

## Fuzzy Bang-Bang Control with ANN Based Voltage Flicker Mitigation Using DVR

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**Abstract:** The quality of electric power is of supreme importance to electrical utilities and their customers. Modern equipments are more sensitive to power system anomalies than in the past. Microprocessor based controls and power electronics devices are sensitive to many types of disturbances. Voltage flicker is caused by loads that exhibit continuous, rapid variations in load current. The phenomenon of flickering has been known since the introduction of power supply networks. However, it grew rapidly along with the increase in the number of loads and the increase in the power consumed. Electric arc furnace is the main generator of voltage flicker which affects the performance of other sensitive loads connected with the system. Hence, mitigation of voltage flicker becomes inevitable. FACTS devices have been gradually introduced for voltage flicker compensation. Dynamic Voltage Restorer (DVR) has been widely used to mitigate voltage flicker. The DVR with series active compensation capability opposed to variations of the arc resistance and suppress voltage flicker at the source. The control strategy adopted to mitigate flicker in an effective and robust manner is the key issue. A scheme based on fuzzy bang-bang control with ANN is proposed for flicker mitigation using DVR in this study. Two dimensional fuzzy control rules are framed based on Lyapunov function analysis and selection of control rule with best response to current state is done using Artificial Neural Network (ANN). Using the proposed control algorithm, the DVR will contribute to the mitigation of flicker without deteriorating the effect of the other compensating devices. The control algorithm is simulated on a power system model with arc furnace load. Numerical simulations show the effectiveness of the controller in compensating voltage flicker.

**Key words:** Voltage flicker, fuzzy bang-bang control, DVR, Lyapunov function analysis, artificial neural network, India

### INTRODUCTION

The relationship between power quality and distribution system has been a subject of interest for several years. The concept of power quality describes the quality of the supplier voltage in relation to the transient breaks, falling voltage, harmonics and voltage flicker (Sun *et al.*, 2002). Voltage flicker is the disturbance of lightning induced by voltage fluctuations. Very small variations are enough to induce lightning disturbance for human eye for a standard 230 V, 60 W coiled-coil filament lamp. The disturbance becomes perceptible for voltage variation frequency of 10 Hz and relative magnitude of 0.26%. Huge non-linear industrial loads such as the electrical arc furnaces, pumps, welding machines, rolling mills and others are known as flicker generators (Collantes-Bellido, 1997). In this respect, the quality of supplied voltage is significantly reduced in an electrical power system and the oscillation of supplied voltage appears to be a major problem. Electric arc furnace, the main generator of voltage flicker, behaves in the form of a constant reactance and a variable resistance. The

transformer-reactance system is modeled as a lumped reactance, a furnace reactance (included connection cables and busses) and a variable resistance (Zouiti *et al.*, 1998) which models the arc. Connecting this type of load to the network produces voltage variation at the common point of supply to other consumers. The relative voltage drop is expressed by Eq. 1:

$$\frac{\Delta U}{U_n} = \frac{R\Delta P + X\Delta Q}{U_n^2} \quad (1)$$

Where:

$\Delta P$  and  $\Delta Q$  = The variation in active and reactive power  
 $U_n$  = The nominal voltage  
 $R$  and  $X$  = Short circuit resistance and reactance

Since  $R$  is usually very small in comparison to  $X$ ,  $\Delta U$  is proportional to  $Q$  (reactive power). Therefore, voltage flicker mitigation depends on reactive power control. Two types of structures can be used for the compensation of the reactive power fluctuations which are shunt structure and series structure (Roberts, 2002; Montanari *et al.*,

2003). In the shunt type of compensation, the reactive power consumed by the compensator is kept constant at a sufficient value. In the series structure, all the efforts are done to decrease the voltage drop described before and finally, the reactive power is kept constant despite the load fluctuations by controlling the line reactance. In addition to the aforesaid procedures for the compensators, the active filters are used for the voltage flickers mitigation as well (Dolezal *et al.*, 2005). Furthermore, the mitigating devices based on Static VAR Compensator (SVC) such as Thyristor Switched Capacitor (TSC), Thyristor Controlled Reactor (TCR) and Fixed Capacitor Thyristor Controlled Reactor (FCTCR) are the most frequently used devices for reduction in the voltage flicking. SVC devices achieved an acceptable level of mitigation but because of their complicated control algorithms, they have problems such as injecting a large amount of current harmonics to the system and causing spikes in voltage waveforms. In this respect, the FACTS devices based on voltage-source converters have been able to improve the problems related to SVC. Flicker compensation in arc furnace power systems using the DVR is explained by Sedraoui *et al.* (2011). The control strategy adopted to mitigate flicker plays a key role for effective mitigation. Different control algorithms for flicker mitigation are presented in (Dolezal *et al.*, 2005). A new technique based on a novel control algorithm which extracts the voltage disturbance to suppress the voltage flicker is presented by Mienski *et al.* (2009) and Jain *et al.* (2010). The technique is to use DSTATCOM for voltage flicker compensation to overcome the aforementioned problems related to other techniques. The concept of instantaneous reactive power components is used in the controlling system. The design and control strategy based on the instantaneous power calculation are detailed by Sedraoui *et al.* (2011). This study proposes a scheme based on fuzzy bang-bang control. Using Fuzzy Logic Control (FLC) based on bang-bang control, the UPFC will mitigate flicker. The FLC design is based on Lyapunov function analysis and is simulated on a power system model with arc furnace load. Artificial neural network is used for the selection of fuzzy rule that best suits the current state.

