POWER QUALITY COMPENSATION USING SMES COIL WITH FLC

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ABSTRACT
This paper presents a Power quality compensation using SMES (Superconducting Magnetic Energy Storage) Coil with FLC (Fuzzy Logic Control) to protect consumers from the voltage Sag. Using the proposed control strategy, the voltage of the inverter capacitors in SMES can be independently controlled; also, the minimum power and switching losses as well as the proper convection can be achieved using this same strategy. The distribution network, sensitive industrial loads and critical commercial operations suffer from outages and service interruptions which can cost financial losses to both utility and consumers.To investigate the effectiveness and reliability of the proposed approach in stabilizing capacitor voltage, SMES performance using the presented approach is compared with that of SMES when the capacitors of the three-level inverter are replaced with equal and ideal voltage sources. Due to the characteristic of high energy density and quick response, a superconducting magnet is selected as the energy storage unit to improve the compensation capability in Power system. The compensation capability of a SMES Coil depends primarily on the maximum voltage injection ability and the amount of stored energy available within the Coil. SMES Coil can provide the most commercial solution to mitigation voltage sag by injecting voltage as well as power into the system. By using the Fuzzy Logic controller the number of membership function can be minimized and the time response of controller become faster.This comparison is carried out from the power-quality point of view and it is shown that the proposed switching strategy with a Fuzzy Logic Controller is highly reliable. Using MATLAB Simulink, the models of the SMES with FLC is established, and the simulation tests are performed to evaluate the system performance.

INDEX TERM - *Power quality, DVR, SMES, Fuzzy Logic controller, Voltage Sag*.

I. INTRODUCTION

Power quality is one of the most important topic that electrical engineering have been noticed in recent years. Voltage sag is one of the problems related to power quality. This phenomenon happen continuously in transmission and distribution systems. Power quality problems, such as voltage sag which arise due to a fault or a pulsed load, can cause interruption on critical load. Even relay and conductors in motor starters can be sensitive to voltage sag resulting in shutdown of a process. Improper operation of the equipment has cased reduction in the business revenue and also losses to the environment. Voltage sag are very hazardous during the control of equipment in the process industry. Any failure of control result in the breakdown of process and, therefore, loss of raw materials and production time and event risk to human life.

DVR installed on a sensitive load, restores the line voltage to its nominal value within the response time of a few milliseconds thus avoiding any power disruption to the load. Modem Pulse-Width Modulated (PWM) inverters capable of generating accurate high quality voltage waveforms form the power electronic heart of the new Custom Power devices. Because the performance of the overall control system largely depends on the quality of the applied control strategy, a high performance - controller with fast transient response and good steady state characteristics is required [1].

The DVR supplies the active power with help of SMES and required reactive power is generated internally without any means SMES storage. DVR can compensate voltage at both transmission and distribution sides. Usually a DVR is installed on a critical load feeder. During the normal operating condition (without sag condition) DVR operates in a low loss standby mode [3]. During this condition the DVR is said to be in steady state. When a disturbance occurs (abnormal condition) and supply voltage deviates from nominal value, DVR supplies voltage for compensation of sag and is said to be in transient state. The DVR is connected in series between the load and the supply voltage [3].

Fuzzy polar first introduced by Takashi Hiyama in 1991. Fuzzy Polar is a decision that the optimal method of mapping the signal in polar areas. These parameters are controlled by Fuzzy Polar on polar fields.. Each position in the polar areas represents major control signals required. The main principle of the fuzzy polar shift which determines the magnitude of the input signal to be controlled to the equilibrium conditions (desired conditions). Signal to be controlled is represented in two polar parameters of magnitude and angle. In the basic application, the function of the fuzzy polar controller is used to replace the function of the PI (Hiyama et. Al., 1993). Control signal given by the fuzzy polar to be robust so that the input signal provides a more optimal results. [7]

DVRs in general on the three wire method using blocking transformer with the assumption that the fault is a three phase ground fault. When an interruption occurs, the components of one phase ground zero with a role big enough so that the resulting lack of a good recovery (Chung et. Al., 2001) using four-wire, zero sequence is controlled zero so that the resulting good restore voltage.

Recently new FL methods have been applied to Custom Power Devices, especially for active power filters .The operation of DVR is similar to that of active power filters in that both compensators must respond very fast on the request from abruptly changing reference signals. FL control of DVR in the literature is reported only in [8]. Three-phase supply voltages are transformed into d and q coordinates. The reference values for *Vd* and *V* are compared with these transformed values and then voltage errors are obtained. Two *q*FL controllers evaluating 81 linguistic rules process these errors. Resulting outputs are re-transformed into three-phase domain and compared with a carrier signal to generate PWM inverter signals. The DVR in [1] has no sag detection function, which means that the device is always in operation and generates compensating voltage also for small voltage drops within 10% that causes high losses. In Ref. [1], the results only for balanced sags are presented.

This paper presents a dynamic voltage restorer (DVR) using SMES coil capable of handling deep sags including outage on a low voltage distribution system using Fuzzy Logic controller. This paper aims to create a DVR-based fuzzy logic controller for improving voltage sag in power system. So we get better results and recovery voltage during voltage sags can be achieved without the shift in nominal voltage phase angle and harmonics can be well damped. The results of this simulation show that DVR based fuzzy logic controller can compensate balanced voltage sag better than PI controller.The proposed DVR has the capability of both balanced and unbalanced voltage sag/swell compensation and can track changes in supply phase. It can easily be implemented in real time application.

