Fuzzy Bang-Bang Control Scheme of USSC for Voltage Sag Mitigation due to Short Circuits and Induction Motor Starting in Distribution System

M.Mohammadi, A.Mohammadi Rozbahani, S.Abasi Garavand, M.Montazeri, H.Memarinezhad
Department of Electrical Engineering, College of Engineering, Borujerd Branch, Islamic Azad University, Borujerd, Iran

Article Info	ABSTRACT
	Unified series shunt compensator (USSC) has been widely used to mitigate various power quality disturbances in distribution network. The USSC is almost similar to the UPFC, but the only differences are that the UPFC inverters are in shunt series connection and used in transmission systems whereas the USSC inverters are in series-shunt connection and used in distribution systems. USSC, it is possible to compensate a different power quality problem as compared to DSTATCOM and DVR. It is noted that, mitigated load voltage by the DVR is lower than mitigated value obtained by USSC. In other words the USSC can mitigate voltage sag better in compared to DVR and D-STATCOM. Also in case of voltage flicker, unbalance and harmonics elimination it is much effective. Similarly, D-STATCOM is unable to control power flow. It is seen that the proposed USSC can mitigate variety of power quality (PQ) problems. Hence due to multi capability of USSC in power quality improvement, this paper presents the scheme based on fuzzy bang-bang control for USSC. Using Fuzzy Logic Control (FLC) based on bang-bang control; the USSC will contribute to improve voltage sag without deteriorating the effect of the other compensating devices.

Corresponding Author:

Ashkan Mohammadi Rozbahani
Department of Electrical Engineering, College of Engineering, Borujerd Branch,
Islamic Azad University,
Borujerd, Iran,
Email: mr.ashkan@iaub.ac.ir

1. INTRODUCTION

Voltage sag can cause loss of production in automated process since voltage sag can trip a motor or cause its controller to malfunction. Various methods have been applied to reduce or mitigate voltage sags. The conventional methods are by using capacitor banks, introduction of new parallel feeders and by installing uninterruptible power supplies (UPS) [1]. Coil hold-in devices are one of traditional mitigation method. These devices are connected between the AC supply and the contactor and can generally allow a contactor to remain energized [2]. A ferroresonant transformer, also known as a constant voltage transformer (CVT), is a transformer that operates in the saturation region of the transformer B-H curve. Voltage sags down to 30 % retained voltage can be mitigated through the use of ferroresonant transformers [3]. Flywheel systems use the energy stored in the inertia of a rotating flywheel to mitigate voltage sags.

In the most basic system, a flywheel is coupled in series with a motor and a generator which in turn is connected in series with the load. The flywheel is accelerated to a very high speed and when voltage sag occurs, the rotational energy of the decelerating flywheel is utilized to supply the load [4]. To compensate the voltage sag in a power distribution system, appropriate devices need to be installed at suitable locations. These devices are typically placed at the point of common coupling [PCC] which is defined as the point of the network changes. A SVC is a shunt connected power electronics based device which works by injecting

reactive current into the load, thereby supporting the voltage and mitigating the voltage sag [5]. The DVR is one of the custom power devices which can improve power quality, especially, voltage sags [6]. The DVR injects three single-phase voltages in series with incoming supply voltages.

The magnitude and phase angle of injected voltage are variables which result in variable real and reactive power exchange between the DVR and the sensitive load or the distribution system Others have investigated new methods to improve power quality [7]. Usually the control voltage of the DVR in mitigating voltage sag is derived by comparing the supply voltage against a reference waveform [8]. There are many solutions in mitigating the power quality problems at a distribution system such as using surge arresters, active power filters, isolation transformer, uninterruptible power supply and static VAR compensator are some of new methods. In [9] authors proposed a new D-STATCOM control algorithm which enables separate control of positive and negative sequence currents and decoupled control of d- and q-axes current components. In [10] the mitigation of voltage flicker and reduction in THD by using STATCOM has been investigated.

Reference [11] use real time digital simulation of power electronic system which is a heavily computer intensive operation, and based on VSC D-STATCOM power system. From the studies, it is shown that all these equipments are capable in solving power quality problems.

