Fuzzy Logic Based Simulation of DVR and D-STATCOM in Power Systems for Power Quality Improvement

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Abstract: A power quality problem is an occurrence manifested as a non- standard voltage, current or frequency that results is a failure or mis-operation of end user requirements. Significant financial cost losses due to utility distribution networks, industrial loads and critical commercial operations which suffer from various types of outages and service interruption. The present work is to identify the prominent concerns in this area and hence that measures the quality of the power of recommended using soft computing method especially fuzzy control systems. In this paper the application of fuzzy techniques used for correcting the voltage sag, swell and interruption in a distributed system. At present a newly available power electronics devices, are emerging for custom power applications. The distribution static compensator (DSATCOM) and the dynamic voltage restorer (DVR) are most effective devices; both of them based on the "Voltage Source converters" (VSC) principle. A "Dynamic Voltage Restorer" (DVR) injects a voltage in series with the system voltage and a "Distribution static compensator" (D-STATCOM) injects a current into the system to correct the power quality problems. Comprehensive results are presented to assess the performance of each device as a potential custom power solution. The PI controller used in this paper to process the error signal generated at the required angle to drive the error near to zero. In this paper a PI-like FKBC (fuzzy knowledge based controller) is employed in place of conventional PI- controller.

Keywords: D-STATCOM, DVR, Voltage Sag, Swell, FKBC

1. Introduction

One of the most common power quality problems today is voltage dips. In a three-phase system a voltage dip is by nature a three phase phenomenon, which affects both the phase to phase and phase to ground voltages. In power system are single phase or multiple-phase short circuits are typical fault currents leads to high currents results in a voltage drop over the network impedance. For an industry a voltage is worse due to voltage dip, but voltage dip occur more often and cause severe problems and economical losses [1]. Utilities often focus on disturbances from end-user equipment as the main power quality problems. Faults due to lightening, is one of the most common causes to voltage dips on over head lines.

There are different ways to mitigate voltage dips swell and interruptions in the transmission and distribution systems. At present some custom power devices such as Distribution static compensator (D-STATCOM) and Dynamic Voltage Restorer (DVR) are most effective devices, both of them based on the Voltage Source Converts (VSC) principles [2]. A new PWM- based control scheme has been implemented to control the electronic valves in the two- level VSC used in the D-STATCOM and DVR (S.V. Ravikumar & S. Siva Nagaraju 2007). The fuzzy PI- controller to process the error signal generates the required angle to drive the error to zero. A PI-like FKBC is designed to process the error signal to operate the PI- controller.

2. Dynamic Voltage Restorer, (DVR)

The series voltage controller is connected in series with the protected load in fig.1. The VSC diagram of a DVR, which is a circuit representing the Thevenin's equivalent circuit of DVR system. converter generates the reactive power needed while the active power is taken from energy storage [2]. Fig.2 shows the schematic diagram of a DVR, which is a circuit representing the Thevenin's equivalent circuit of DVR system.



Figure 1: Standard configuration of DVR

The system impedance Zeh depends on the fault level of the load bus. The series injected voltage of the DVR can will be .

$$V_DVR=V_L+Z_th I_L-V_th \dots(1)$$

Where VL=Desired load voltage magnitude, $Z_th=Load$ impedance (Thevenin[^] simpedance), $=R_th+jX_th$.

 $\label{eq:logical_logical_logical} I_L=Load \quad Current, \quad V_th=System \quad voltage \quad during \quad fault \\ condition \quad$

The load current is given by:

$$I_L=((P_L+ZQ_L))/V_L$$
(2)

When V_L is considered as a reference. E_q (1) can be rewritten as:

$$V_DVR \angle \propto = V_L \angle 0 + Z_th I_L \angle (\beta - \theta) - V_th \angle \delta....(3)$$

Here $\propto\!\!,\beta$ and δ are the angle of V_DVR , Z_th and V_th respectively and 0 is load power factor angle. Also $\theta{=}[\![\tan]\!]^{(-1)}[\![(Q]\!]_L/P_L)$. The complex power injection of the DVR can be written as: S_DVR=V_DVR I_L^*. It may be mentioned here that when the injected voltage V_DVR is kept in quadrature with I_L no active power injection by the

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DVR is required to correct the voltage. The DVR itself is capable of generating the reactive power.

