Fuzzy Controlled DSTATCOM for Voltage Sag Compensation and DC-Link Voltage Improvement

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ABSTRACT  
In this paper we propose fuzzy control of DC-link capacitor voltage of three-phase four-wire DSTATCOM for power quality improvement in distribution network. It is designed to compensate reactive power and to eliminate harmonic currents. DSTATCOM regulates the voltage at the point of common coupling (PCC) by injecting reactive power to the PCC. During load changes there is considerable variation in DC capacitor voltage. In this work a fuzzy logic based controller is proposed to improve the transient performance of the DC-link voltage. The validity and effectiveness of the control strategy has been verified by theoretical analysis and MATLAB simulation.

Keywords  
DSTATCOM, PCC, Fuzzy Controller

INTRODUCTION  
Power system is a complex network made of thousands of buses and hundreds of generators. The basic structure of a power system contains a generating plant, a transmission system and a distribution system. Now a day, available power is not sufficient to fulfil the demands of load. Nonlinear loads such as computer, printer, SMPS and reactive power loads (fan, pump) available in residential and commercial establishments draw nonlinear load currents which distort the supply voltage and inject harmonics in to the supply system. Due to the demand supply mismatch, power flow in some of the transmission lines are overloaded, which has as an overall effect of deteriorating voltage profiles, power quality and decreasing system stability. Series capacitor, shunt capacitor, and phase shifter are different devices used to increase the power system transmission lines load ability. All these devices are controlled mechanically, so these units are relatively slow. In the past engineers suggested conventional solutions for mitigating power quality problems using thyristors and other semiconductor devices. The best way to solve this problem at distribution systems at minimum cost is by using the Custom Power devices. In this paper, we have implemented fuzzy controller to control the DC-link voltage of DSTATCOM and compared the output voltage regulation results with conventional PI controller. Total harmonic distortion of source current and load current are also evaluated to ensure the power quality.

Section II describes the modeling aspect of DSTATCOM. IV implements fuzzy controller for DSTATCOM and section V shows the results.

DSTATCOM  
D-STATCOM (Distribution Static Compensator), which is schematically depicted in Figure 1, consists of a voltage source converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through an interfacing inductor [5]. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the ac system. The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:
1. Voltage regulation and compensation of reactive power
2. Correction of power factor.
3. Elimination of current harmonics.

The AC terminals of the VSC are connected to the Point of Common Coupling (PCC) through an inductance, which could be a filter inductance or the leakage inductance of the coupling transformer.
The quantity of reactive power flow is proportional to the difference in the two voltages. It is to be noted that voltage regulation at PCC and power factor correction cannot be achieved simultaneously. For a DSTATCOM used for voltage regulation at the PCC, the compensation should be such that the supply currents should lead the supply voltages; whereas, for power factor correction, the supply current should be in phase with the supply voltages. The main aims of the DSTATCOM are

a) To help maintain near unity power factor by canceling the effect of poor load power factor

b) To cancel the effect of harmonics due to load so that the current drawn from the source is nearly sinusoidal

c) To help offset the effect of unbalanced loads.

Ref [1] describes the concept of voltage sag and explains how voltage sag can affect the power quality. There are IEEE standard guidelines for power quality which can be found in [2,3,6].

**DSTATCOM AS COMPENSATOR**

The schematic diagram of 3 phase, 4 wire is shown in figure 2. $V_{ac}$, $V_{sb}$ and $V_{sc}$ are voltage sources. The load and compensator are connected at the PCC. Under balanced supply voltages and for unity power factor operation, reference compensator current based on instantaneous symmetrical component theory is represented as

\[
i_{ja}^* = i_{sa} - i_{ja} = \frac{V_{sa}}{\Delta} P_{avg} + P_{loss}\tag{1}
\]

\[
i_{jb}^* = i_{sb} - i_{jb} = \frac{V_{sb}}{\Delta} P_{avg} + P_{loss}\tag{2}
\]

\[
i_{jc}^* = i_{sc} - i_{jc} = \frac{V_{sc}}{\Delta} P_{avg} + P_{loss}\tag{3}
\]

Here, $\Delta = \sum_{j=a,b,c} V_{sj}^2$ is called average load power.

\[
P_{loss} = k_p V_{dc}^{ref} - V_{dc} + k_i \int V_{dc}^{ref} - V_{dc} \, dt\tag{4}
\]

\[
P_{avg} = \frac{1}{T} \int V_{sa}i_{ja} + V_{sb}i_{jb} + V_{sc}i_{jc} \, dt\tag{5}
\]

$V_{dc}^{ref}$ is reference capacitor voltage and $V_{dc}$ is actual capacitor voltage. $K_p$ and $K_i$ are proportional and integral gain respectively.