The best equipment to solve this problem at distribution systems at minimum cost is by using Custom Power family of D-STATCOM. By using a unified approach of series-shunt compensators it is possible to compensate for a variety of power-quality problems in a distribution system including sag compensation, flicker reduction, unbalance voltage mitigation, and power-flow control [12]. Since this device is able to mitigate several of power quality disturbances, therefore this paper focuses on this device and presents a new control strategy based fuzzy logic bang-bang control to mitigate voltage sag.

2.   VOLTAGE SAG CONCEPTS

Voltage sag is reduction in supply voltage magnitude followed by voltage recovery after a short period of time. In the IEEE Standard 1159-1995, the term "sag" is defined as a decrease in rms voltage to values between 0.1 to 0.9 p.u, for durations of 0.5 cycles to 1 min [8-10]. The two main causes of voltage sags are network faults and the starting of equipment which draw large currents, particularly direct-on-line motors. Voltage sag is characterized in terms of the following parameters, magnitude of sag and duration of sag and phase-angle jump. Depending on the type of fault, sag can be balanced or unbalanced. Naturally for the Three phase to ground (ABC-G) fault the sag is symmetrical (balanced) in all three phases as shown in Figure 1.

Whereas for unbalanced faults like A-G, B-C, BC-G the sag is unsymmetrical in all three phases, as shown in Figure 2.
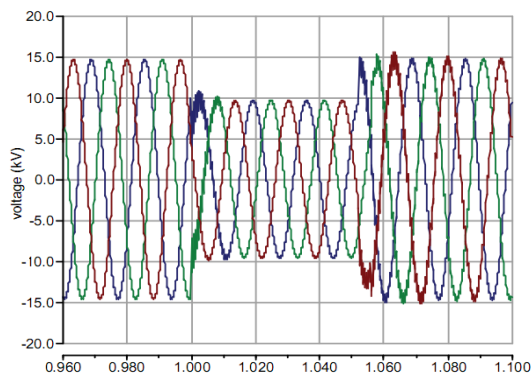

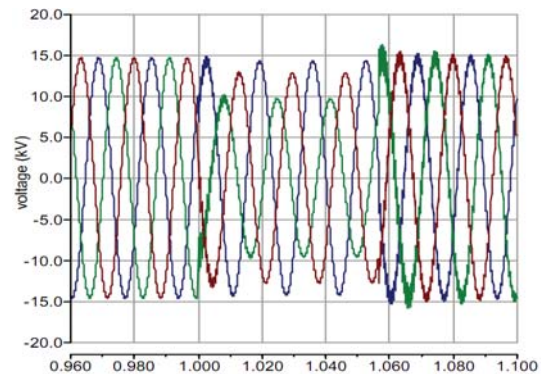Figure 1. Balanced voltage sag in three phases

Figure 2. Balanced voltage sag in three phases

Voltage sags are measured using specialized power quality monitoring instrumentation. The instrumentation must be configured with a sag threshold voltage. That is, a voltage level that will trigger a sag capture when the rms voltage falls below it. Figure 3 shows a graphical representation of a voltage sag including the sag threshold and the parameters (duration, retained voltage) used to report the sag.
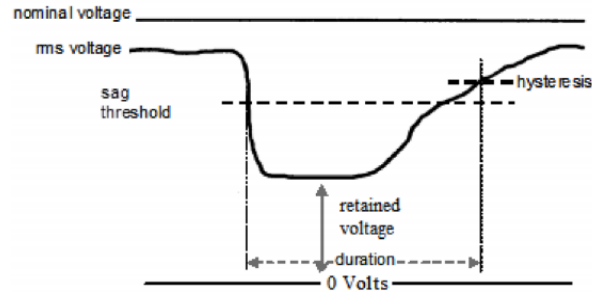
Figure 3. Graphical representation of voltage sag

3. USSC MODELING

The Unified Series Shunt Compensator is a combination of series and shunt voltage source inverters as shown in Figure 4. The basic components of the USSC are two 12-pulse voltage source inverters composed of forced commutated power semiconductor switches, typically Gate Turn Off thyristor valves. One voltage source inverter is connected in series with the line through a set of series injection transformers, while the other is connected in shunt with the line through a set of shunt transformers.