### DVR FOR FLICKER MITIGATION

A series connected converter based mitigation device, the Dynamic Voltage Restorer (DVR) is the most economical and technically advanced mitigation device proposed to protect sensitive loads from voltage flicker shown in Fig. 1. The amount of energy storage

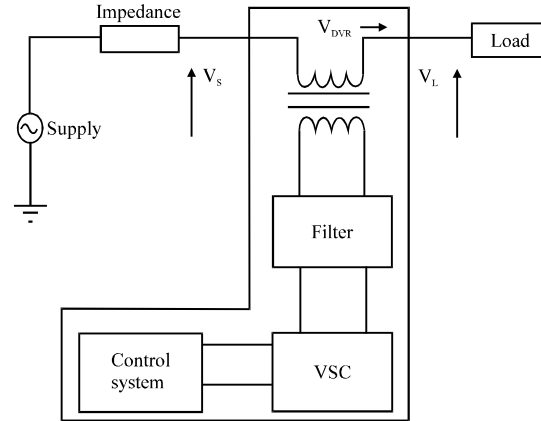


Fig. 1: Dynamic voltage restorers

within the DVR becomes one of the main limiting factors in mitigating long duration voltage sags. Therefore, researchers presently pay greater attention to the DVR energy storage and its optimum use. DVR with external storage battery is used in this research for flicker mitigation. The series voltage controller is connected in series with the protected load as shown in Fig. 1. Usually, the connection is made via a transformer but configurations with direct connection via power electronics also exist. The resulting voltage at the load bus bar equals the sum of the grid voltage and the injected voltage from the DVR. The converter generates the reactive power needed while the active power is taken from the energy storage. The energy storage can be different depending on the needs of compensating. The circuit on left hand side of the DVR represents the Thevenin equivalent circuit of the system. When the system voltage ( $V_{th}$ ) drops, the DVR injects a series voltage  $V_{DVR}$  through the injection transformer so that the desired load voltage magnitude  $V_L$  can be maintained. The series injected voltage of the DVR can be written as:

$$V_{DVR} = V_L + Z_{th}I_L - V_{th} \quad (2)$$

Where:

- $V_L$  = The desired load voltage magnitude
- $Z_{th}$  = The load impedance
- $I_L$  = The load current
- $V_{th}$  = The system voltage

The load current  $I_L$  is given by:

$$I_L = \left[ \frac{(P_L + j^*Q_L)}{V_L} \right]^* \quad (3)$$

When  $V_L$  is considered as a reference, Eq. 2 can be rewritten as:

$$V_{DVR} \angle \alpha = V_L \angle 0 + Z_{th} I_L \angle (\beta - \theta) - V_{th} \angle \delta \quad (4)$$

Here  $\alpha$ ,  $\beta$  and  $\delta$  are the angle of  $V_{DVR}$ ,  $Z_{th}$  and  $V_{th}$  respectively and  $\theta$  is the load power factor angle,  $\theta = \tan^{-1}(Q_L/P_L)$ . The complex power injection of the DVR can be written as:

$$S_{DVR} = V_{DVR} I_L^* \quad (5)$$

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 DVR is required to correct the voltage. It requires the injection of only reactive power and the DVR itself is capable of generating the reactive power. Note that DVR can be kept in quadrature with  $I_L$  only up to a certain value of voltage flicker and beyond which the quadrature relationship cannot be maintained to correct the voltage flicker. For such a case, injection of active power into the system is essential. The injected active power must be provided by the energy storage system of the DVR.

For simulation studies of DVR under steady-state condition, it is modeled as voltage source with appropriate impedance as shown in Fig. 2. The voltage source can be represented by the relationship between the voltages and amplitude modulation ratios and phase shifts of DVR.