Section II explains the PQ SMES Coil based DVR with FLC Model, section III describes the Dynamic Voltage Restorer (DVR), section IV explains the Superconducting Magnetic Energy Storage (SMES) in DVR, section V explains the Inverter Control Strategies of DVR, section VI presents the simulation results and discussions and section VII gives the conclusion

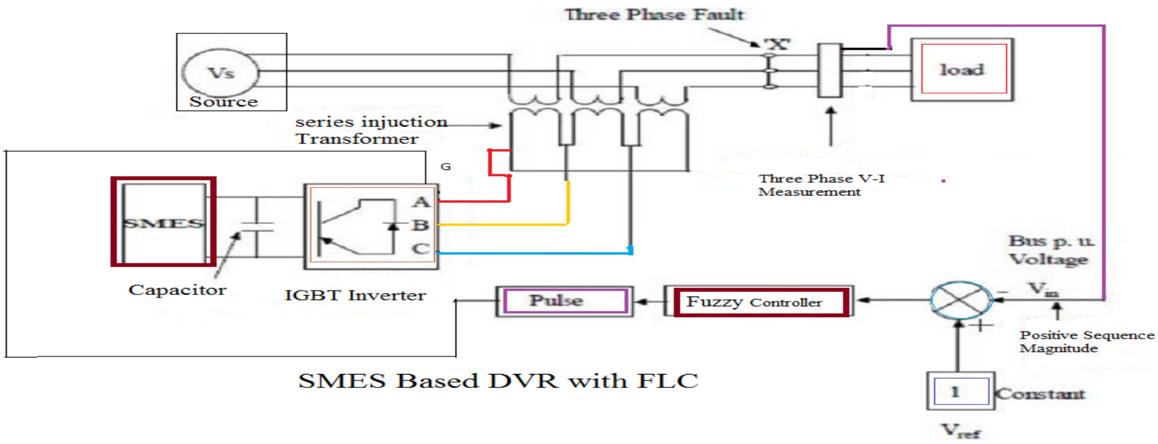

Figure 1.1. SMES Based DVR with FLC

II. PQ SMES COIL BASED DVR WITH FLC MODEL

Typically basic configuration DVR consists of Booster Transformer, Voltage Source Inverter, System Control, Energy Storage which consists of the source DC and Blocking Transformer. When an interruption occurs, the voltage at the sensitive load bus has decreased. Booster transformer inject voltage transformer will provide in accordance with the decrease in voltage at load bus voltage at load bus so sensitive to be constant. Booster Transformer get the injection voltage source from the Voltage Source Inverter (VSI) which is controlled by the Voltage Regulator. The amount of voltage injection given by Voltage Source Inverter (VSI) was formulated as follows:

$$Ul = Us + U\,inj \quad (1)$$

where,
Ul = voltage sensitive load
Us = voltage sags
U inj = voltage injection
Installation DVR on a simple distribution system model shown in Figure 2.1

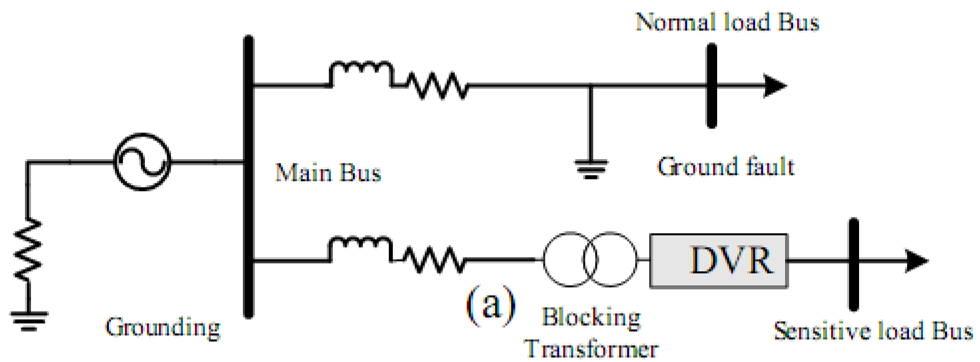

Figure 2.1 Distribution system model with the installation of a typically DVR.

When the voltage sags into a voltage asymmetry is restored to normal voltage symmetry. At normal voltage conditions, the power load on each phase can be written as follows.

$$S_l = U_l . I_l^* = P_l + jQ_l \quad (2)$$

where,
I l = load current
Pl= active power
Ql= reactive power
To obtain the recovery voltage is required injection power from the DVR so that the power flow of each phase is shown in equation (2.3).

$$S_l = (P + jQ)_l = (P + jQ)_s + (P + jQ)_{inj} \qquad (3)$$

where,
(P+ jQ)s represents sags quantity
(P+ jQ) inj represents DVR injection quantity

Blocking Transformer on conventional DVR is used to prevent voltage / zero sequence currents that occurred at the time of disturbance on the bus or other feeder that led to sensitive load. Blocking Transformer which installed on system with winding configuration Y-Δ caused zero sequence impedance infinite. However Blocking Transformer can't operate on 3 phase 4 wire system. So we need a controller that can control the zero sequence components when single phase to ground fault occurs.

In the distribution system with neutral point grounding, most faults are single phase to ground disturbance. Single phase to ground fault on the normal load feeder will result in voltage sags on the feeder sensitive load. Phasor diagram when there is a single phase to ground disturbance is shown in Figure 2.2. Condition of voltage at the sensitive load prior to fault can be described in equation (4, 5, 6).

$$V^a = V^{a(0)} + V^{a(1)} + V^{a(2)} \qquad (4)$$
$$V^b = V^{b(0)} + V^{b(1)} + V^{b(2)} \qquad (5)$$
$$V^c = V^{c(0)} + V^{c(1)} + V^{c(2)} \qquad (6)$$