The dc terminals of the two inverters are connected together and their common dc voltage is supported by a capacitor bank [13]. The USSC is almost similar to the UPFC, but the only differences are that the UPFC inverters are in shunt series connection and used in transmission systems whereas the USSC inverters are in series-shunt connection and used in distribution systems [14].
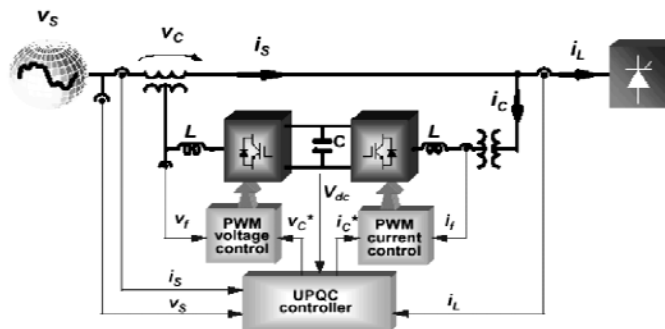

Figure 4. General Configuration of Unified Series Shunt Compensator-USSC

4. CAPABILITIES OF USSC VERSUS D-STATCOM AND DVR

Since the introduction of FACTS and custom power concept [15], devices such as unified power-flow controller (UPFC), synchronous static compensator (STATCOM), dynamic voltage restorer (DVR), solid-state transfer switch, and solid-state fault current limiter are developed for improving power quality and reliability of a system [16], [17]. Advanced control and improved semiconductor switching of these devices have achieved a new area for power-quality mitigation. Investigations have been carried out to study the effectiveness of these devices in power-quality mitigation such as sag compensation, harmonics elimination, unbalance compensation, reactive power compensation, power-flow control, power factor correction and flicker reduction [18-19]. These devices have been developed for mitigating specified power-quality problems. By using a unified approach of series-shunt compensators it is possible to compensate for a variety of power-quality problems in a distribution system including sag compensation, flicker reduction, unbalance voltage mitigation, and power-flow control [11]. Usually individual custom power devices such as DSTATCOM and DVR focus on solving specific power quality problems in a distribution system. However, by using USSC, it is possible to compensate a different power quality problem as compared to DSTATCOM and DVR as indicated in Table 1 [20].

Table 1. Power quality mitigation using USSC versus others custom power devices

Power Quality Mitigation	DVR	D-STATCOM	USSC
Voltage Flicker	YES	Limited	YES
Voltage Sag Compensation	NO	YES	YES
Unbalance	NO	YES	YES
UPS Mode	YES	YES	YES
Power Flow Control	NO	NO	YES
Harmonic Elimination	NO	YES	YES

It is noted that, mitigated load voltage by the DVR is a steady state value but this value is lower than mitigated value obtained by USSC. In other words the USSC can mitigate voltage sag better in compared to DVR and D-STATCOM. Also in case of voltage flicker, unbalance and harmonics elimination it is much effective. Similarly, D-STATCOM is unable to control power flow. It is seen that the proposed USSC can mitigate variety of PQ problems [21].

5.   USSC INSTALLATION IN DISTRIBUTION SYSTEM

Before modeling the USSC, all distribution system components, i.e., lines and cables, loads, transformers, large motors and generators have to be converted into equivalent reactance (X) and resistance (R) on common bases. The main system component models are used in the formulation of impedance matrix for voltage sag calculation [22]. In steady state analysis, the series and shunt inverters of the USSC are presented by two voltage sources V_{dq} and V_{sh} respectively as shown in Figure 5.
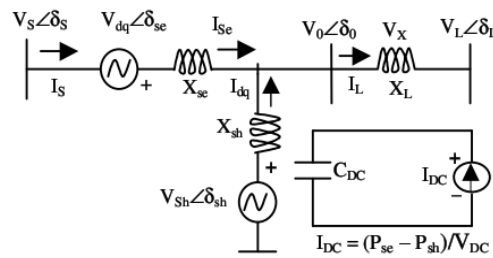

