SMES BASED DVR AGAINST VOLTAGE SAG USING ANFIS SYSTEM

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Abstract: Voltage sag is a most significant problem in the power system which may bring great economic losses to the sensitive customers. The superconducting magnet energy storage (SMES) based DVR is introduced to overcome this problem. Fuzzy controller is very common in the control of DVR. The main problem of fuzzy controller is parameters associated with the membership function and the rules are broadly from the intuition of the experts. To alleviate this problem, Adaptive neuro-fuzzy inference system (ANFIS) controller design is proposed. Sugeno fuzzy controller is used with two inputs and one output. The control system and the output data is according to the error and error rate. The appropriate fuzzy controller is generates by ANIFIS. The proposed design method gives reliable powerful fuzzy controller with a minimum number of membership functions and the performance of DVR is minimize the THD.

Keywords: Superconducting Magnet Energy Storage (SMES), Dynamic Voltage Restorer (DVR), Adaptive Neuro-Fuzzy Inference System (ANFIS), Voltage sag, Total Harmonic Distortion (THD).

1. INTRODUCTION
Voltage sags is a one of the most important power quality problems in the power distribution systems. Voltage sag is decrease a rms ac voltage from 0.1-0.9 p.u of the nominal voltage, at the power frequency, of duration from cycles to a few seconds. Voltage sags are spawn by remote faults, such as single line-to-ground fault, double line to ground fault and three phase fault on the power distribution system.[1] The SMES based DVR is introduced to improve the performance of power system and voltage sag compensation as it is having high power rating with maximum efficiency than any other energy storage devices.[2] Dynamic voltage restorer is one of the most effective custom power device .it is series connected topology. The basic operating principle of the DVR is to insert a voltage of required magnitude and phase to conserve the desired amplitude and waveform for the load side voltage and it is used to improve the power quality and restore the quality of voltage in the sensitive load side [3]. Energy storage unit and large amplitude is essential to improve the compensation capability of DVR during the supply of power transfer when occurring the voltage sag. SMES is an energy storage device that stores the energy in the form of DC. Its contains a superconducting coil, field cryogenic system and the power conversion/conditioning of the system (PCS). Once the super conducting coil is charged, the current does not vanish and indefinitely stored the magnetic energy, the SMES is used to improve the power quality. The SMES system has highly efficient energy storage, quick response and power controllability [4].

In our proposed system adaptive neuro-fuzzy inference system (ANFIS) based PWM converter control is used in the control section. In fuzzy logic based design is not required to describe the mathematical model. But, The conventional fuzzy controller parameters are associated with the membership function is the main problem and the rules depend broadly on the intuition of the experts and it is required to change the parameters, it is done by trial and error only. In fuzzy inference system there is no scientific optimization methodology [5]. To overcome this problem, Adaptive Neuro-Fuzzy Inference System (ANFIS) is introduced.

This paper introduces Dynamic Voltage Restorer (DVR) and its operating principle, also presents the proposed Sugeno fuzzy controller which was generated using ANFIS method design for compensating the voltage sag. Then, simulation results using MATLAB-SIMULINK were illustrated and discussed.

2. RELATED WORK
In paper [1] the author S. Ezhilarasan and G. Balasubramaniam 2013 works on the power quality problem. Voltage sag and harmonics disturbed are main occurrence in power quality problem. Dynamic Voltage Restorer (DVR) is introduced to improve the power...
quality. DVR is installed between the source voltage and critical or sensitive load. The performance improvement of the DVR is based on PI with Fuzzy Logic Controller.

In paper [6] the author M. Swathi priya and T. Venkatesan 2014 has studied the voltage sag compensation in medium voltage level using Dynamic Voltage Restorer(DVR). DVR working is based on proportional integral (PI) control technique.

T.Arun Srinivas etal., 2015 [7] proposed the three-phase Dynamic Voltage Restorer(DVR). This topology is used for voltage sag compensation with a photo voltaic voltage fed boost converter for the compensation of voltage sag for medium voltage power system. Fuzzy control technique is used for the efficient compensation under the voltage sag condition.

Md. Riyasalt and Md. Ashraful Hoque 2011[8] illustrated the fast and efficient Dynamic Voltage Restorer(DVR) for mitigating the power quality problem in industrial distribution system. The proposed DVR employs the classical Fourier Transform technique for detection and quantification of voltage disturbances events.

Sandesh jain etal.,2012 [9] has discussed about voltage sag/swell occurs due to the three phase fault, ground fault and phase to ground fault in the transmission line and harmonics occurs due to the connection of controlled six pulse converter to the main drive load. Fuzzy controller methodology is used. DVR is connected in series with the distribution feeder at medium voltage. The THD and amount of unbalance in load voltage are decreased with the application of DVR.