According to the theoretical concepts, the rotation of series voltage phasor  $V_{pq}$  with angle  $\rho_{pq}$  causes variation of both the transmitted real power  $P$  and the reactive power  $Q$  with  $\rho_{pq}$  in a sinusoidal manner. For validating the proposed circuit model of DVR, the magnitude of series injected voltage is kept constant at 2KV and its angle is varied from  $0^\circ$ - $360^\circ$ . The variation in real and reactive power is shown in Table 1. It is observed that the variation of real and reactive power is sinusoidal with variation in angle  $\rho_{pq}$ , thus coinciding with theoretical concepts. It is evident that the reactive power is maximum at  $90^\circ$ , medium at  $0^\circ$  and minimum at  $270^\circ$ .

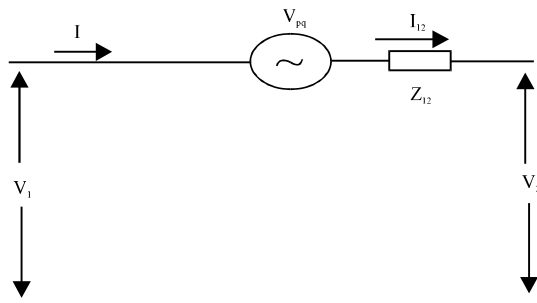


Fig. 2: Voltage source model of DVR

The control circuit of DVR is shown in Fig. 3. Changing state of switches  $C_0$ ,  $C_1$  or  $C_2$  as can regulate the voltage injected by the series controller. The output of series converter can be bang-bang controlled to three different values:

$$\begin{aligned} V_{series} &= |V| \angle 0 && \text{When switch } C_0 \text{ is closed} \\ V_{series} &= |V| \angle 90 && \text{When switch } C_1 \text{ is closed} \\ V_{series} &= |V| \angle 270 && \text{When switch } C_2 \text{ is closed} \end{aligned}$$

Where  $V_{series}$  is the voltage injected by the DVR;  $|V|$  is the maximum magnitude of voltage that can be injected by the DVR. From Table 1, it can be seen that the transmitted real power is maximum at angle  $90^\circ$ , minimum at angle  $270^\circ$  and medium at angle  $0^\circ$ . Hence, these values are selected in the switching function.

The target of damping control is to conduct proper switching of  $C_0$ ,  $C_1$  or  $C_2$  at strategic times as to quickly mitigate voltage flicker.

Table 1: Variation of real and reactive powers of DVR with variation in angle

$\rho_{pq}$ (deg)	P (MW)	Q (MVAR)
0	0.245	1.15
50	0.310	1.47
90	0.330	1.56
120	0.318	1.51
150	0.285	1.36
180	0.245	1.16
240	0.168	0.80
270	0.159	0.75
300	0.175	0.80
360	0.246	1.15

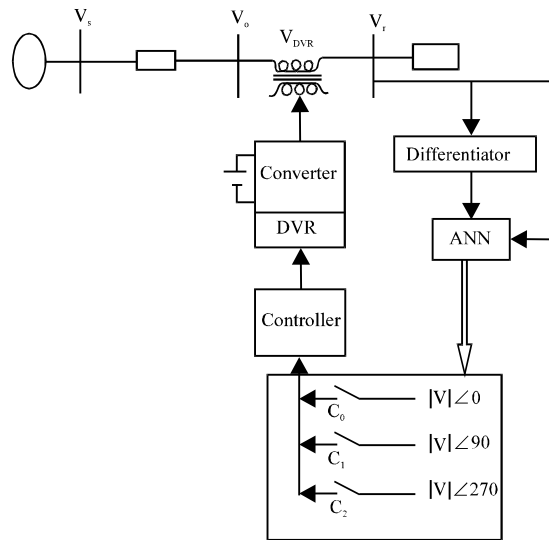


Fig. 3: Control circuit of DVR

**FLC DESIGN**

The design of FLC is based on Lyapunov function analysis. The Lyapunov energy function is formed based on power flow equation. The voltage flicker produces power oscillations. Hence, damping power oscillations is equivalent to mitigating flicker. The power flow equation for power system model shown in Fig. 4 is given as:

$$P = \frac{V_s V_r}{x} \sin \delta_0 \quad (6)$$

Differentiating Eq. 6 with respect to  $\delta_0$  and  $V_r$ :

$$\frac{dP}{d\delta_0} = \frac{V_s V_r}{x} \cos \delta_0 \quad (7)$$

$$\frac{dP}{dV_r} = \frac{V_s}{x} \left( \frac{dV_r}{dt} \right) \sin \delta_0 \quad (8)$$

Lyapunov energy function is formed by combining Eq. 7 and 8 as:

$$\epsilon_T = \frac{V_s}{x} \left( \frac{dV_r}{dt} \right) \sin \delta_0 + \frac{V_s V_r}{x} \cos \delta_0 \quad (9)$$

Damping the total Lyapunov function will also damp power oscillations through mitigation of voltage flicker. The ultimate objective of this research is to implement FLC at the line in which DVR is connected.