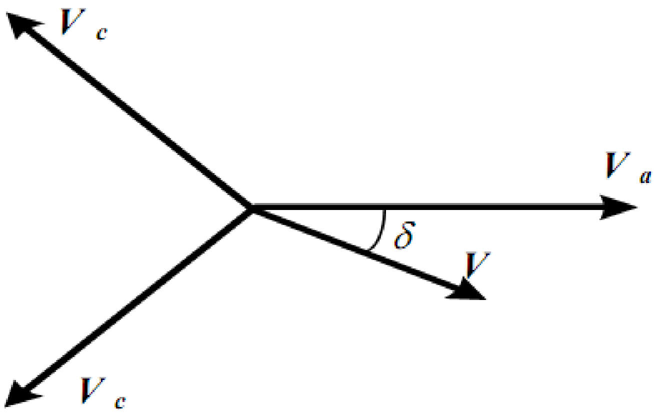

Figure 2.2. Phasor voltage of three phases during a phase to fault ground

During the disturbances, the voltage equation can be written into,

$$\begin{aligned} V_a &= V\cos\delta + jV\sin\delta \\ \overline{V_b} &= -\frac{1}{2} - \frac{1}{2} j\sqrt{3} \\ \overline{V_b} &= -\frac{1}{2} + \frac{1}{2} j\sqrt{3} \end{aligned} \qquad (7)$$

where,
V = magnitude sags voltage
ð= phase angle jump

Zero sequence components during fault can be explained in the following:

$$\overline{V_0} = \frac{1}{3}(\overline{V_a} + \overline{V_b} + \overline{V_c})$$

$$\overline{V_a} = V\cos\delta + jV\sin\delta$$

(8)

From equation (8) shows that zero sequence components was not equal to *0*. This shows that the zero sequence components must be compensation. Compensation method *d, q* and *0* for voltage regulator control DVR using Fuzzy logic controller, modeled in Figure 2.2.

III. DYNAMIC VOLTAGE RESTORER (DVR)

The conventional circuit configuration of the DVR is shown in Figure 3.1 Dynamic voltage restorer is a series connected device is used for mitigating voltage disturbances in the distribution system (Lee, *et al*., 2004). The DVRs can be used and are already in operation (W.E. Brumsickle, *et al*., 2001). DVR maintains the load voltage at a nominal magnitude and phase by compensating the voltage sag/swell, voltage unbalance and voltage harmonics presented at the point of common coupling (Mahesh, *et al*., 2008; Jowder, *et al*., 2009; Ramachandaramurthy, *et al*., 2004). These systems are able to compensate voltage sags by increasing the appropriate voltages in series with the supply voltage, and therefore avoid a loss of power. In 1994, L.Gyugyi (Patent No. 5329222) proposed an apparatus and a method for dynamic voltage restoration of utility distribution network. This method uses real power in order to inject the faulted supply voltages and is commonly known as the Dynamic Voltage Restorer (Gyugyi, *et al*., 1994). The DVR should capable to react as fast as possible to inject the missing voltage to the system due to sensitive loads are very sensitive to voltage variations (Chan, *et al*., 2006). The DVR is a series conditioner based on a pulse width modulated voltage source inverter, which is generating or absorbing real or reactive power independently. Voltage sags caused by unsymmetrical line-to line, line to ground, double-line-to-ground and symmetrical three phase faults is affected to sensitive loads, the DVR injects the independent voltages to restore and maintained sensitive to its nominal value. The compensation of harmonics and mitigates voltage transients has been discussed in (Li, *et al*., 2001).

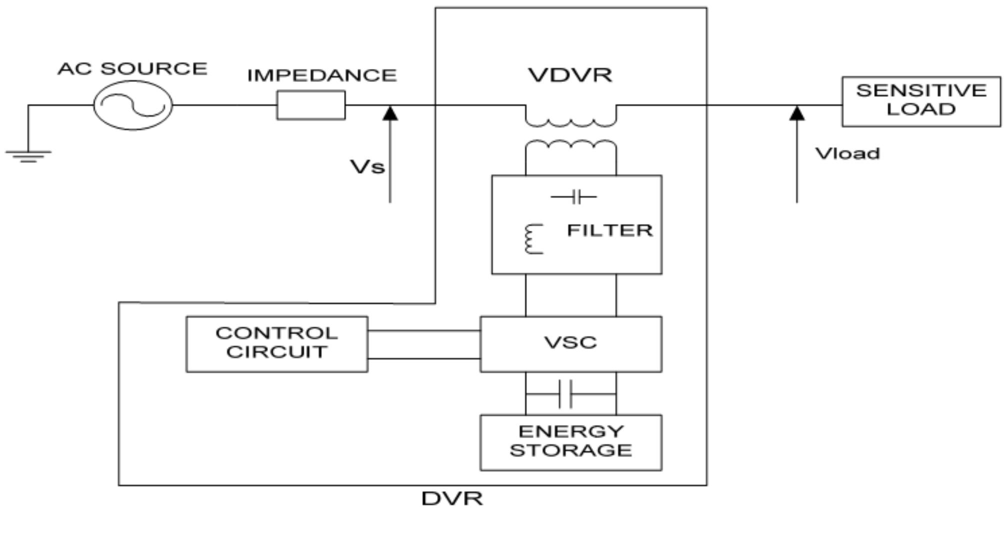

Figure 3.1. Dynamic Voltage Restorer (DVR)

The DVR device consists of five main sections; (i) Energy Storage Unit**:** It is responsible for energy storage in DC form. Flywheels, lead acid batteries, Superconducting Magnetic Energy Storage (SMES) and Super-Capacitors can be used as energy storage devices, the estimates of the typical energy efficiency of four energy storage technologies are: batteries – 75 %, Fly wheel – 80 %, Compressed air – 80%, SMES – 90% [5]. (ii) Inverter: It is used to convert DC power to AC power [6]. (iii) Passive Filters**:** It is clear that higher order harmonic components distort the compensated output voltage. Filter is used to convert the PWM inverted pulse waveform into a sinusoidal waveform. This is achieved by removing the unnecessary higher order harmonic components generated from the DC to AC conversion in the VSI. (iv) By-Pass Switch: This switch is used to protect the inverter from high currents. In case of a fault or a short circuit on downstream, the DVR changes into the bypass condition where the VSI inverter is protected against over current flowing through the power semiconductor switches [3]. (v) Voltage Injection Transformers: In a three-phase system, three Single-phase transformer units or one three phase transformer unit can be used for voltage injection purpose [3].