2.1 D-STAT COM (Shunt voltage. controller)

D-STATCOM, which is schematically depicted in fig. 3



Figure 3: D-STATCOM used as custom power devices

It consists of a two level VSC, a dc energy storage device, a compiling transformer connected in shunt to the distribution network through a compiling transformer. The VSC converters the dc voltage across the storage device in to a set of three phase ac output voltages. Suitable adjustment of the phase and magnitude of the D-STAT COM output voltages allows effective control of active and reactive power exchanges between the D-STATCOM and the ac system, thus allowing the device to absorb or generate controllable active and reactive power [6].

In fig3 the shunt injected current Ish corrects the voltage sag by adjusting the voltage drop across the system impedance Zth . The value of Ish can be controlled by adjusting the output voltage of the converter. The shunt injected Ish can be written as (see fig 3)

$$I_sh=I_L-I_s=I_L-(V_th-V_L)/Z_th$$
 , $I_sh \angle \eta=I_L \angle -\theta-$ V_th/Z_th $\angle (\delta-\beta)+V_I/Z_th$ $\angle -\beta$

The complex power injection of D-STATCOM can be expressed as : $S_sh=V_L I_sh^*$ It may be mentioned that the effectiveness of the D-STATCOM in correcting voltage sag depends on the value of Z_th or fault level of the load bus. When the shunt injected current I_sh is kept in quadrature with V_L the desired voltage correction can be achieved without injecting any active power into the system. When the value of I_sh is minimized, the same voltage correction can be achieved with minimum apparent power injection into the system. The control scheme of D-STATCOM and DVR are same.

2.1.1 Test System for DVR and D-STATCOM

Single line diagram of the test system for DVR and D-STATCOM are shown in fig 4 & fig5 respectively. DVR test system is composed of 0.13 kv, 50 Hz generation system feeding two transmission lines through a three winding transformer connected in $\gamma/\Delta/\Lambda$,13/115/15 kv. such transmission lines feed two distribution networks through two transformers connected in $\gamma\gamma$,230/11/11 kv. A varying

load is connected to the 11 kv, secondary side of transformer. A two level D-STATCOM is connected in the 11kv. A tertiary winding to provide instantaneous voltage support at the load point. A capacitor on the dc side provides the D-STATCOM energy storage capabilities.



Figure 4: Single Line diagram of the test system for DVR



Figure 5: Single line diagram of the test system for D-STATCOM

2.2 PI-Controller

The controller input is an error signal obtained from the reference voltage and the value rms of the terminal voltage measured and processed error by a output is the angle δ , provided to the PWM signal generator. The PI-Controller process the error signal generated at the required angle to drive the error to zero. Fig6 shows indirect PI-Controller.



The simulated signal V control is phase – modulated by means of the angle $\boldsymbol{\delta}$

 $V_{A}=sin[0](wt+s),$ $V_{B}=sin[(wt+s-2\pi/3),$ $V_{C}=sin[(wt+s)+2\pi/3]$

The modulated signal V control is compared against a triangular signed V_{T} in order to generate the switching signals for the VSC valves [5-9].

2.3 PI-like FKBC

2.3.1 Knowledge Representation inFKBCs

A knowledge based controllers (KBC) can be identified as a highly specialized knowledge based systems (KBS) designed for performing a specific task during a particular phase of the lifecycle of a process control system Knowledge here means a model which provides a conceptual structure to capture those aspects of the process which accurately represent its behavior. In our study use of a KBS replaces completely the

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conventional control element of a process control system and is known as a "Direct Expert control system (DECS)". One particular instance of the class of DECS, is the so- called "Fuzzy knowledge Based Controller (FKBC)" which employs a knowledge representation technique and inference engine based on fuzzy logic. DECSs constitutes a class of KBCs based on having the KBS in the closed loop, thus replacing completely the conventional control element i.e. PI-controller. One particulars subclass of DECSs are the FKBCs.

