC-Q [6]. To locate and classify the different types of power quality (PQ) events or disturbances, a lot of PQ associated algorithms has been improved at present. In order to improve the PQ [7], non-natural neural networks (ANNs) and fuzzy logic are mostly used in addition.

A NFC based UPQC, where the DC link capacitor discharging time has been diminished by installing a bias voltage generator has been proposed in the reference [8]. The input of bias voltage generator has been produced through the NFC. The amalgamation of neural network based controller and FLC is NFC. First of all, the fault voltage and transform of error voltage of SCIG has been found out. After that, the voltage deviation has been applied separately to FLC and NN-based controller. The yield voltage of FLC and NN-based controller has been calculated, and next the mean voltage of two methods has been related to the bias voltage generator. The power quality of the system has been enhanced ultimately.

Normally, regulating the voltage between the two dynamic converter is the purpose of the dc link capacitor. However, the voltage regulating time of capacitor is too elevated due to longer discharging time. In text, for regulating the dc link voltage, many soft computing methods such as fuzzy logic, neural network, ANFIS, neuro-fuzzy etc, are offered.

The genetic algorithm (GA) plays an imperative role in optimizing the output of neural network and fuzzy logic in the dc link voltage rule process. The conventional GA can never guarantee stable optimization response times. Based on the possibilities in ratio to fitness values the genetic operators are changed in conventional GA. Especially, the dissimilarity between the shortest and the longest optimization response time is a lot larger than with conventional gradient techniques. The adaptive GA offered top results attained when compared to conventional GA. Other than, the computational difficulty of adaptive GA is elevated than classical GA, as it takes more time to touch the solution. In this paper, cuckoo search algorithm (CSA) based NFC will be suggested for developing the performance of UPQC to compensate the voltage sag with a very fast dynamic response.

II. PROPOSED CONTROL STRATEGY OF UPQC

The proposed UPQC system is the combination of CSA and network based fuzzy system. The CSA algorithm can overcomes the drawback of the NFC and improve its performance. The CSA algorithm is used to optimize the output of the neural network. Then based on the CSA output, an optimized fuzzy system is developed. In the optimized interference system, the rules are generated based on the optimal value of the regulated voltage.

So, the dc link capacitor voltage regulation and the voltage injection problems are solved quickly. All these processes have improved the performance of UPQC system compared to the conventional system. The structure of the proposed CSA-NFC based UPQC system is illustrated in Fig.2.

![Fig.2 Proposed CSA-NFC based UPQC system](image)

Fig. 2 depicted the structure of the proposed UPQC system with the working of the CSA-NFC exposition. Here, the input voltage, line voltage, output voltage, regulated voltage, and injected voltage are denoted as $V_s$, $V_{line}$, $V_{load}$, $V_R$, and $V_{inj}$ respectively. If the injected voltage satisfies the conditions;

If $V_s < \sqrt{(V_{load}^2 - V_{reg}^2)}$, then $V_{reg} = \sqrt{(V_{load}^2 - V_{reg}^2)}$

And, if $V_s > \sqrt{(V_{load}^2 - V_{reg}^2)}$, then $V_{inj} = V_s$

Then the voltage sag of the system is compensated perfectly. The active power of the system depends on the injected voltage of the transformer. So, the minimum injection of active power is achieved by regulating the dc-link voltage of the system. The regulation of voltage of the dc-link capacitor depends on the requirement of the UPQC system. The CSA-NFC based dc link voltage regulation is explained in the following sections.

A. ANN Based DC-link Voltage Regulation

For determining the dc link capacitor controlled voltage reference to the value of error and the change of error voltage, ANN a non-natural intelligence technique is utilized. The input layer, hidden layer, and output layer of the network are represented as $(H_{11}, H_{12})$, $(H_{21}, H_{22}, ..., H_{2N})$, and $H_{31}$ correspondingly. The weight allotted from input layer to hidden layer is indicated as $w_{11}$, $w_{12}$, $w_{1N}$, $w_{21}$, $w_{22}$ and $w_{2N}$, the weight allotted from hidden layer to output layer is indicated as $w_{211}$, $w_{212}$, ..., $w_{2N1}$. Here, Back Propagation (BP) training algorithm is used for training the network.

The stages occupied in training the neural network are specified below,

Stage 1:

Initialize input, output, and weight for every neuron. Here, $c$ and $e$ are the inputs of the network and capacitor regulation voltage $V_{R}^{NN}$ is the output of the network.