IV. SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) IN DVR

SMES is stores energy in the magnetic field developed due to the flow of direct current in a coil of superconducting material cooled below its critical temperature. Stored energy can be released by discharging the coil whenever required. To maintain the coil in its superconducting state, it is immersed in liquid helium pervasive in a vacuum-insulated cryostat [15]. Block diagram representation of SMES system is shown in Fig.4.1 [4]

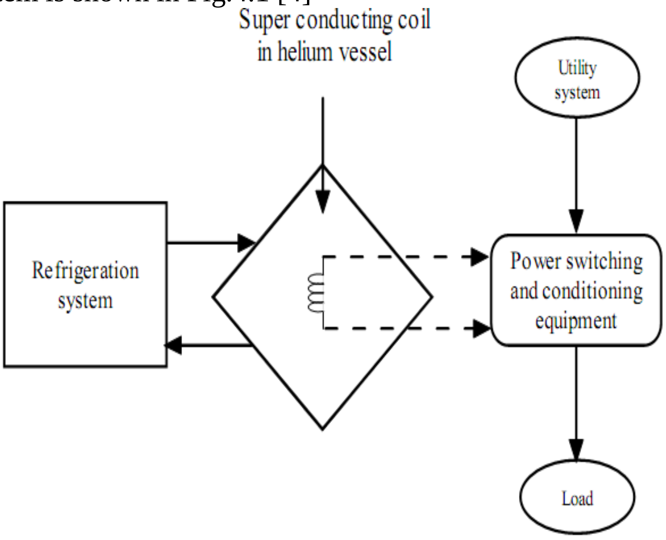

Figure 4.1. SMES Scheme

The energy stored in the coil is given by equation (9)

$$E = (0.5)\,LI^2 \qquad (9)$$

Where; E is Energy stored in (W.s)
L is Inductance of coil (H)
I is DC current flow through coils (A)

Superconducting magnetic energy storage (SMES) use superconducting coils as an energy storage component. And the flow of direct current in the superconducting coils creates magnetic field to store electric power. The most important advantages of SMES include: 1) high power and energy density with excellent conversion efficiency, and 2) fast and independent power response in four quadrants. When applied in power systems, SMES acts as a controllable active and reactive power source. Through regulating the power transmission between the superconducting coil and the ac power system, SMES can level the load variation, increase transmission capacity, enhance voltage stability and frequency stability, and improve the dynamic stability of power system. In SMES systems, it is the power conditioning system (PCS) that handles the power transfer between the superconducting coil and the ac system. According to topology configuration, there are two kinds of PCSs: current source PCS and voltage source PCS [4]. For inherent current source characteristic of a superconducting coil, the current source PCS have more advantages to be applied in SMES.

An SMES device is a DC current device that stores energy in the magnetic field. The Dc current flowing through a superconducting wire in a large magnet creates the magnetic field. Since energy is stored as circulating current, energy can be drawn from an SMES unit with almost instantaneous response with energy stored or delivered over periods ranging from a fraction of second to several hours.

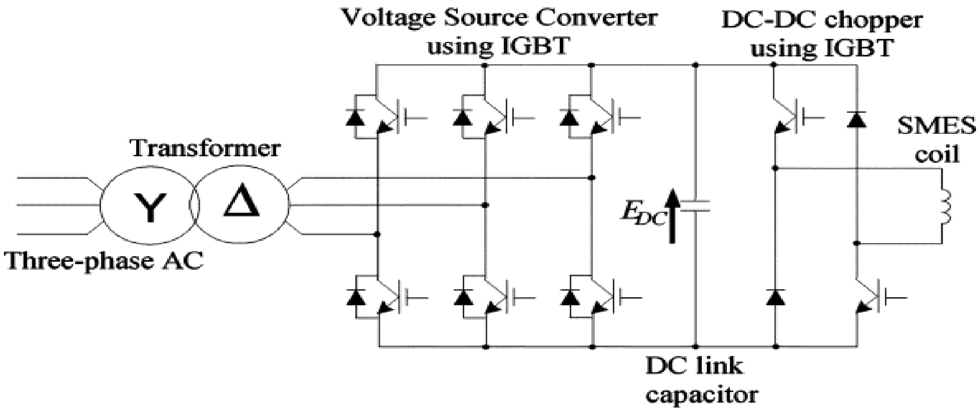

Fig. 4.2 shows the basic configuration of the VSC-based SMES

4.1 VSC-BASED SMES

The basic configuration of the VSC-based SMES unit, which consists of a Wye-Delta transformer, a six-pulse pulse width modulation (PWM) rectifier/inverter using insulated gate bipolar transistor (IGBT), a two-quadrant dc-dc chopper using IGBT, and a superconducting coil or inductor. The PWM converter and the dc-dc chopper are linked by a dc link capacitor. The PWM VSC provides a power electronic interface between the ac power system and the superconducting coil. The control system of the VSC The FLC controllers is determine the reference d- and q-axis currents by using the difference between the dc link voltage and reference value , and the difference between terminal voltage and reference value , respectively. The reference signal for VSC is determined by converting d- and q-axis voltages which are determined by the difference between reference d-q axes currents and their detected values. The PWM signal is generated for IGBT switching by comparing the reference signal which is converted to three-phase sinusoidal wave with the triangular carrier signal. The dc voltage across the capacitor is kept constant throughout by the six-pulse PWM converter .The superconducting coil is charged or discharged by a two-quadrant dc-dc chopper. The dc-dc chopper is controlled to supply positive (IGBT is turned ON) or negative (IGBT is turned OFF) voltage to SMES coil and then the stored energy can be charged or discharged. Therefore, the superconducting coil is charged or discharged by adjusting the average voltage across the coil which is determined by the duty cycle of the two-quadrant dc-dc chopper. When the duty cycle is larger than 0.5 or less than 0.5, the stored energy of the coil is either charging or discharging. In order to generate the PWM gate signals for the IGBT of the chopper, the reference signal is compared with the triangular signal.

V. INVERTER CONTROL STRATEGIES OF DVR

The DVR for power quality improvement in the distribution system. Most of the reported DVR systems are equipped with a control system that is configure to mitigate voltage sags/swells. Other DVR applications that include power flow control, reactive power compensation, as well as limited responses to power quality problems. The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected under system disturbances.