3. DYNAMIC VOLTAGE RESTORER

The DVR is efficient to generate are absorb reactive power but the active power injection of the device must be provided by an external energy storage of the system [10]. The DVR voltage detection time is very short.

3.1. Basic configuration of DVR

The DVR consists of injection transformer, harmonic filter, storage devices, voltage source converter (VSC), DC charging circuit, and control and protection system.

3.2. Voltage Injection Transformer

The function of the transformer is to connect the DVR with the distribution network via the HV windings and the voltage source converters generate the compensating voltage to the incoming supply. If the transformer is not designed properly, the result is improper operation of the DVR due to the voltage saturation.

The injected voltage of a DVR can be expressed as

\[
|V_{inj}| = |V_{presag}| - |V_{sag}|
\]

\[
|V_{DVR}| = |V_{inj}|
\]

\[
|V_{DVR}| = |V_{presag}| - |V_{sag}|
\]

3.3. Output Filter

The main objective of the output filter is to conserve the harmonic voltage content generated by the voltage source inverter to the permissible level. It has small rating approximately 2% of the load.

3.4. Voltage source inverter

A VSI is a power electronic system it consists of switching devices (IGCTs, GTOs), and it’s generate a sinusoidal voltage at any required frequency, magnitude and phase angle. VSI is used to temporarily replace the supply voltage or to generate the part of the supply voltage.

3.5. DC energy storage system

The DC energy storage device is used to real power requirement of the DVR during compensation. The Various storage technologies such as flywheel energy storage, Super-conducting magnetic energy storage (SMES) and Super capacitors, In this method SMES energy storage device is used as a energy storage device Due to the characteristics of high energy density, high dynamic range, infinite cycling capability, quick response, energy recovery rate close to 100%. A super conducting magnet is selected as the energy storage unit to improve the performance of compensation capability of DVR and high power rating with maximum efficiency [11].
The compensation voltage sag can be limited by a limited DVR power rating. The equation for the injected voltage of DVR[12].

\[ V_{DVR} + V_{sf} = V_{LOAD} + Z_T I_{LOAD} \]  
(1)
\[ V_{DVR} = V_{LOAD} + Z_T I_{LOAD} - V_{sf} \]  
(2)

Where \( Z_T = R_T + jX_T \)

\[ V_{DVR} \] is the voltage supply by the DVR \( V_{LOAD} \) is the Desired load voltage magnitude \( Z_T \) is the load impedance \( I_{LOAD} \) is the load current

\[ V_{sf} \] is the system voltage during fault condition

Calculation of current in load side

\[ V_{LOAD} I_{LOAD} = P_L + jQ_L \]  
(4)
\[ I_{LOAD} = \left[ \frac{(P_L + jQ_L)}{V_{LOAD}} \right] \]

Where load voltage consider as a reference.

\( P_L \) is load active power

\( Q_L \) is load reactive power

The DVR voltage can be written as

\[ V_{DVR} = \sqrt{2} \sin(\theta) \left( I_{LOAD} \right) \]

\[ V_{DVR} = \sqrt{2} \cos(\theta) \left( I_{LOAD} \right) \]

(5)

Where \( \alpha, \beta \) and \( \delta \) are the angles of \( V_{DVR}, Z_T \) and \( V_{sf} \) respectively.

\[ \theta = \tan^{-1} \left( \frac{Q_L}{P_L} \right) \]  
(6)

Where \( \theta \) is the load power factor angle

The observable electrical power inoculation from DVR is given with

\[ S = V_{DVR} \times I_L. \]

4. PROPOSED SYSTEM

The proposed circuit is mainly build focusing on the three phase fault in the system. The fault analysis undergone here is taken for either the two phase fault or the three phase fault occurring for the linear load and the closed loop analyzer block is connected on the load side for the fault clearance which have the linear transformer and the LC filter which is connected to the DC link and the DC chopper circuit.

Figure 1: Block diagram of implemented DVR

Figure 2: Block diagram of proposed system
4.1. ANFIS Based Controller Design

Adaptive networks that is functionally equivalent to fuzzy inference systems. In this methodology introduce ANFIS network architecture and its hybrid learning rule. The learning algorithm tunes the membership functions of a sugeno-type fuzzy inference system using the training input are output data. An implementation of a represented fuzzy inference system using a back propagation (BP) neural network, it consists of a five layer

\[ O_i^1 = M_i(x_i) \]  
(1)

\[ O_i^1 \cdot \text{Output of node I in layer 1} \]

\[ x_i - E \text{ input of the ANFIS , } i=1,2,...,P \]  

\[ M - \text{node function associated with every node} \].The node functions \( M_1, M_2, ..., M_q \) is equal to the membership functions \( \mu(x) \). Its used in the regular fuzzy systems. \( q \) is the number of nodes for each input.

