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ADAPTIVE ANN EXTRACTION FOR VOLTAGE FLICKER ESTIMATION AND MITIGATION USING IDVR

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ABSTRACT

Electric power quality broadly refers to maintaining a near sinusoidal bus voltage at rated magnitude and frequency. The flicker occurs due to voltage fluctuations. The FACTS devices like SVC's, STATCOM, UPFC and DVR have been able to solve the voltage flicker problems by rapidly controlling the reactive power. In the case of two different sensitive loads in an industrial park fed from two different feeders with different voltage levels, protection from voltage flicker can be done by two DVRs having common dc link called IDVR. This would cut down the cost of the custom power device, as sharing a common dc link reduces the dc link storage capacity significantly compared to that of a system whose loads are protected by clusters of DVRs with separate energy storages. The control strategy adopted to mitigate flicker plays a key role for effective mitigation. In this paper, adaptive ANN is used for generating reference control signal for PWM controller to mitigate flicker using IDVR. A Newton-Raphson based algorithm is proposed for ANN to extract flicker components. Voltage flicker can also be estimated using the output of proposed adaptive ANN. The control structure is decentralized and does not need any coordination with other compensating devices. The structure of proposed algorithm is easy to understand, easy to implement and attractive from a view-point of engineering. The model is simulated in MATLAB/SIMULINK platform and IDVR controller's performance is evaluated. Numerical simulation proved the effectiveness of the adaptive ANN controller in compensating voltage flicker.

Keywords: voltage flicker, power quality, Newton-Raphson method, ANN, interline dynamic voltage restorer.

1. INTRODUCTION

A modern consumer requires high quality power supply for their sensitive loads. Voltage flicker has become an important power quality issue. It is reported that a small voltage fluctuations of less than 0.5% in the frequency range of 5-10 Hz can cause visible lamp voltage flicker [M. Bollen *et al*., 2006]. The main sources of voltage fluctuations can be divided into two main categories which are step voltages changes in regular time interval and cyclic voltage changes. Loads that lead to voltage fluctuations are arcing furnaces, welding machines, rolling mills, mine winders, large capacitor bank used for power factor improvements and electric boilers. An example of a low voltage load that leads to voltage fluctuations are copying machine, X-ray equipments, drives for lifts, pumps, fans, refrigerators and electric cookers [R. C. Dugan, *et al*., 2006]. In certain circumstances, superimposed inter harmonics in the supply voltage can lead to oscillating luminous flux. Sources of inter harmonics which are responsible for flickers, include static frequency converters, sub-synchronous converter, induction machines and arc furnaces [Angelo Baggini. P, 2008]. Voltage flicker affect motor starting results in temperature rise and motor overloading. It affects control systems; reduce the lifetime as well as degradation of performance of the electronic, incandescent, fluorescent and CRT devices. It has been also observed that the voltage fluctuations led to small speed variations of electrical motor results in variations in final quality of products [J. A. Arrillaga *et al*., 2008]. The voltage variations and mitigation studies for equipments like arc furnaces, electric welders, motors, generators and wind turbines, can be found in [M.M. Morcos, *et al*., 2005]. In [J. Jatskevich, *et al*., 2008], the UIE/IEC flicker meter for flicker measurements and adaptive VAR compensator (AVC) model has developed. Using line current measurements, instantaneous voltages were estimated and a state estimation method for monitoring the voltage flicker have been proposed in [Mahmoud Mazadi *et al*., 2009]. In [Weihao Hu *et al*., 2009], the authors have proposed a new method of voltage flicker mitigation by controlling active power for variable speed wind turbine. The flicker measurements and effective mitigation methodologies can be studied in [Garcia-Cerrada *et al*., 2000; Z. Zhang *et al*., 2001]. The limits of flicker emission for an individual fluctuating load must be determined in order to assure that the total flicker injection from all types of loads does not exceeding the planning levels. Procedure for determining the requirements for connecting large fluctuating loads to MV and HV levels are explained in IEC 61000-3-7. Flicker emission planning levels provided by IEC must be always less than or equal to the compatibility levels for LV and MV systems. The IEC 61000-3-3 provides and explains voltage flicker emission limits for the equipments connected to LV systems. The standard IEC 61000-4-15 gives the functional and design specifications for flicker measurement apparatus to indicate the correct flicker perception level for all practical voltage fluctuation waveforms. In this, the overall response from the instrument input to output is given for a sinusoidal and rectangular voltage change at frequencies between 0.5 and 25 Hz. It also includes a performance test to define a set of rectangular voltage changes of different frequencies and depths for which the short time flicker