Stage 2:
The inputs of training data set i.e. e and \( \dot{e} \) are specified to the classifier and decide the BP error as,

\[
BP_{\text{error}} = V_{R(\text{tar})}^{NN} - V_{R(\text{out})}^{NN}
\]

where, \( V_{R(\text{tar})}^{NN} \) is the objective output and \( V_{R(\text{out})}^{NN} \) is the network output.

Stage 3:
Calculate the network output as,

\[
V_{R(\text{out})}^{NN} = \alpha + \sum_{n=1}^{N} w_{2n} V_{R}^{NN}(t)
\]  

Where,

\[
V_{R}^{NN}(t) = \frac{1}{1 + \exp(-w_{1n}e - w_{2n}\Delta e)}
\]

Eq. (2) and (3) signifies the activation function of output layer and hidden layer respectively.

Stage 4:
Transform the weights of all neurons as \( w(t) \), where, \( w(t) \) is the change of weight at time \( t \), which can be determined as,

\[
\Delta w(t) = \gamma \cdot V_{R(\text{tar})}^{NN} \cdot (V_{R(\text{tar})}^{NN} - V_{R(\text{out})}^{NN})
\]

In eq (4), \( \gamma \) is the learning rate that normally varies from 0.2 to 0.5.

Stage 5: Do again the process from step 2, until the BP error reaches a minimal value i.e,

\[
BP_{\text{error}} \leq \frac{1}{10}
\]

Once the process is finished, the network is well-trained and it would be suitable for providing \( V_{R}^{NN} \) values for any error and change of error voltage.

B. ANN output optimized by cuckoo search algorithm (CSA)

Cuckoo search is one of the meta-heuristic algorithms which used to solve the problem belongs to optimization. In this paper CSA algorithm is used to optimize the output of ANN; and the optimal fuzzy rules generated by the optimized output. Here, the input of the cuckoo search algorithm is the input of neural network and the output is the regulated voltage. This algorithm is inspired by the required brood performance of cuckoo species in combination with the Levy flight behavior of some birds and fruit flies in nature [9]. The three idealized rules are considered to describe the cuckoo search in simply which are: 1) Each cuckoo lays one egg at a time, and dump its egg in randomly chosen nest; 2) The best nests with high quality of eggs will carry over to the next generations; 3) The number of available host nests is fixed, and the egg laid by a cuckoo is discovered by the host bird with a probability [10]. In the case of minimization problems, the quality or fitness of a solution can simply be proportional to the minus value of the objective function [11]. The flow chart of cuckoo search for proposed approach is described in Fig.3.

C. Steps of cuckoo search

Step (i): Initialization

The first step of CSA is initialization. In the step, the error \( (V_e) \) and change of error of voltage \( (\Delta V_e) \) of WECS-SCIG is calculated. From the initialized values, the randomized solution is generated and the initialized value is described as follow,

\[
Y_i = \begin{bmatrix}
Y_{i}^{(0)} & Y_{i}^{(1)} & \cdots & Y_{i}^{(N_i-1)}
\end{bmatrix}
\]

Where \( Y_i \) is the random value which incorporates by the error and change of error voltage, \( N_i \) is the length of the value.

Step (ii): Evaluation
During evaluation, the current best nest is calculated from the initialized values.

Step (iii): Loop construction

In the step, the error and change of error of the system and the regulated voltage are determined. Then, check the voltage error minimized or not. If the capacitor voltage is regulated, cuckoo turns the location by randomly and evaluates the fitness function. Otherwise, generate a new egg in CSA, a Levy flight is performed using the coordinates of an egg selected randomly which can represented as follow,

$$x_{i+1}^t = x_i^t + \alpha \Theta \text{Levy } \gamma(A)$$  \hfill (6)

Where, \( \Theta \) denotes the entry wise multiplication, is the step size and \( \text{Levy } \gamma(A) \) is the levy distribution.