The output of every node in layer 2 is the product of all the incoming signals

\[ O_i^2 = M_i(x_i) AND M_j(x_j) \]  
(2)

\[ each \text{ node output represents the firing strength of the reasoning rule. In layer 3 each firing strength of the rule is compared with the sum of all the firing strengths. } \]

The normalized firing strengths are computed in this layer a

\[ O_i^3 = \frac{O_i^2}{\Sigma_i O_i^2} \]  
(3)

Layer 4 implements the sugeno-type inference system. A linear combination of the input variables of ANFIS \( x_1, x_2, ..., x_p \) plus a constant term, \( C_1, C_2, ..., C_p \) form the output of each IF- THEN rule. The output of the node is a weighted sum of these intermediate outputs.

\[ O_i^4 = O_i^3 \Sigma_j P_j x_j + C_j \]  
(4)

\( P_1, P_2, ..., P_p \) and \( C_1, C_2, ..., C_p \) layers are referred to as the consequent parameters.

The node in layer 5 produces the sum of its inputs using weighted average method.

\[ O_i^5 = \Sigma_i O_i^4 \]  
(5)

4.2. Sugeno Model

Assume the fuzzy inference system has two input \( x \) and \( y \) and one output \( z \). A first order sugeno model has rules as the following

Rule 1: If \( x \) is a \( A_1 \) and \( y \) is a \( B_1 \) then \( f_1 = p_{1x} + q_{1y} + r_1 \)

Rule 2: If \( x \) is a \( A_2 \)

\[ y \text{ is a } B_2 \text{ then } f_2 = p_{2x} + q_{2y} + r_2 \]

Figure 3: Model of ANFIS structure

ANFIS distinguishes itself from normal fuzzy logic systems by the adaptive parameters. Both the premise and consequent parameters are adjustable. The remarkable feature of the ANFIS is its hybrid learning algorithm. The parameter of the ANFIS is divided into two steps. The first step is consequent parameters training, the least square (LS) method is used the output of the ANFIS is a linear combination on of the consequent parameters.
The premise parameters are fixed at this step. The consequent parameters have been adjusted; the approximation error is back propagated through every layer to update the premise parameters as the second step. This part of the adaptation procedure is based on the gradient descent principle. This is the same as in the training of the back propagation (BP) neural network.

4.3. Fuzzy Control Rules

ANFIS structure with sugeno model accommodate 9 rules are exploited in this technique like mf1, mf2, mf3

Table 1: Fuzzy control rule table

<table>
<thead>
<tr>
<th>$e/\Delta e$</th>
<th>mf1</th>
<th>mf2</th>
<th>mf3</th>
</tr>
</thead>
<tbody>
<tr>
<td>mf1</td>
<td>mf1</td>
<td>mf1</td>
<td>mf1</td>
</tr>
<tr>
<td>mf2</td>
<td>mf1</td>
<td>mf2</td>
<td>mf2</td>
</tr>
<tr>
<td>mf3</td>
<td>mf1</td>
<td>mf2</td>
<td>mf3</td>
</tr>
</tbody>
</table>

4.4. ANFIS Procedure

Step 1: Load input data and output data

Step 2: Initialize the fuzzy system GENFIS commands

Step 3: Give the parameters for learning iterations (epochs) tolerance (error)

Step 4: Start learning process ANFIS stop when tolerance is achieved.

Hybrid learning algorithm method used to adjust the parameters of membership functions'.

5. SIMULATION RESULTS

The simulation of fault occurring system is specified with all the fundamental parameters in Table 2.