Figure 5. Equivalent circuit of USSC

X_{sc} and X_{sh} represents the reactance of the transformers associated with the series and shunt voltage source inverters, respectively. Therefore, voltage equation of series and shunt inverters can be expressed as follows:

$$V_s = -V_{dq} + I_{se}(jX_{se}) + V_0 \tag{1}$$

$$V_s + V_{dq} - I_{se}(jX_{se}) = V_{sh} + I_{dq}(X_{sh}) \tag{2}$$

$$I_s = I_{se} = I_{dq} + I_L = \frac{V_{sh} - V_0}{X_{sh}} + I_L \tag{3}$$

Where I_{sc} and I_{dq} are the series and shunt inverter currents, respectively.
The voltage across the distribution line reactance, X_L is:

$$V_X = V_s + V_{dq} - I_{se}(jX_{se}) - V_L =$$
$$V_0 - V_L = X_L . I_L \tag{4}$$

Where, I_L is distribution line current.
The voltage, V_X, across the distribution line can be changed by changing the inserted voltage, V_{dq},

which is in series with the distribution line. If we consider $V_{dq}=0$, the distribution line sending end voltage, V_S, leads the load voltage by an angle δ i.e $\delta_S - \delta_L$.

The resulting real and reactive power flows at the load side are P and Q, which are given as follows:

$$P_{ussc} = \frac{V_0.V_L}{X_L}\sin\delta \tag{5}$$

$$Q = \frac{V_0.V_L}{X_L}(1-\cos\delta) \tag{6}$$

With an injection of V_{dq}, the distribution line voltage V_0 will lead the load voltage V_L, and $\delta_0 > \delta_L$. , thus the resulting line current and amount of flow Will be changed. With a larger amount of V_{dq} injection, V_0 now lags the load voltage V_L, and $\delta_0 < \delta_L$.

Consequently, the line current and power flow will be reversed.

6. CONTROL STRATEGY OF VOLTAGE SAG MITIGATION

Series converter provides the main function the USSC by injecting a voltage Vdq with controllable magnitude Vdq and phase angle δ_{se} in series with the line via an insertion transformer. This injected voltage acts essentially as a synchronous ac voltage source. The feeder current flows through this voltage source resulting in reactive and real power exchange between it and its ac system. The reactive power exchanged at the ac terminal (ie. at the terminal of series injection transformer) is generated internally by the converter. The real power exchanged at the ac terminal is converted into dc power, which appears at the dc link as a positive or negative real power demand.

According to the theoretical concepts, the rotation of series voltage phasor Vdq with angle δ_{se} cause variation of both the transmitted real power 'P' and the reactive power 'Q' with δ_{se} in a sinusoidal manner. For validating the proposed circuit model of USSC, the magnitude of series injected voltage is kept constant at 2KV and its angle is varied from 0o to 360o. The variation in real and reactive power is investigated and it is observed that the variation of real and reactive power is sinusoidal with variation in angle, thus coinciding with theoretical concepts. It can be seen that the transmitted real power is maximum at angle 90o, minimum at angle 270o and medium at angle 0o. Hence, these values are selected in the switching function. The target of damping control is to conduct proper switching of C0, C1 or C2 at strategic times as to quickly mitigate voltage sag.

The output of series converter can be bang-bang controlled to three different values:

$$\text{Vdq} = \begin{cases} |V|\angle 0 & When \quad switch \quad C0 \quad is \quad closed. \\ |V|\angle 90 & When \quad switch \quad C1 \quad is \quad closed. \\ |V|\angle 270 & When \quad switch \quad C2 \quad is \quad closed. \end{cases} \tag{7}$$

Where Vdq is the voltage injected by the USSC; is the maximum magnitude of voltage that can be injected by the USSC.

Fuzzy logic controller is an intelligent technique which has been implanted in the control of facts devices on power system. Mridul Jha. and S.P. Dubey in [23] investigated the Neuro-Fuzzy based controller for a three phase four wire shunt active power filter . Also some authors have utilized the fuzzy approach in the control of renewable energies. By [24] the implementation of fuzzy logic controller in photovoltaic power generation using boost converter and boost inverter has been analyzed. The ultimate objective of this work is to implement fuzzy logic controller at the line in which USSC is connected. The inputs to fuzzy logic controller are V and δ measured at USSC terminals. For the output, the fuzzy logic controller will choose one of the three switch states from C0, C1 and C2 through competition. A simple fuzzy logic scheme comprises three functioning blocks, namely fuzzification, implication and inference, and selection of control. Input data are processed through these three blocks sequentially.