The fuzzy logic controller is known as PWM converter is actually non linear, but the PI controller is a linear controller. so it will maintained the stability of this converter in a local area. Various control strategy, have been proposed for three phase voltage source PWM converter. They can be divided into two main groups.

5.1. NON LINEAR CONTROL

Due to the usage of power semiconductor switches in the VSI, then the DVR is categorized as non-linear device. In case of when the system is unstable, the model developed does not explicitly control target so all the linear control methods cannot work properly due to their limitation.

(i): **Fuzzy Control*:*** Fuzzy logic control of DVR for voltage injection is reported in (Bayindir, *et al.*, 2007). Its design philosophy deviates from all the previous methods by accommodating expert knowledge in controller design. It is derived from fuzzy set theory introduced by (Zadeh, 1965). FL controllers are an attractive choice when precise mathematical formulations are not possible. In (Jurado, *et al.*, 2004) discussed about the implementation of FL in DVR. The advantages of this controller is capability to reduced the error and transient overshoot of PWM.

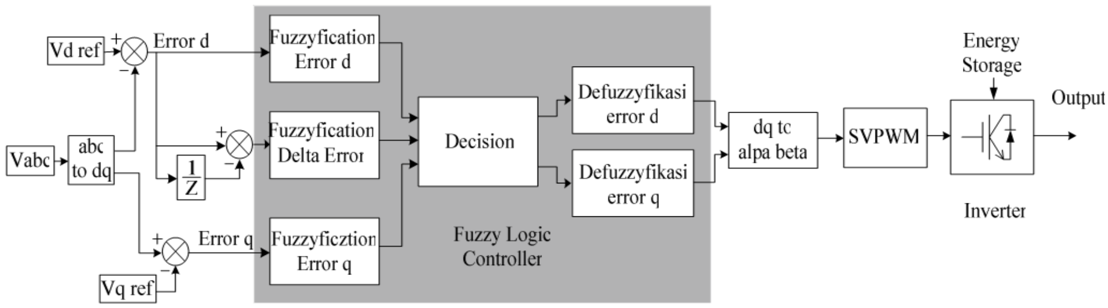

Figure 5.1. Fuzzy Logic Controller (FLC)

The control system employs *abc-to-dq* transformation to obtain Vd and V_q. During normal and symmetrical conditions, the voltage will be constant Vd=1.0 and Vq=0. However during faults, it varies. Comparing these with Vd and V_q references result in *error d* and *error q*. Fuzzy logic with 4.2 inputs of *error d*, *error q* and Δ error d is applied to maintain the injection voltage. The membership functions are shown in Figure 3 and 4 respectively. In Figure 3, the level is divided into negative (N), zero (Z), positive very small (PVS), positive medium small (PMS), positive small (PS), positive medium large (PML), positive large (PL), positive very large (PVL)

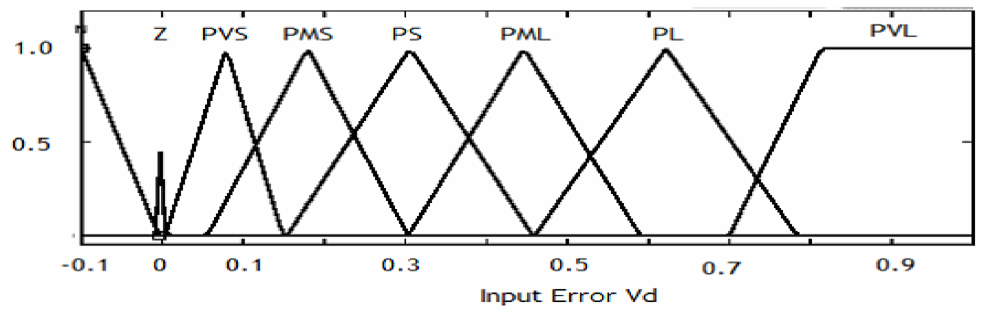

Figure 5.2 Membership function of *error d*

In Figure 4.3, the membership divides into negative very ver large (NVVL), negative very large (NVL), negative large (NL), negative medium large (NML), negative small (NS), negative medium small (NMS), negative very small (NVS), zero (Z) and positive small (PS).

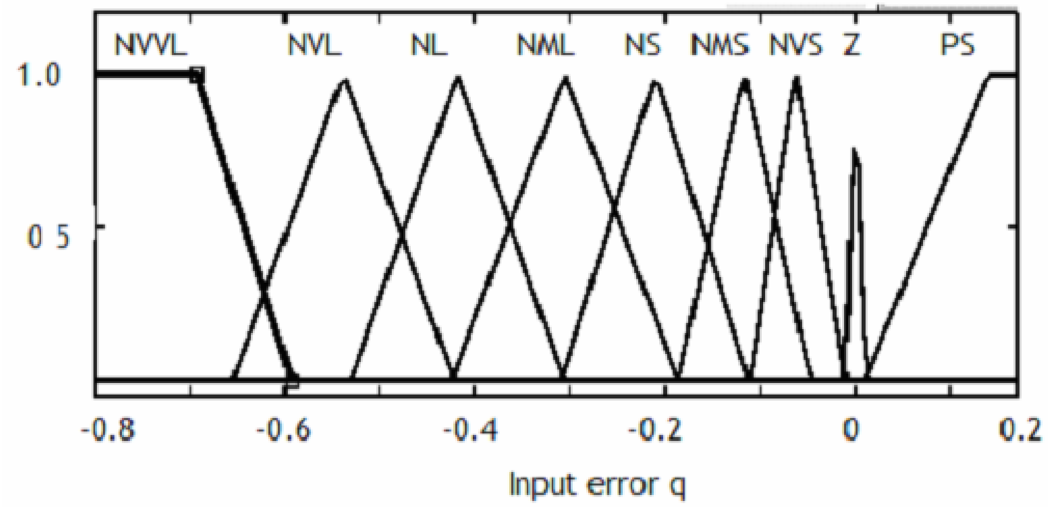

Figure 5.3. Membership function of *error q*

The defuzzyfication consists of 2 parameters: Vd and Vq as shown in Fig. 4.4 and 4.5. The output Vd comprises 4 main levels: negative (N), small (S), medium (M) and large (L) positive. The Small positive has 3 levels: S1, S2 and S3. The Medium positive divides into 5: M1 to M5. The Large positive consists of 3 parts: L1, L2 and L3.