The inputs to FLC are  $V$  and  $\Delta V$  measured at DVR terminals. For the output, the FLC will choose one of the three switch states from  $C_0$ ,  $C_1$  and  $C_2$  through the use of ANN. A simple fuzzy logic scheme comprises three functioning blocks, namely fuzzification, implication

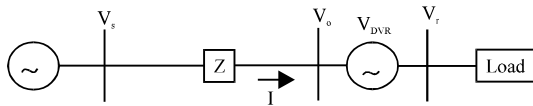


Fig. 4: Power system model

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 14 distinct linguistic levels; namely  $A_{1-14}$ , for input  $V$  and 8 distinct linguistic levels; namely  $B_{1-8}$ , for  $\Delta V$ . 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 (Fig. 4).

**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  $\Delta V$ ), researchers obtain a two-dimensional rule base with  $14 \times 8$  linguistic levels as in Table 2. The rule base is a collection of fuzzy conditional statements in the form of if-then rules. Determination of control rules corresponding to  $V$  and  $\Delta V$  ( $dV_r/dt$ ) is based on trial and error procedure as:

- Find  $\delta_0$  for all switching states using Eq. 10
- Substitute distinct value of  $V_r$  and  $dV_r/dt$  ( $\Delta V$ ) in Eq. 9
- Find the value of  $\delta_0$  which minimizes Eq. 9
- The corresponding switching state is selected as the control rule:

$$\delta_\sigma = \tan^{-1} \left( \frac{V_{DVR}}{V_0} \right) \quad (10)$$

$$\delta_0 = \delta \pm \delta_\sigma$$

Where:

$\delta_0$  = The angle between  $V_r$  and  $V_s$

$\delta_\sigma$  = The angle between  $V_0$  and  $V_r$

$\delta$  = The angle between  $V_0$  and  $V_s$

Table 2: Two-dimensional fuzzy control rules

$\Delta V/V$	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$	$A_7$	$A_8$	$A_9$	$A_{10}$	$A_{11}$	$A_{12}$	$A_{13}$	$A_{14}$
$B_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$
$B_2$	$C_1$	$C_1$	$C_1$	$C_1$	$C_2$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$
$B_3$	$C_1$	$C_1$	$C_1$	$C_2$	$C_2$	$C_2$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$
$B_4$	$C_1$	$C_1$	$C_2$	$C_2$	$C_2$	$C_2$	$C_0$	$C_0$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$	$C_1$
$B_5$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_0$	$C_0$	$C_1$	$C_1$	$C_1$	$C_1$	$C_2$	$C_1$
$B_6$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_1$	$C_1$	$C_1$	$C_2$	$C_2$	$C_1$
$B_7$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_1$	$C_2$	$C_2$	$C_2$	$C_1$
$B_8$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_2$	$C_1$

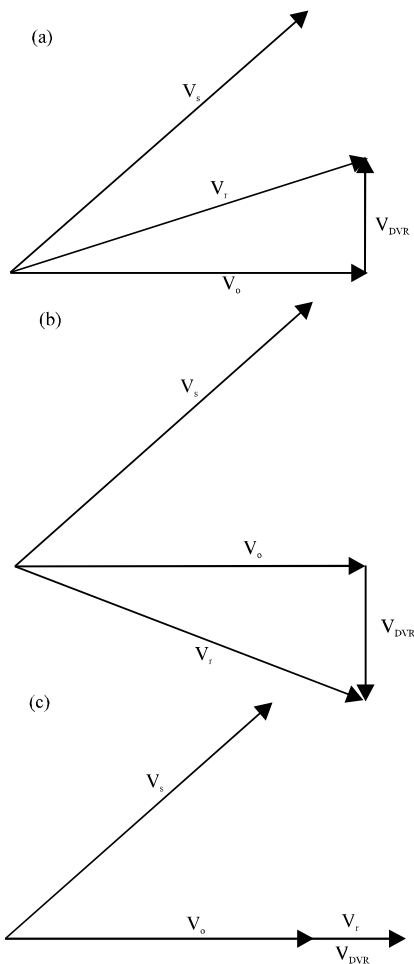


Fig. 5: Phasor diagram for different switching states; a) Switch  $C_1$  is closed; b) Switch  $C_2$  is closed; c) Switch  $C_0$  is closed

In Eq. 10, sign is positive when  $C_2$  is closed and sign is negative when  $C_1$  is closed. The angle  $\delta_o$  is zero when  $C_0$  is closed from phasor diagram shown in Fig. 5.