Fuzzification: Crisp input data need to be converted into membership grades to which they belong to each of the associated linguistic levels. These levels are represented by fuzzy sets. Fuzzification serves as data preprocessor for implications of linguistic rules in a later stage. There are 10 distinct linguistic levels, namely A1-10, for input V and 5 distinct linguistic levels, namely B1-5, for δ. Membership functions for the corresponding fuzzy sets are distinct and triangular. A heuristic trial-and-error procedure is needed to find the appropriate fuzzy partitioning by comparing the present and desired response for fuzzy logic control.

Implication and inferencing: Various fuzzified inputs are fed into a fuzzy rule base for implication and inferencing. Linguistic control rules are constructed based on observations of dynamic behaviors and switching curves.

With the use of two state inputs (V and δ), we obtain a two-dimensional rule base with 10x5 linguistic levels as in Table 2.

Table 2. Two-dimensional fuzzy control rules

δ	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
B_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1	C_1
B_2	C_1	C_1	C_1	C_1	C_2	C_1	C_1	C_1	C_1	C_1
B_3	C_1	C_1	C_1	C_2	C_2	C_2	C_1	C_1	C_1	C_1
B_4	C_1	C_1	C_2	C_2	C_2	C_2	C_0	C_0	C_1	C_1
B_5	C_2	C_2	C_2	C_2	C_2	C_2	C_0	C_0	C_1	C_1

The rule base is a collection of fuzzy conditional statements in the form of 'if-then' rules. Each rule carries a weight α_i (called firing strength), which is a measure of the contribution of ith rule to the overall fuzzy control action. The firing strength α_i is defined as:

$$\alpha_i = \mu_A(x_0) \Lambda \mu_V(y_0)$$

(8)

Where $A \in V, B \in \delta$ A; μ denotes grade of membership defined for input state (V and δ), xo and yo are the input variables used at a particular time instant; and Λ is the fuzzy 'AND' operator.

The membership value of each possible switching state C0, C1 and C2 for the FLC is obtained as:

$$\mu_i(C_0) = \frac{\sum \alpha_i}{4} \quad i = 40,41,50,51$$

(9)

$$\mu_i(C_1) = \frac{\sum \alpha_i}{32} \quad i = 1,2,3,...$$

(10)

$$\mu_i(C_2) = \frac{\sum \alpha_i}{14} \quad i = 15,24,25,26,...$$

(11)

The main purpose of selection of control is to choose a non-fuzzy discrete control that best responds to current system oscillations. The final discrete FLC output indicates the final switching state chosen from C0, C1 and C2. The choice is competitive and only one switching state with highest membership μi among C0, C1 and C2 is chosen.

7. SIMULATION AND RESULT

The single line diagram of the network to study the voltage sag mitigation is shown in Figure 6.
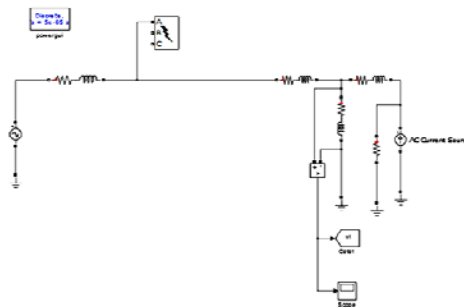

Figure 6. Single line diagram of the network to study the voltage sag mitigation

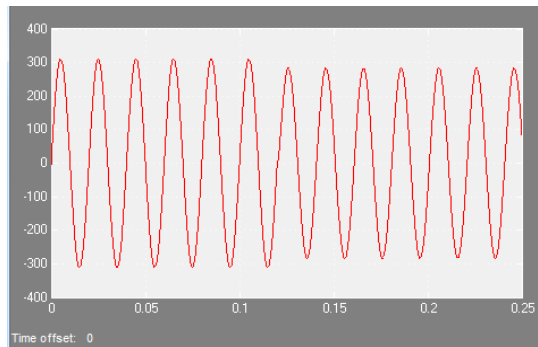Voltage sag at PCC without USSC due to short circuit fault is shown in Figure 7.