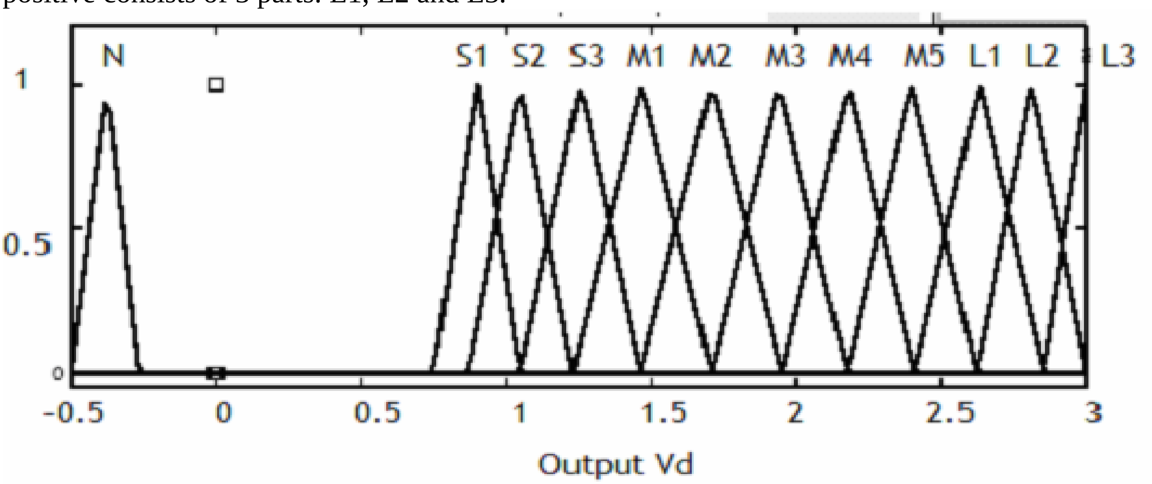

Figure 5.4. Membership function of output Vd

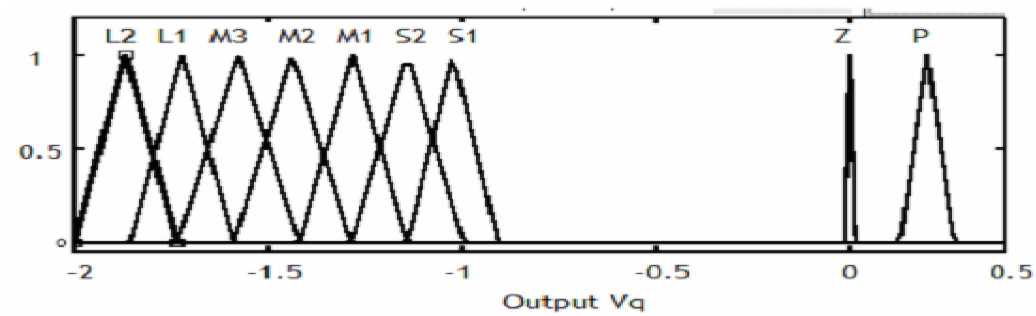

Figure 5.5. Membership function of output Vq

Similarly, membership function of output Vq has levels: small (S), medium (M), large (L) negative, zero (Z) and positive (P) as shown in Fig. 5.

VI. SIMULATION RESULTS AND DISCUSSIONS

A detailed simulation of the SMES Coil based DVR with FLC (Fuzzy Logic Controller) system was performing using MATLAB/SIMULINK program in order to verify the operation. The parameter of the system are as follows (Table- 6.1)

Table -6.1 System Parameters

S.No	Item	Parameters
1	Supply Voltage	380V,50Hz
2	Serious Transformer turns ratio	1:2
3	DC link voltage	400V
4	Filter inductance	6mH
5	Filter Capacitance	4 micro F.
6	Load resistance	200 ohm
7	Load inductance	2.5H
8	Converter rating power	8KvA
9	Switching frequency of converter	5kHz
10	SC rating Energy storage	12.5KJ

In order to understand the performance of the SMES coil based DVR with FLC, in voltage sags a simple distribution network is simulated using MATLAB.