The rule base of the FKBC is divided into two groups of rules:

- 1) First group which is always active i.e. incremental change in control output. These are the so- called active rules.
- 2) Second group which becomes active only when the process output is near or enters the constraint. These are the so- called constraint rules. The incremental change in control output determined from this group of rules is added/ substrate from the one already determined by the first group of rules.

Table 1: Rule

$\Delta \xrightarrow{e}$				
	e e.	SN	S	LP
	LN	SN	LP	LN
	SN	ZO	SN	SN
	ZO	-	ZO	-
	SP	SP	SP	ZO
	LP	LP	LP	SP

Here SN= Small Negative, S= Small, LP= Large Positive. SP= Small Positive, LN= Large Negative, ZO= Zero, e= Change- of error

In the table form of the rule base, the second row and first column, for example,

IF value of e(k) is NS and value of $\Delta e(k)$ is NB THEN value of $\Delta u(k)$ is Z0.

2. 4 Fuzzy Sets

The fuzzy sets for typical rules of PI-like FKBC are shown in fig. 7 in the domain (-6,6). These rules are: IF e is LN and $\triangle e$ is Z0 THEN $\triangle u$ is LP IF e is SN and $\triangle e$ is Z0 THEN $\triangle u$ is PS. IF $\triangle e$ is Z0 and e is LP THEN $\triangle u$ is SN



Figure 7: The fuzzy sets LN, SN, Z0,SP & LP on domain (- 6,6)

2.5 Fuzzyfication Procedure

There are two basic types of inferences i.e. compositions based inference and individual – rule based inference. In composition based inference, the fuzzification procedure is defined in the case of PI-like FKBC. Let the crisp input values of e and Δe be e^* and Δe^* . It is these two values that have to be fuzzified as defined in the form of membership function as given below:-

$$\mu_{e^{\{1 \text{ if } e=e^* \text{ and } e\in \mathcal{E} \\ 0 \text{ otherwise}}}$$

$$\mu_{\Delta e^{\{1 \text{ if } \Delta e=\Delta e^* \text{ and } \Delta e\in \\ 0 \text{ otherwise}}}$$

In the case of individual rule based inference the result defuzzication is obtained as follows:

Let as consider the K-th rule of the PI-like FKBC. IF e is SN and Δe is SP THEN Δu is Z0.

Where the membership functions of linguistic variables SN, SP and Z0 are $\mu_{SN(K)}, \mu_{SP(K)}$ and $\mu_{Z0(K)}$, for the crisp values of e^* and $\triangle e^*$ the fuzzification are $\mu_{SN(e^*)}$ and $\mu_{SP(\triangle e^*)}$.

2.6 Defuzzification Procedure

Out of many defuzzification procedures, centre of Area defuzzification method is chosen.

The centre of Area method is the best well known defuzzification method. In the discrete case $\{U = (u_1, \dots, u_2)\}$ this results in :

$$u^{*} = \frac{\sum_{i=1}^{\ell} u_{i} \mu_{u}(u_{i})}{\sum_{i=1}^{\ell} \mu_{u}(u_{i})} \\ = \frac{\sum_{i=1}^{\ell} u_{i} \cdots u_{k}^{k} \mu_{CLU(k)}(u_{i})}{\sum_{i=1}^{\ell} u_{i} \cdots u_{k}^{k} \mu_{CLU(k)}(u_{i})}$$

Where μ _CLU is membership function of clipped fuzzy set (CLU) fig. 8 shows the two clipped fuzzy sets for the purpose of defuzzification.



Figure 8: Two clipped fuzzy sets for center of area defuzzification.

So this method determines the centre of the area below the combined membership function fig. 8 shows this operation in a graphical way. This defuzzification method takes into account the area A U as a whole. Thus if the areas of two clipped fuzzy sets constituting U over lap (see fig.8), then the over lapping area is not reflected.