Figure 7. Voltage sag at PCC due to short circuit fault

The simulated system with MATLAB/SIMULINK software to study the fuzzy bang-bang controller on voltage sag mitigation using USSC is shown in Figure 8.
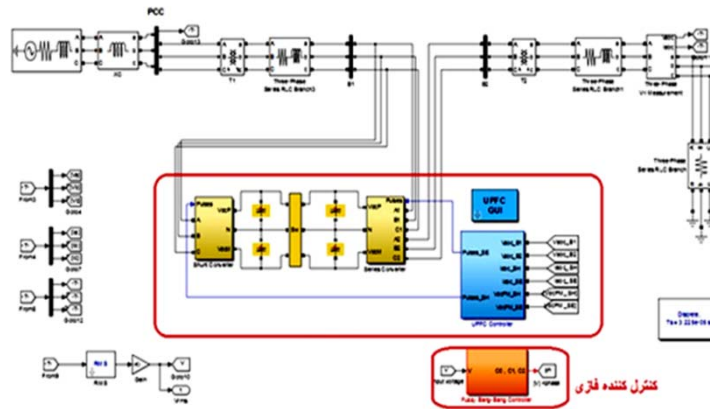

Figure 8. Simulated system in MATLAB/SIMULINK

The control structure of USSC used to illustrate the proposed fuzzy bang-bang controller is shown in Figure 9.
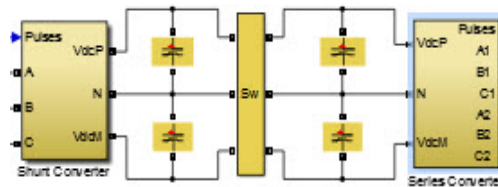

Figure 9. Series and shunt converters of USSC in MATLAB/SIMULINK

The control structure of USSC used to illustrate the proposed fuzzy bang-bang controller is shown in Figure 10. Te shunt converter can be controlled for maintaining constant voltage in dc bus and so it is controlled only to maintain dc bus voltage at *th* desired level.
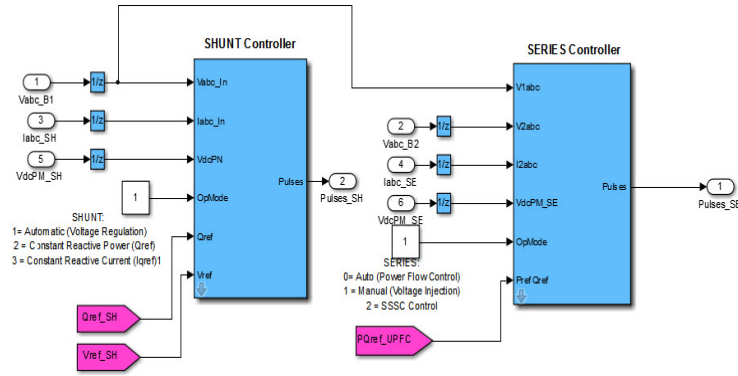
Figure 10. Fuzzy bang-bang controller designed for USSC

Changing state of switches C0, C1 or C2 as shown in Figure 11 can regulate the voltage injected by the series controller.

Figure 11. Changing state of switches C0, C1 or C2

The block diagram of the system control for reference voltage generation is shown in Figure 12.
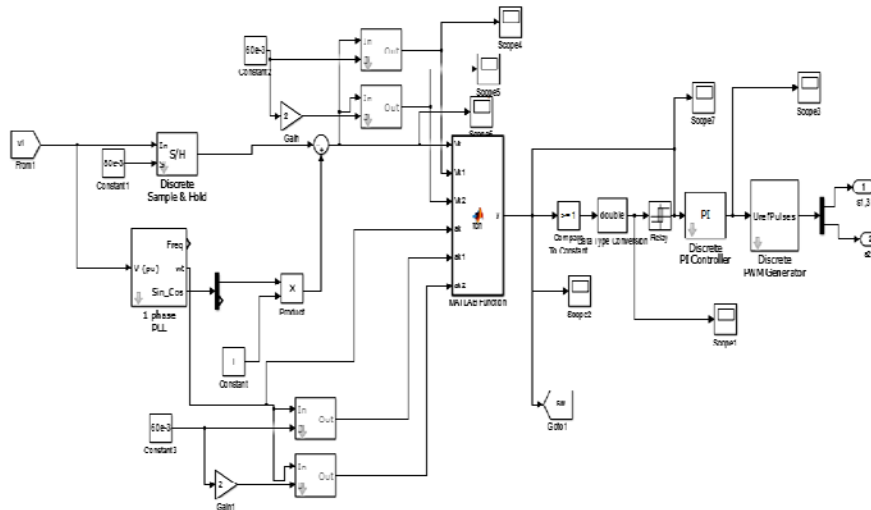

