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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 paper. 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.

Keywords: voltage flicker, fuzzy bang-bang control, DVR, lyapunov function analysis, artificial neural network.

1. 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 [J. 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 230V, 60W 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 [R. Collantes Bellido *et al*., 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 [M. 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 equation (1):

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

Where ΔP and ΔQ are the variation in active and reactive power; U_n is the nominal voltage and R and X are short circuit resistance and reactance. Since R is usually very small in comparison to X, ΔU 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 [B. P. Roberts, 2002; G. C. 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 mentioned above, 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 [J. 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. K *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 [J. 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 R. Mienski *et al*., 2009 and Amit K *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. K *et al*., 2011. This paper 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.

2. 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 Figure-1. The amount of energy storage 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 work for flicker mitigation.

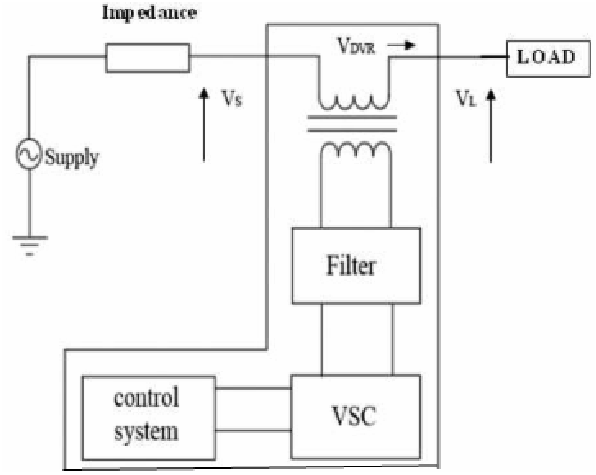


Figure-1. Dynamic voltage restorers.

The series voltage controller is connected in series with the protected load as shown in Figure-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,

$$V_{DVR} = V_L + Z_{th} I_L - V_{th} \tag{2}$$

Where V_L is the desired load voltage magnitude; Z_{th} is the load impedance; I_L is the load current and V_{th} is the system voltage.

The load current I_L is given by:

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

When V_L is considered as a reference, equation (2) can be rewritten as:

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

Here α, β and δ are the angle of V_{DVR}, Z_{th} and V_{th}, respectively, and θ is the load power factor angle, $\theta = \tan^{-1}(Q_L/P_L)$.

The complex power injection of the DVR can be written as:

$$S_{DVR} = V_{DVR} I_L^{*} \tag{5}$$

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 Figure-2. The voltage source can be represented by the relationship between the voltages and amplitude modulation ratios, and phase shifts of DVR.

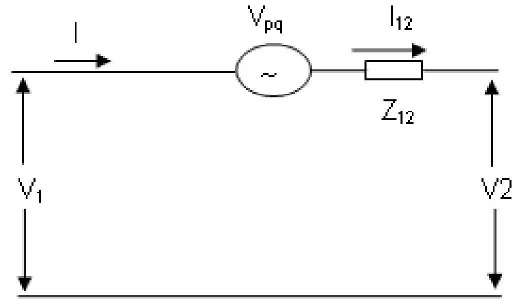


Figure-2. Voltage source model of DVR.

According to the theoretical concepts, the rotation of series voltage phasor V_{pq} with angle ρ_{pq} causes variation of both the transmitted real power 'P' and the reactive power 'Q' with ρ_{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^o to 360^o. The variation in real and reactive power is tabulated in Table-1. It is observed that the variation of real and reactive power is sinusoidal with variation in angle ρ_{pq}, thus coinciding with theoretical concepts. It is evident that, the reactive power is maximum at 90^o, medium at 0^o and minimum at 270^o.

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

S. No.	ρ_{sc} (deg)	P (MW)	Q (MVAR)
1	0	0.245	1.15
2	50	0.310	1.47
3	90	0.330	1.56
4	120	0.318	1.51
5	150	0.285	1.36
6	180	0.245	1.16
7	240	0.168	0.80
8	270	0.159	0.75
9	300	0.175	0.80
10	360	0.246	1.15

The control circuit of DVR is shown in Figure-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:

$V_{series} = |V|\angle 0$ When switch C_0 is closed.

$V_{series} = |V|\angle 90$ When switch C_1 is closed.