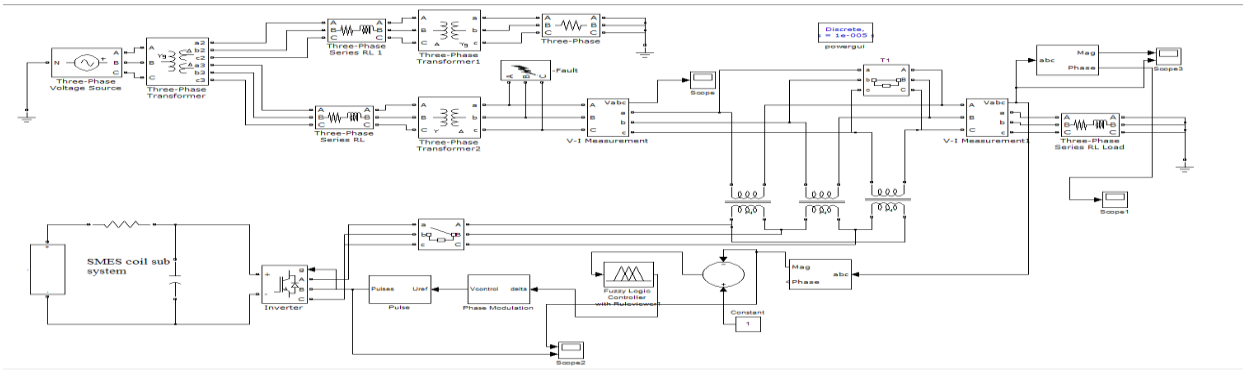

Figure 6.1. Simulation setup

6.1. DVR WITHOUT FLC

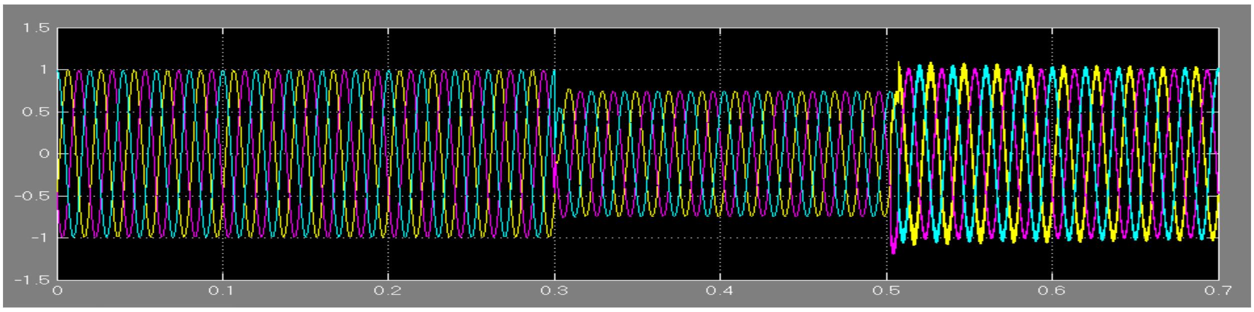

Figure 6.1.1. Voltage sag

Figure 6.1.2 Load voltage with fault

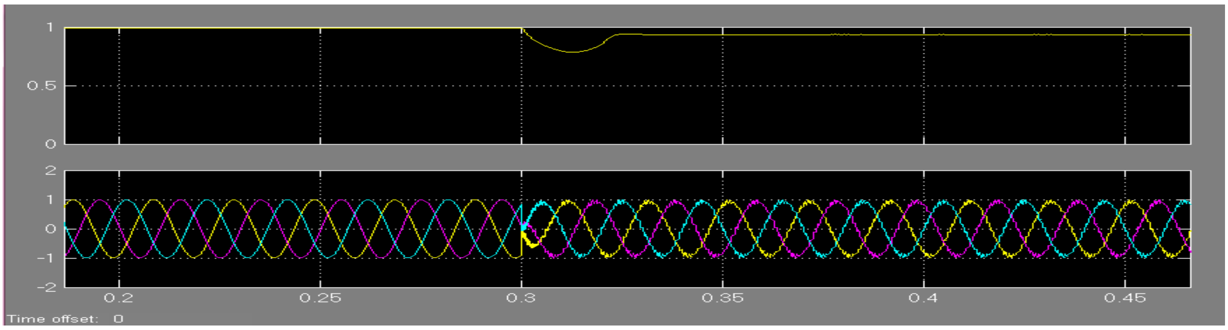

Figure 6.1.3. Sag Compensated Load voltage

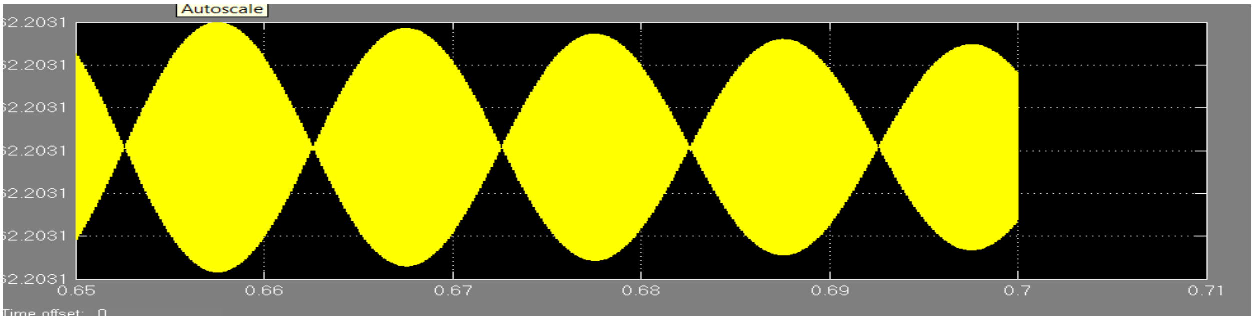

Figure 6.1.4. Phase angle

6.2. SMES Base DVR With FLC

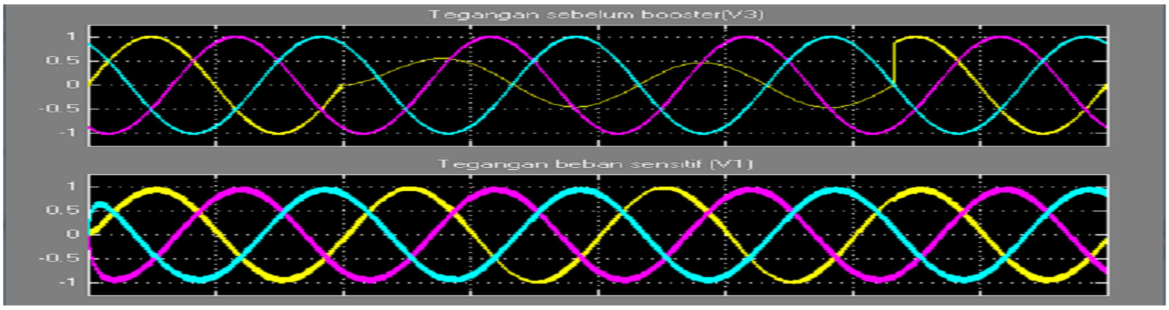

Figure 6.2.1. Voltage sags 50% restoration for 1 phase to ground short circuit disturbance using voltage regulator with Fuzzy control method