Figure 12. System control for reference voltage generation

The inhected voltage by USSC through series converter and its refrence is presented in Figure 13 and Figure 14. Figure 15 ahows the voltage sag compensated by USSC using fuzzy bang-bang based controller.
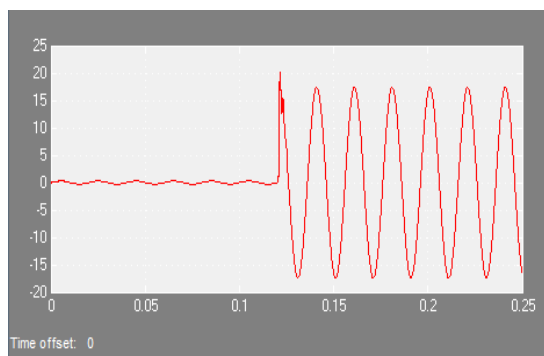
Figure 13. Injected volatge by series converter of USSC to mitigate volatge sag
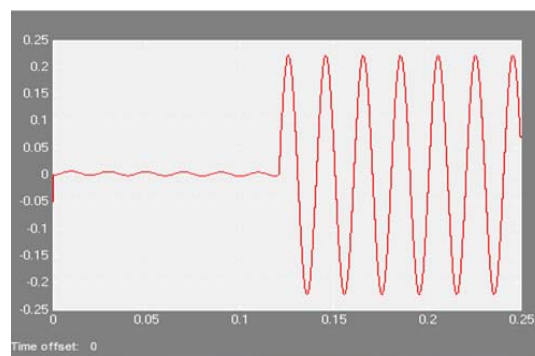

Figure 14. Reference of injected volatge by series converter of USSC to mitigate volatge sag
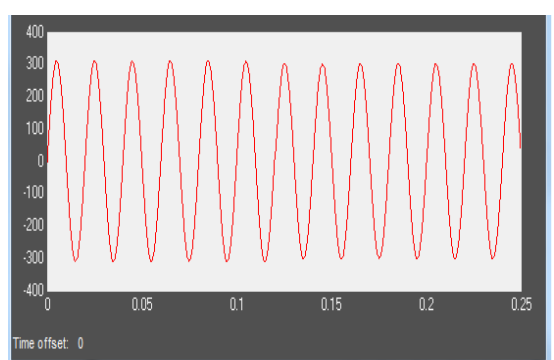

Figure 15. Voltage sag compensated by USSC using fuzzy bang-bang based controller

8.   CONCLUSION

In this paper, USSC controller is derived by using Fuzzy Logic Control (FLC) based on bang-bang control to compensate the voltage sag occurred due to short circuit fault in distribution system. Of course another main reason of voltage sag is motor stating which has not been analyzed in this paper. The model is simulated in MATLAB/SIMULINK platform and USSC controller's performance is evaluated. Numerical simulation proved the effectiveness of the controller in compensating voltage sag. Simulations have been carried out to evaluate the performance of the USSC. Simulation results revealed that the USSC can mitigate effectively voltage sag. The results revealed that the USSC gives a better performance in power quality mitigation especially in voltage sag compensation and power flow control and also provide more power quality solutions as compared to the D-STATCOM and DVR.