$V_{series} = |V|\angle 270$ When switch C_2 is closed.

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^o, minimum at angle 270^o and medium at angle 0^o. 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.

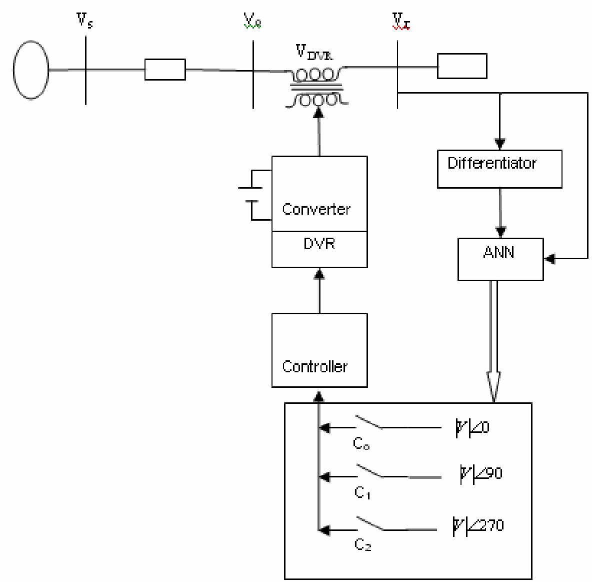


Figure-3. Control circuit of DVR.

3. FLC DESIGN

The design of FLC is based on Lyapunav function analysis. The Lyapunav energy function is formed based on power flow equation. The voltage flicker produces power oscillations. Hence damping power oscillations is equivalent to mitigating flicker.

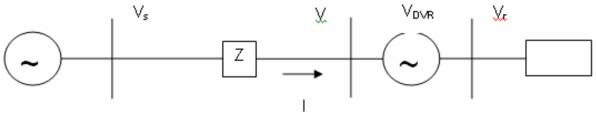


Figure-4. Power system model.

The power flow equation for power system model shown in Figure-4 is given as:

$$P = \frac{V_s V_r}{X} \sin \delta_o \tag{6}$$

Differentiating equation (6), with respect to δ_o and V_r,

$$\frac{dP}{d\delta_o} = \frac{V_s V_r}{X} \cos \delta_o \tag{7}$$

$$\frac{dP}{dV_r} = \frac{V_s}{X}\left(\frac{\mathbf{dV_r}}{\mathbf{dt}}\right) sin\delta_o \tag{8}$$

Lyapunav energy function is formed by combining equations (7) and (8) as:

$$\epsilon_T = \frac{V_s}{X}\left(\frac{\mathbf{dV_r}}{\mathbf{dt}}\right) sin\delta_o + \frac{V_s V_r}{X}\cos\delta_o \tag{9}$$

Damping the total Lyapunov function will also damp power oscillations through mitigation of voltage flicker.

Table-2. Two-dimensional fuzzy control rules.

ΔV/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

The ultimate objective of this work is to implement FLC at the line in which DVR is connected. The inputs to FLC are V and ΔV 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 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 $A_{1\text{-}14,}$ for input V and 8 distinct linguistic levels, namely $B_{1\text{-}8}$, for ΔV. 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 ΔV), we obtain a two-dimensional rule base with 14 x 8 linguistic levels as in Table-2. The rule base is a collection of fuzzy conditional statements in the form of 'if-then' rules.

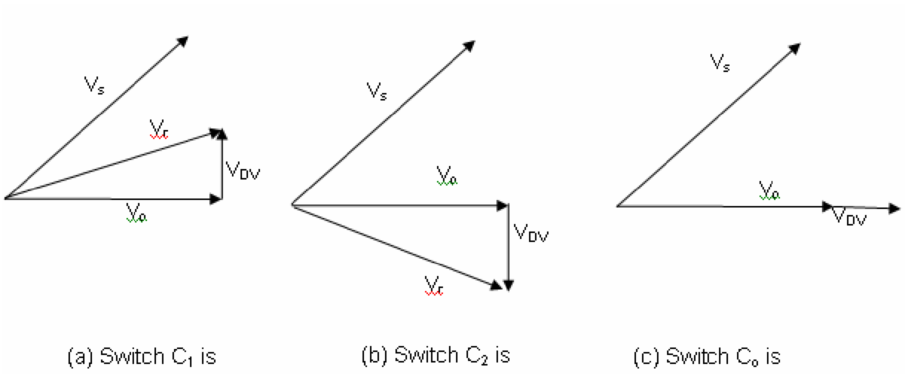
Determination of control rules corresponding to V and ΔV $\left({dV_r}/{dt}\right)$ is based on trial and error procedure described below:

- Find δ_0 for all switching states using equation (10)
- Substitute distinct value of V_r and ${dV_r}/{dt}$ (ΔV) in equation (9)
- Find the value of δ_0 which minimizes equation (9)
- The corresponding switching state is selected as the control rule.

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

$$\delta_o = \delta \pm \delta_\sigma \tag{10}$$

Where δ_o is the angle between V_r and V_s; δ_σ is the angle between V_o and V_r; δ is the angle between V_o and V_s. In equation (10) sign is positive when C_2 is closed and sign is negative when C_1 is closed. The angle δ_σ is zero when C_0 is closed from phasor diagram shown in Figure-5.



(a) Switch C_1 is (b) Switch C_2 is (c) Switch C_o is

Figure-5. Phasor diagram for different switching states.

4. ANN FOR SELECTION OF FUZZY RULES

Depending on the values of V and ΔV, 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 ΔV 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 ΔV. There is only one hidden layer with three neurons and the output layer has three neurons corresponding to switching states C1, C2 and Co. If the output of C1 neuron is 'one', then the switching state for current input should be taken as C1. The output layer is a competitive layer and only the winning neuron will produce and the output of other two neurons will be 'zero'. Hence no two neurons of output layer will produce output 'one' simultaneously.

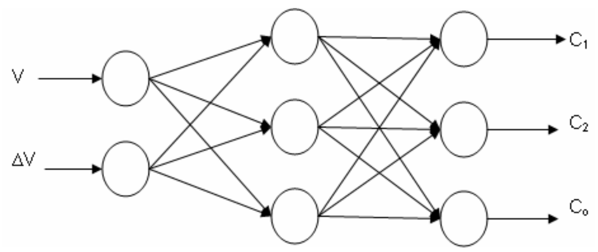


Figure-6. ANN for selection of fuzzy rules.

5. 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 = 0.05Ω, Z_f = 0.0000528 + j 0.000468 Ω and Z_T = 0.0003366 + j0.00322 Ω. The load model is carried out with the data V_{ig} = 350.75 V, I_{max} = 100 kA, τ_1 = 0.01 Sec and τ_2=0.01 Sec. DC link voltage = 1000 V, C = 50000μF, tie reactance = 1.6μH. RMS value of voltage at PCC without DVR and with DVR is shown in Figure-7 and Figure-8, respectively. Voltage flicker without DVR is about 9% (ΔV/V). Flicker is mitigated and is 0.3% which is within IEEE threshold limits, when UPFC is connected at the PCC.

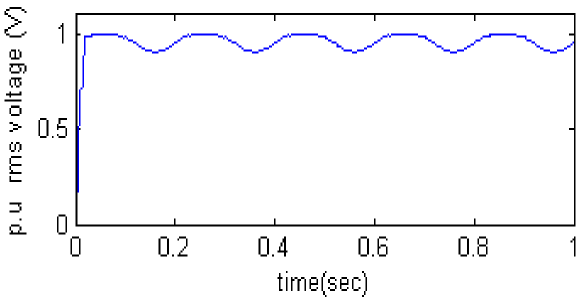


Figure-7. RMS value of voltage at PCC without DVR.

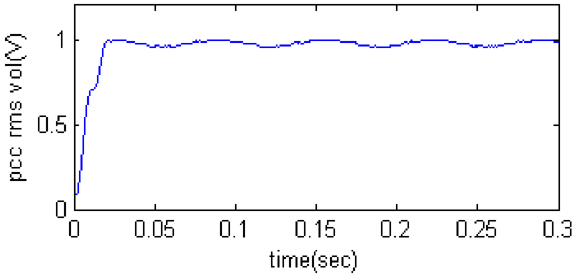


Figure-8. RMS value of voltage at PCC with DVR.

6. CONCLUSIONS

In this paper, 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% (ΔV/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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