3. Simulation Results

3.1 Simulation Results of D-STATCOM Case 1: Simulation Results of voltage sag during single line to ground fault

The first simulation contains no. D-STATCOM and single line to ground fault is applied in Fig.5. via a fault resistance of 0.2 Ω during the period 500-900 ms the voltage sag at the load point is 45% with respect to the reference voltage. Similarly a new set of simulations was carried out but now with the D-STATCOM connected to the system as shown in fig. 10 where the very effective voltage regulation provided by the D-STATCOM can be clearly appreciated.



Figure 9: Voltage at load pt. without DSTATCOM



Figure 10:. Voltage rms at load pt. without DSTATCOM

Case 2: Simulation result of voltage interruption during three phase fault

The first simulation contains no D-STATCOM and three phase fault is applied via a fault resistance of 0.001 Ω during the period 500-900 ms. The voltage at the load point is 0% with respect to the reference voltage is shown in fig.11. Similarly. a new set of simulation was carried out but now with the D-STATCOM connected to the system. The load voltage shown in fig. 12.



Figure 11:. Voltage rms at load pt. without DSTATCOM



Figure 12: Voltage rms at load pt. DSTATCOM

Case 3: Simulation results of voltage swell

First simulation carried out with no D-STATCOM and three phase capacitive load applied during the period 450-850ms. The voltage swell at the load point is 10% with respect to the reference voltage as shown in fig. 13 and the test system for the simulation of D-STATCOM for swell is shown in fig14.



Figure 13: Voltage rms at load pt. without DSTATCOM



3.2 Simulation Results of DVR

Case 1: Simulation results of voltage sag during single line to ground fault

The first simulation contains no DVR and single line to ground fault is applied in fig 15 via a fault resistance of 0.3Ω during the period 450-850ms . The voltage sag at the load point is 25% with respect to the reference voltage. The second simulation is carried out using the same scenario as above but now with the DVR in operation. The total simulation period is 1350 ms. when the DVR is in operation the voltage sag is mitigate almost completely and the rms voltage at the density load point is maintained at 97% as shown in fig.16.



Figure 15: Voltage rms at load pt. without DVR,



Case 2: result of voltage interruption during three phase fault

The first simulation contains no DVR and capacitive load is applied at load1. during the period 500-900ms. The voltage swell at the load point is 25% with respect to the reference voltage. The second simulation is carried out using the same seenario as above but now with the DVR in operation. The total simulation period is 1400 ms. Fig. 17 shows the rms voltage at the load point for the case when the system operates with no DVR. When the DVR is in operation the voltage swell is mitigated almost completely and the rms voltage at the sensitive load point is maintained normal. The PWM control scheme the magnitude and the phase of the injected voltages restoring the rms voltage very effectively. The swell mitigation is performed with a smooth, stable and

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rapid DVR response; two transient undershoots are observed as in fig.18 when the DVR comes in and out of operation.



Figure 17: Voltage rms at load pt. without DVR.



Figure 18: Voltage rms at load pt. with DVR

The first simulation contains no DVR and three phase fault is applied at point A. via a fault resistance of 0.001Ω doing the period 450-850 ms. The voltage at the load point is 10% with respect to the reference voltage. The second simulation is carried out using the same scenario as above but now with the DVR in operation. The total simulation period is 1350 ms. When the DVR is in operation the voltage sag is mitigated almost completely, and the rms voltage at the sensitive load point is maintained at 97%

4. Conclusion

This paper has presented the power quality problems such as voltage dips, swells and interruption consequences and mitigation techniques by custom power electronic devices DVR and D-STATCOM. This design and applications of DVR and D-STATCOM for voltage sags, interruptions, swells and comprehensive results are presented. A new PWM based control scheme has been implemented to control the electronic valves in the two levels VSC used in the D-STATCOM and DVR. As opposed to fundamental frequency switching schemes already available in the MATI AB/SIMULINK this PWM control scheme only requires voltage measurement. This characteristic makes it ideally suitable for low voltage custom power applications. The simulations carried out showed that the DVR provides relatively better voltage regulation capabilities. It was observed that the capacity for power compensation and voltage regulation of DVR and D-STATCOM depends on the rating of the dc storage device.

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