Table 2: General Specification of the Distributed Line

<table>
<thead>
<tr>
<th>SYSTEM PARAMETER</th>
<th>SPECIFICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line voltage</td>
<td>3Φ,415Vac</td>
</tr>
<tr>
<td>Frequency</td>
<td>50HZ</td>
</tr>
<tr>
<td>Impedance</td>
<td>0.001+0.005j</td>
</tr>
<tr>
<td>Harmonic filter</td>
<td>Lr=0.5mH, Cr=2uF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>50hz</td>
</tr>
<tr>
<td>Injection transformer</td>
<td>1:1</td>
</tr>
<tr>
<td>SMES coil</td>
<td>7.5h</td>
</tr>
<tr>
<td>Fault</td>
<td>225ms</td>
</tr>
<tr>
<td>Sag voltage</td>
<td>50v</td>
</tr>
<tr>
<td>Sag compensation voltage</td>
<td>50v</td>
</tr>
</tbody>
</table>

Table 3: Real and Reactive Power of the Distribution System Under Fault Condition

<table>
<thead>
<tr>
<th>Condition</th>
<th>Real power (kw)</th>
<th>Reactive power (kw)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without DVR</td>
<td>14</td>
<td>0.9</td>
</tr>
<tr>
<td>With fuzzy DVR</td>
<td>23</td>
<td>1.4</td>
</tr>
<tr>
<td>With ANFIS DVR</td>
<td>23.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The SMES based dynamic voltage restorer circuit in the distribution system is shown below in Fig 4.
Effective custom power of DVR is exploited to improve the power quality and besides to improve the power from any disturbances in the distributed line. DVR is used to protection and quality of Voltage at the sensitive load. The SMES based DVR provides ideal opportunity to voltage sag compensation. SMES has been exploited to improve performance of power system with high power rating and max efficiency [13]. Here we deal with SMES power quality application based on DVR for sag compensation.

The control block of DC chopper circuit shown below in Fig 5. This eliminates the harmonic contents in the phase voltage. This DVR gets the input from the PWM inverter that which gives the control signal for compensation. This DVR acquire the input from the PWM inverter that which gives the control signal for compensation.

The control block shown above receives the parameters by conversion process of abc/dq transform during fault condition and compares with the reference value that which is fed ot the DVR block. The error is filetered not just by comparing the dq values but with the defalut value set to the error comparator block.

The sugeno control structure is shown above in Fig 7. that which gives the comparative output of the membership functions.
ANFIS structure is shown above in Fig 8.

Figure 9: d-axis rule

The d-axis rule is shown above in Fig 9. This controls the axis d.

Figure 10: Fuzzy surface

Figure 11: q-axis rule

The q-axis rule is shown above in Fig 11. This controls the axis q.

Figure 12: Fuzzy surface

Figure 13: Voltage and current waveform without DVR

The input and output current and voltage waveform during current and voltage waveform at fault without DVR is shown above in Fig 13.

Figure 14: voltage sag present without DVR

Voltage sag present without DVR of the system is shown above in Fig 14.
Figure 15: Real and reactive power without DVR

The real and reactive power of the three phase distribution line under fault condition whose duration is from 0.04 sec to 0.25 sec without any control techniques is shown in the graph above in Fig 15.

Figure 16: Voltage and current with ANFIS DVR

The input and output voltage and current waveforms after the fault compensation using ANFIS DVR is shown above in Fig 16.

Figure 17: Voltage sag compensation with ANFIS DVR

Voltage sag compensation with ANFIS DVR of the system is shown above in Fig 17.

Figure 18: Real and reactive power with ANFIS DVR

The real and reactive power after the introduction of ANFIS DVR control block is shown above in Fig 18. where the fault period is rectified in upright routine.

Figure 19: THD without DVR

The total harmonic distortion value at fault condition before DVR control is shown above in Fig 19. The value reaches for about 1.00% for 50Hz.

Figure 20: THD with ANFIS DVR
The Total Harmonic Distortion THD value after fault compensation primarily sag compensation is shown above in Fig 20. Where the range has reduced to 0% for 50Hz.

<table>
<thead>
<tr>
<th>THD</th>
<th>Without DVR</th>
<th>With fuzzy DVR</th>
<th>With ANFIS DVR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1%</td>
<td>0.12%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Table 4: THD Observed values in MATLAB SIMULINK

The power factor for the 3 phase system with the ANFIS controlled SMES based DVR for the sag compensation has been obtained as 0.8.

Table 4: THD Observed values in MATLAB SIMULINK

Figure 21: THD comparison in %

SMES ANFIS control based DVR is shown in above Fig 23.

Figure 22: Power factor improvement SMES based DVR

Figure 23: SMES ANFIS control based DVR

A real and reactive power comparison without DVR and with ANFIS DVR is shown above in Fig 24.

6. CONCLUSION

The compensation on sag in three phase system at distribution end, when eliminated, enhances the stability of the supply power and also the sustained of the power factor without variation as it is tightly coupled to THD where the results implies when compared with the DVR control without the combination of SMES coil and ANFIS based DVR. This controller has no gains to adjust and solve the problem of traditional fuzzy controller gains tuning and it’s most cost effective.
REFERENCES