The dc-link capacitor voltage waveform contains ripple because according to the instantaneous symmetrical component theory, the compensator supplies the oscillating part of the active power also. Thus there is always a zero average oscillating power exchange between the compensator and the load. This leads to a reduction or an increase in the dc capacitor voltage. For good current injection and thus compensation, maintaining the dc capacitor value close to the reference value is very important which is achieved by a PI controller. $P_{loss}$ is controlled to ensure that the dc capacitor voltage does not deviate from the reference value. A PI controller is preferred to regulate the dc link voltage as the presence of the integral term ensures zero steady state error. The input to the PI controller is the error in the dc link voltage and the output is the value of the $P_{loss}$ which depends on the value of $K_p$, $K_i$ and the error in dc link voltage. Thus, it is important to tune $K_p$ and $K_i$ properly. Because of the inherent non-linearity and complexity of the system, it is difficult to tune the gains of the controller. The input to the PI controller is the error in the dc link voltage and the output is the value of the $P_{loss}$ which depends on the value of $K_p$, $K_i$ and the error in dc link voltage. Thus, it is important to tune $K_p$ and $K_i$ properly.
Fuzzy Controller for DStatcom

PID controllers are extensively used in industry for a wide range of control processes and provide satisfactory performance once tuned when the process parameters are well known and there is not much variation[12]-[13]. However, if operating conditions vary, further tuning may be necessary for good performance. Since many processes are complicated and nonlinear, for such type of processes fuzzy logic based control seems to be a good choice.

Fuzzy logic is a technique which incorporates heuristics in automatic control which is very useful to control highly nonlinear, complex system whose mathematical model may or may not be known. Where classical controllers like PI or PID controller are available, fuzzy logic is used to enhance the performance of the controller.

The schematic diagram of fuzzy inference system is shown in figure 3.

![Fuzzy Inference System](image1)

**Figure 3 Fuzzy Inference System**

To control the capacitor voltage signal using fuzzy logic based controller is used in this paper. The control scheme is shown in figure 4.

![Fuzzy control scheme](image2)

**Figure 4 Fuzzy control scheme**

There are two inputs of fuzzy logic based controller, namely $e_n$ and $ce_n$. Here,

$$e_n = V_{dc}^{ref} - V_{dc}$$ and

$$ce_n = e_n - e_{n-1}$$

The crisp values of error and change in error is converted in to fuzzy values using fuzzification block. The output of fuzzification block is given to the fuzzy inference mechanism where according to fuzzy rule base, a proper action is considered. The final fuzzified output is given to de-fuzzification block where the fuzzified value is converted to crisp value.

**Fuzzification**

It takes in the crisp input signals and assigns a membership value to the membership function under whose range the input signal falls. Typical input membership functions are triangular trapezoidal or exponential. Seven triangular membership functions have been chosen: NL (Negative Large), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive Large) for both $e_n$ and $ce_n$. The input membership functions are shown in figure 5.

![Input Membership functions](image3)

**Figure 5 Input Membership functions**

**Inference Mechanism**

In fuzzy inference system, a fuzzy rule base is developed. The rule base for this controller is shown in table I.

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Mamdani fuzzy inference system is used to develop the rule base. The rule base can be read as

\[
\text{IF } e \text{ is NL and } c e \text{ is NL THEN } u \text{ is PL}
\]

Because there are 7 linguistic variables in each input membership functions, there are 49 possible rules in the rule base. In real time system, executions of fuzzy rule base with higher number of rules are time taking, so fuzzy rule base reduction methods are used. This paper investigates the time taken by the fuzzy controller for implementation of control action.

**Defuzzification**

De-fuzzification process is the inverse of fuzzification process and is implemented after fuzzy inference mechanism. The fuzzy inference mechanism provides an output in fuzzy format which has to be converted in to crisp format. For this fuzzy to crisp conversion, de-fuzzification is used. There are different de-fuzzification methods such as centroid method, weighted average methods etc. are available in literature.

**Results**

This section provides the results and discussion part of the paper. The DSTATCOM model is simulated in MATLAB/Simulink environment. By using the Fuzzy Logic Controller instead of the PI Controller gives better transient response. The DC Link voltage is suddenly increased above the reference value. And it is brought back to its reference value. A good voltage control is also achieved by implementing Fuzzy logic control. Also the steady state is reached faster. The simulation is done with nonlinear load. Load current and load voltage without using DSTATCOM is shown in figure 7(a) and (b) respectively.

DC-link voltage is controlled using PI controller and fuzzy controller. The comparative graph is shown in figure 8 where Fig. 8(a) shows the DC-link voltage controlled using PI controller and fig. 8(b) shows the DC-link voltage controlled using fuzzy controller. After the fuzzy control implementation, Total Harmonic Distortion of load current and source current are evaluated.
This paper investigates the time taken for implementation of fuzzy controller with different number of rules.

<table>
<thead>
<tr>
<th>Description</th>
<th>Number of rules</th>
<th>Time of execution</th>
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<tbody>
<tr>
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<tr>
<td>Symmetrical rule base</td>
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<td>0.1 sec</td>
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<tr>
<td>Reduced asymmetrical rule</td>
<td>14</td>
<td>0.05 sec</td>
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<tr>
<td>Reduced symmetrical rule base</td>
<td>14</td>
<td>0.09 sec</td>
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The time computation table shows that with reduced rule base, the time of execution also decreases.

**Conclusion**

The paper discusses the performance of DSTATCOM for a three phase three wire system. The fuzzy logic supervisor varies the gain of the PI controller during the transient period in a way that improves performance. The system has been modeled and simulated in the MATLAB. The results are presented for nonlinear load and THD of Load voltage 0.29% and THD for load current is 0.55%. The simulation results show reduction in voltage deviation of the dc link voltage with faster settling time. Instantaneous symmetrical component theory has been used for compensation of load. Simulated results demonstrate good dc bus voltage regulation, reduced source harmonic currents, improved power factor and stable operation.

**REFERENCES**