Step (iv): Fitness evaluation

The fitness function of the solution is evaluated and which represented as follow,

$$I_C = \frac{d(V_{c,\Delta e})}{dt}$$  \hfill (7)

Step (v): Solution construction

At the end of maximum iteration, check the final solution and whether the solution is satisfied, stop the process.

otherwise till to extend the satisfied condition. So, briefly the CSA algorithm is according to;

Initialize the population of ‘K’ host nest \( N_k \),

For all \( N_k \) do

Calculate fitness function \( F_k = f(N_k) \)

End for

While (Number of iterations < Maximum number of iteration) or (Stopping criteria satisfied) do

Cuckoo \( N_j \) generate by taking a Levy flight from random nest,

\( F_j = f(N_j) \)

Choose a random nest ‘i’

If \( (F_j > F_k) \) then,

\( N_k \leftarrow N_j \), \( F_k \leftarrow F_j \)

End if

Abandon a fraction of the worst nests, New nests build at new locations via Levy flight to replace nests lost. Estimate fitness function of new nests and rank all solutions.

End while.

D. DC-link voltage regulation by fuzzy controller

In the reimbursement of PQ problem [12], Fuzzy controller plays an essential role. Fuzzification, decision-making, and defuzzification are the three main steps occupied in fuzzy controller. The method of changing the crisp value into fuzzy value is known as fuzzification. The shape of fuzzy sets might be triangular, trapezoidal and more. At this point, a triangular fuzzy set is used. To the conclusion making process, the fuzzified output is then applied which holds a set of rules. The input for bias voltage generator is chosen from FIS using the fuzzy rules [13]. After that, the defuzzification procedure is carried out and the fuzzified computed voltage \( V_{k}^F \) is decided based on linear Takagi-Sugeno outputs. The inputs of fuzzy scheme are \( e \) & \( \dot{e} \), and the output is \( V_{k}^F \). The linguistic variables of \( e \), \( \dot{e} \), and \( V_{k}^F \) are negative big, negative small, zero, positive small, positive big and it is named as NB, NS, ZE, PS, PB in the rule base. The improved fuzzy rules are tabulated as in Table 1.

<table>
<thead>
<tr>
<th>( e )</th>
<th>( \dot{e} )</th>
<th>NB</th>
<th>NS</th>
<th>ZE</th>
<th>PS</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
<td></td>
</tr>
<tr>
<td>NS</td>
<td>NB</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td></td>
</tr>
<tr>
<td>ZE</td>
<td>NB</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>NS</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
<td></td>
</tr>
<tr>
<td>PB</td>
<td>ZE</td>
<td>PS</td>
<td>PB</td>
<td>PB</td>
<td>PB</td>
<td></td>
</tr>
</tbody>
</table>

III. RESULTS AND DISCUSSION

The proposed CSA-NFC based UPQC was implemented in MATLAB. Then, the voltage sag clearing performance of the proposed UPQC was tested with wind farm based SCIG. The CSA algorithm implementation parameters are tabulated as in Table 2. The implementation parameters of the proposed UPQC and tested system are represented in Table 3. The fuzzy controller design parameters are tabulated in Table 4. The simulink model of the proposed system is illustrated in Fig.4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-link Capacitor ( (C) )</td>
<td>10( \mu )F</td>
</tr>
<tr>
<td>Number of Iteration ( (N_i) )</td>
<td>100</td>
</tr>
<tr>
<td>Number of Chromosomes ( (N_c) )</td>
<td>50</td>
</tr>
<tr>
<td>Sub-Chromosomes ( (N_s) )</td>
<td>10</td>
</tr>
<tr>
<td>Number of Genes ( (N_g) )</td>
<td>5</td>
</tr>
<tr>
<td>Error Voltage ( (V_e) )</td>
<td>( \pm 100 )</td>
</tr>
<tr>
<td>Change of error Voltage ( (\Delta V_e) )</td>
<td>( \pm 50 )</td>
</tr>
</tbody>
</table>
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Table 4 Parameters of designed fuzzy controller

<table>
<thead>
<tr>
<th>Type</th>
<th>Takagi-Sugeno</th>
</tr>
</thead>
<tbody>
<tr>
<td>Num Inputs</td>
<td>2</td>
</tr>
<tr>
<td>Num output</td>
<td>1</td>
</tr>
<tr>
<td>Num Rules</td>
<td>25</td>
</tr>
<tr>
<td>And Method</td>
<td>Min</td>
</tr>
<tr>
<td>Or Method</td>
<td>Max</td>
</tr>
<tr>
<td>Imp Method</td>
<td>Min</td>
</tr>
</tbody>
</table>