REFERENCES

[1]   PT Nguyen, TK Saha. DVR against balanced and unbalanced Voltage sags: Modeling and simulation. *IEEE-School of Information Technology and Electrical Engineering, University of Queesland*, Australia, 2004.
[2]   SR Mendis, MT Bishop, JF Witte. Investigations of voltage flicker in electric arc furnace power systems. *IEEE Industry Applications Magazine*. 1996; 2(1): 28 – 34.
[3]   RW Boom. Superconductive Magnetic Energy Storage for Electric Utilities--A review of the 20 year Wisconsin Program. *Proceedings of the International Power Sources Symposium*. 1991; 1: 1-4.
[4]   AliZa'fari. Mitigation of Flicker using STATCOM with Three-Level 12-pulse Voltage Source Inverter, *World Academy of Science Engineering and Technology*. 2011; 73: 263-268.
[5]   VJ Gosbell, D Robinson, S Perera, The Analysis of Utility Voltage Sag Data, *International Power Quality Conference*, Singapore. 2002.
[6]   Yop Chung, Dong-Jun Won, Sang-Young Park, Seung-Il Moon andJong-Keun Park. The DC link energy control method in dynamic voltage restorer system. *International journal on Electric power and energy system*. 2003; 25(7): 525-531.
[7]   T Larsson, C Poumarede. STATCOM, an efficient means for flicker mitigation. *IEEE Power Engineering Society Winter Meeting*. 1999; 2: 1208-1213.

[8]   Dinavahi V, Iravani R, Bonert R. Design of a real-time digital Simulator for a D-STATCOM system; *Industrial Electronics, IEEE Transactions* on. 2004; 51(5): 1001-1008.

[9]   NH Woodley, L Morgan, A Sundaram. Experience with an inverter-based dynamic voltage restorer. *IEEE Transactions on Power Delivery.* 1999; 14(3): 1181-1186.

[10] S Chandrasekhar, et al., Mitigation of Voltage flicker and reduction in THD by using STATCOM, *International Journal of Electrical and Computer Engineering (IJECE).* 2013; 3(1): 102-108.

[11] JG Nielsen, F Blaabjerg, N Mohan. Control Strategies for Dynamic Voltage Restorer compensating Voltage Sags with Phase Jump. *Proceedings of 16th Annual IEEE Applied Power Electronics Conference and Exposition 2001*, APEC 2001; 2: 1267-1273.

[12] MA Hannan, A Mohamed. Unified Series-Shunt Compensator Modeling and Simulation, *IEEE, National Power & Energy Conference (PECon) 2004 Proceedings*, KuaIa Lumpur, Malaysia.

[13] S Asha Kiranmai, M Manjula, AVRS Sarma. Mitigation of Various Power Quality Problems Using Unified Series Shunt Compensator in PSCAD/EMTDC, *16th National power systems conference.* 2010.

[14] M A Hannan, A Mohamed, A Hussain. Dynamic Phasor Modeling and EMT Simulation of USSC, *Proceedings of the World Congress on Engineering and Computer Science*, WCECS. San Francisco, USA. 2009; 1.

[15] Arnez RL, LC Zanetta. Unified power flow controller (UPFC): Its versatility in handling power flow and interaction with the network. I*IEEE/PES Asia Pacific Transmission and Distribution Conference and Exhibition.* 2002; 1338-1343.

[16] Hingorani NG, L Gyugyi. Understanding FACTS Concept and Technology of Flexible AC Transmission System. *IEEE Press*, New York. 2000.

[17] Su C, G. Joos. Series and shunt active power conditioners for compensating distribution system faults. *Procedding of the Canadian Conference on Electrical and Computer Engineering.* 2000; 1182-1186.

[18] Jin Nan, Tang Hou Jun, Yao Chen, Wu Pan. Topology and Control of Chopper Type Dynamic Voltage Regulator, *International Review of Electrical Engineering (IREE),* February, 2011; 6(2part A): 160-168.

[19] Hendri Masdi, Norman Mariun, S. Bashi, Azah Mohamed. Voltage Sag Compensation in Distribution System due to SLG Fault Using D-STATCOM, *International Review of Electrical Engineering (IREE).* 2010; 5(6,part B): 2836-2845.

[20] MA Hannan, A Mohamed, A Hussain, Majid al Dabbay. Development of the Unified Series-Shunt Compensator for Power Quality Mitigation, *American Journal of Applied Sciences.* 2009; 6(5): 978-986.

[21] Mridul Jha, SP Dubey. NeuroFuzzy based Controller for a Three Phase Four Wire Shunt Active Power Filter, *International Journal of Power Electronics and Drive Systems (IJPEDS).* 2011; 1(2): 148-155.

[22] Abubakkar Siddik A, Shangeetha M. Implementation of Fuzzy Logic controller in Photovoltaic Power generation using Boost Converter and Boost Inverter. *International Journal of Power Electronics and Drive Systems (IJPEDS).* 2012; 2(3): 249-256.