### ANN FOR SELECTION OF FUZZY RULES

Depending on the values of  $V$  and  $\Delta V$ , the corresponding linguistic levels are to be identified. Then by using Table 2, the correct switching state has to be determined. The switching state has to be determined for various values of  $V$  and  $\Delta V$  at different ranges which is used as training data for training feed forward perceptron neural network. The ANN has two neurons in the input layer for two inputs  $V$  and  $\Delta V$ . There is only one hidden layer with three neurons and the output layer has three neurons corresponding to switching states  $C_1$ ,  $C_2$  and  $C_0$ . If the output of  $C_1$  neuron is 1 then the switching state for

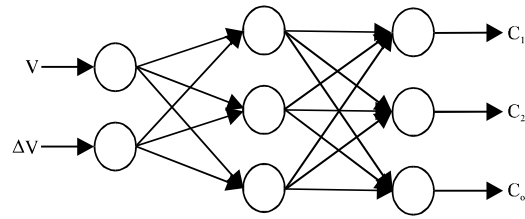


Fig. 6: ANN for selection of fuzzy rules

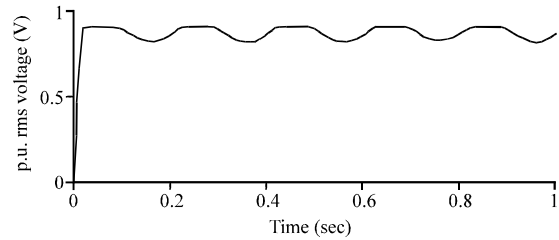


Fig. 7: RMS value of  $v$  voltage at PCC without DVR

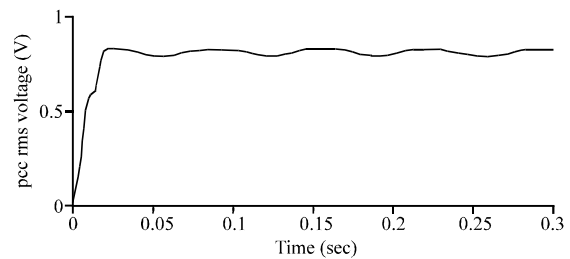


Fig. 8: RMS value of voltage at PCC with DVR

current input should be taken as  $C_1$ . The output layer is a competitive layer and only the winning neuron will produce and the output of other two neurons will be 0. Hence, no two neurons of output layer will produce output 1 simultaneously (Fig. 6).

**Simulation study:** The performance of the UPFC, to mitigate the voltage flicker caused by electric arc furnaces is studied by applying Fuzzy Logic Control (FLC) based on bang-bang control algorithm.

The various parameters of the simulation study of the system are  $V_{source} = 566$  V,  $f = 50$  Hz,  $R_g = 0.05$   $\Omega$ ,  $Z_f = 0.0000528 + j0.000468$   $\Omega$  and  $Z_T = 0.0003366 + j0.00322$   $\Omega$ .

The load model is carried out with the data  $V_{ig} = 350.75$  V,  $I_{max} = 100$  kA,  $\tau_1 = 0.01$  sec and  $\tau_2 = 0.01$  sec. DC link voltage = 1000 V,  $C = 50000$   $\mu$ F, tie reactance = 1.6  $\mu$ H. RMS value of voltage at PCC without DVR and with DVR is shown in Fig. 7 and 8, respectively. Voltage flicker without DVR is about 9% ( $\Delta V/V$ ). Flicker is mitigated and is 0.3% which is within IEEE threshold limits when UPFC is connected at the PCC.

## CONCLUSION

In this study, DVR controller is derived by using Fuzzy Logic Control (FLC) based on bang-bang control with ANN. The FLC is based on Lyapunov energy function analysis. The proposed control strategy is based on local input signals. The structure of the algorithm is easy to understand, easy to implement and attractive from view point of engineering. The model is simulated in Matlab/Simulink platform and DVR controller's performance is evaluated. Voltage flicker without DVR is about 9% ( $\Delta V/V$ ). Flicker is mitigated and is 0.3% which is within IEEE threshold limits when UPFC is connected at the PCC. Numerical simulation proved the effectiveness of the controller in compensating voltage flicker.

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