Fig. 4 Simulink model of the proposed CS-NFC based UPQC system

Table 5 Voltage sag duration by different methods

<table>
<thead>
<tr>
<th></th>
<th>UPQC with PI controller</th>
<th>UPQC with NFC</th>
<th>UPQC with GA-NFC</th>
<th>UPQC with adaptive GA-NFC</th>
<th>UPQC with CSA-NFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage sag duration (sec)</td>
<td>0.04</td>
<td>0.03</td>
<td>0.025</td>
<td>0.015</td>
<td>0.009</td>
</tr>
</tbody>
</table>

In Fig. 5, the PQ problem is randomly occurred at 3.05 sec instant and voltage sag clearing performance is analyzed by different techniques. The error and change of error voltage is calculated by compare with the reference voltage signal. Then, the error and change of error voltage is applied to ANN and the corresponding regulated (compensated) voltage is determined. ANN output is optimized by CSA and the optimal control fuzzy rules are generated. The fuzzy system generates the regulated voltage which is injected to the line. In this paper, voltage sag considered for evaluating the performance of proposed model. The analyzed results compared with conventional model such as NFC, GA-NFC, and adaptive GA-NFC. The voltage sag clearing performance of UPQC with PI controller, UPQC with NFC, UPQC with GA-NFC, UPQC with adaptive GA-NFC, and UPQC with CSA-NFC are illustrated in Fig. 5, Fig. 6, Fig. 7, Fig. 8, and Fig. 9, respectively.

In Fig. 5, the PQ problem randomly occurred at 3.05 sec and voltage sag clearing performance is analyzed by different techniques. The error and change of error voltage is calculated by compare with the reference voltage signal. Then, the error and change of error voltage is applied to ANN and the corresponding regulated (compensated) voltage is determined. ANN output is optimized by CSA and the optimal control fuzzy rules are generated. The fuzzy system generates the regulated voltage which is injected to the line. In this paper, voltage sag considered for evaluating the performance of proposed model. The analyzed results compared with conventional model such as NFC, GA-NFC, and adaptive GA-NFC. The voltage sag clearing performance of UPQC with PI controller, UPQC with NFC, UPQC with GA-NFC, UPQC with adaptive GA-NFC, and UPQC with CSA-NFC are illustrated in Fig. 5, Fig. 6, Fig. 7, Fig. 8, and Fig. 9, respectively.

In Fig. 5, the voltage sag is occurred at 3.05 sec. and compensated by UPQC at 3.09 sec. But when improving the performance of UPQC by NFC, GA-NFC, adaptive GA-NFC and CSA-NFC; the voltage sag is compensated by taking less time. The voltage sag compensated duration performances of different methods are tabulated in Table 5. The comparison performance and analysis are shown that, the proposed CSA-
NFC based UPQC compensate the voltage sag duration effectively when compared with other controllers with UPQC. The proposed UPQC takes very less time for compensating voltage dip which can be seen in the comparison chart.

IV. APPENDIX

Power system with WECS-SCIG and UPQC parameters introduced as below (Table 6):

<table>
<thead>
<tr>
<th>Device</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>132 Y / 20 Δ (KV)</td>
</tr>
<tr>
<td>T2</td>
<td>20 Y / 0.575 Δ (KV)</td>
</tr>
<tr>
<td>T3</td>
<td>132 Y / 20 Δ (KV)</td>
</tr>
<tr>
<td>T. L. 1</td>
<td>0.1153 (Ω/km), 1.05 (mH/km), 15(km)</td>
</tr>
<tr>
<td>T. L. 2 &amp; 3</td>
<td>0.135 (Ω/km), 1.25 (mH/km), 7.5(km)</td>
</tr>
<tr>
<td>WECS-SCIG</td>
<td>1.5MW, 575V, 1810rpm, R=31.5m</td>
</tr>
</tbody>
</table>

V. CONCLUSION

The proposed CSA-NFC based UPQC was implemented and the output performances were evaluated. For evaluating the performance of proposed UPQC, the voltage sag was considered and the voltage sag clearing performance was analyzed. The voltage sag was applied randomly at different time instant and as per the variation, the regulated voltage was calculated. The voltage sag clearing performance of proposed UPQC was compared with traditional UPQC, NFC-UPQC, GA-NFC-UPQC, and adaptive GA-NFC-UPQC. The comparative analysis shows that, the proposed UPQC compensate the voltage sag by taking less time when compared with other systems. Thus, the proposed UPQC is solving the PQ problem effectively.

REFERENCES