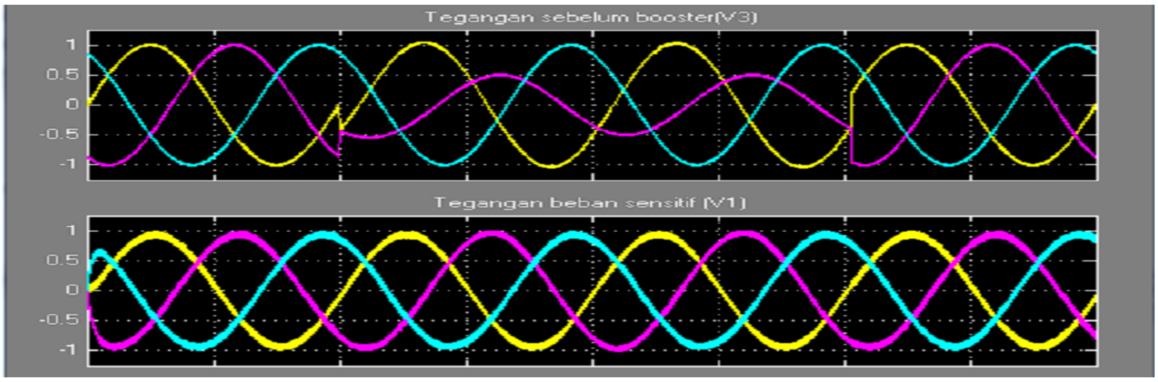

Figure 6.2.2 Voltage sags 50% restoration for 2 phase short circuit disturbance using voltage regulator with Fuzzy control method

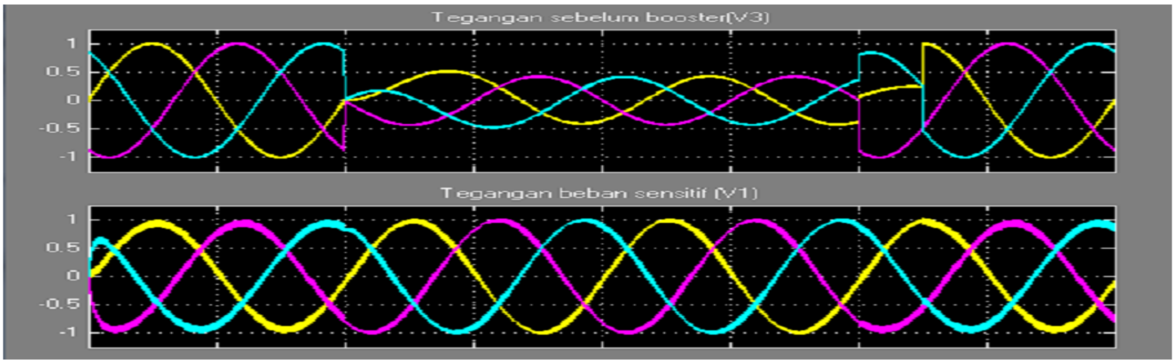

Figure 6.2.4. Voltage sags 50% restoration for 3 phase short circuit disturbance using voltage regulator with Fuzzy control method

For the system considered for study with DVR, in order to compensate the sag occurred during the three phase fault an FLC controller is designed. To generate the fuzzy inference system and for training of the FLCcontroller, initially the conventional Proportional Integral (PI) controller which can effectively mitigate the occurrence of sag in voltage than the DVR system is designed. The PI parameters are selected as Kp=0.5 and Ki=50.The effect of the FLC with DVR and conventional PI is tested on the test system by incorporating each controller individually. The magnitude of three-phase per unit load voltage with DVR& PI controller and with SMES based DVR & FLC respectively. The Comparison of pu RMS load voltage of a test system with DVR & FLC and with DVR & PI. From the figures it is evident that the DVR with FLC controller showed better performance than the PI controller during three-phase to ground fault for duration of 100ms. When the above figures of pu RMS load voltages are observed, it is clearly understood that the % mitigation of sag has improved in the system incorporated with DVR and FLC. It's clearly shows that the effect of transients is completely reduced and the settling time is improved to 0.25s.
Table.6.2 shows the comparative analysis in mitigation of sag in load voltage with respect to time in seconds by incorporating various controllers individually. From the table it is shown that the performance of the test system has improved with DVR and FLC in mitigating sag in the pu magnitude of load voltage and pu magnitude of RMS load voltage.

Table 6.2- Percentage of restored voltage and error voltage correction

Phase	DVR based PI Controller			SMES coil Based DVR with FLC		
	Before injected	After Injected	Error Correction	Before injected	After Injected	Error Correction
A,B,C	50%	110%	10%	50%	100%	0%
A,B,C	30%	98%	2%	30%	97%	3%

Table 6.3- Comparative Analysis in Mitigation of Sag in Load Voltage

S.No	Type of controller	Time to mitigation of sag
1	Without DVR	2ms
2	DVR	1.4ms
3	DVR with PI	0.9ms
4	SMES coil based DVR with Fuzzy	0.6ms

VII. CONCLUSIONS

Voltage sag due to short circuit fault have become one of the most important power quality problem facing industrial customer. As complexity of electrical equipment used in the industrial plant increased. The SMES coil with FLC is the minimum power and switching losses as well as the proper convection can be achieved using this same strategy. The equipment is becoming more sensitive to voltage sag. This work aims to help the improvement of DVR technology by adopting Fuzzy control approaches and new storage device (SMES coil) to the system. The SMES coil with FLC is mitigate the sag is very fast (0.6ms) while compare other device like without DVR , With DVR, DVR with PI Controller ect., The response and performance of the designed SMES based DVR with FLC were evaluated using MATLAB/Simulink .

By applying successfully new sag detection method to DVR, the protection devices can quickly be triggered to make the DVR on-line or off-line and the compensation process has simultaneously been initiated. This indicates that the designed system has superior performance to mitigate the balanced and unbalanced voltage sags. The sag start and end times were quickly detected with no oscillations.

VIII. FUTURE WORK

The SMES coil with FLC is the minimum power and switching losses as well as the proper convection can be achieved using this same strategy. The response and performance of the designed SMES based DVR with various intelligent can be evaluated using MATLAB/Simulink.

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