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severity, P must be 1.00 ± 5 %.It includes standard models for 230 V, 60 W and 120 V, 60 W lamps. The flicker meter can be used to for the loads that are already in operation. However, direct measurement using flicker meter cannot be applied in the design or planning stage of an installation. In these cases, some analytical methods are required so that flicker severity level should not exceed than the planned level. Such analytical method also helps in determining and finalizing mitigation methodology [Walid G *et al*., 2009]. The IDVR [D. Mahinda Vilathgamuwa *et al*., 2008] scheme provides a way to transfer real power between sensitive loads in individual line through the common dc link of the DVRs, as it does in the Interline Power flow Controller (IPFC). However, the lines in the IPFC originate from a single grid substation while the lines in the IDVR voltage sag by importing real power from the dc link, the other DVRs replenish the dc-link energy to maintain the dc-link voltage at a specific level using Current source Inverter [Dong Shen *et al*., 2002]. An example of a potential location for such a scheme is an industrial park where power is fed from different feeders connected to different grid substations, those that are electrically far apart. The sensitive loads in this park may be protected by DVR connected to respective loads. The dc links of these DVRs can be connected to a common terminal, there by forming an IDVR system. This would cut down the cost of the custom-power device, as sharing common dc link reduces the size of the dc-link storage capacity substantially, compared to that of a system in which loads are protected by clusters of DVRs with separate energy storage systems. Voltage flicker mitigation using IDVR system is considered in this work. The control strategy adopted to mitigate flicker plays a key role for effective mitigation. In this paper, adaptive ANN is used for generating reference control signal for PWM controller to mitigate flicker using IDVR. A Newton-Raphson based algorithm is proposed for ANN to extract flicker components. Voltage flicker can also be estimated using the output of proposed adaptive ANN.

2. IDVR OPERATION

A typical IDVR scheme is shown in Figure-1. The IDVR system consists of several DVRs in different feeders sharing a common dc link. A two-line IDVR system shown in Figure-1 employs two DVRs connected to two different feeders originating from two grid substations. These two feeders could be of the same or different voltage level. When one of the DVR compensates for voltage sag, the other DVR in IDVR system operates in power-flow control mode to replenish dc link energy storage which is depleted due to the real power taken by the DVR working in the voltage-flicker compensation mode. Propagation of voltage flickers due to momentary fault in the power system depends on many factors, such as voltage level and fault currents etc., Voltage flickers in a transmission system are likely to propagate to larger electrical distance than that in a distribution system. Due to these factors and as the two feeders of the IDVR system in Figure-1 are connected to two different grid substations, it is reasonable to assume that the voltage flicker in Feeder-1 would have a lesser impact on Feeder-2. Therefore, the upstream generation-transmission system to the two feeders can be considered as two independent sources. These two sources are represented by the Thevenin's equivalent impedances Z_{L1} and Z_{L2} connected to the buses B_1 and B_2 as in Figure-1. Z_{L1} and Z_{L2} are calculated based on the fault level at B_1 and B_2.

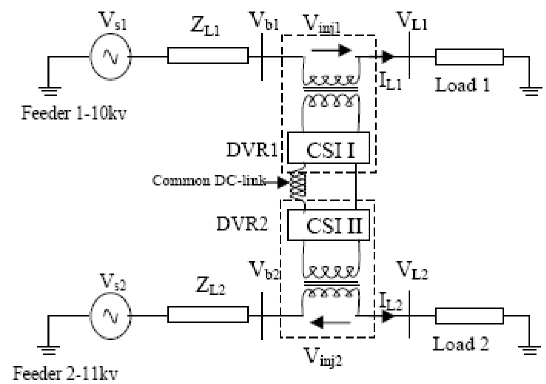

Figure-1. Schematic representation of the IDVR.

The circuit model of IDVR used for flicker mitigation in multi line distribution system is shown in Figure-2.

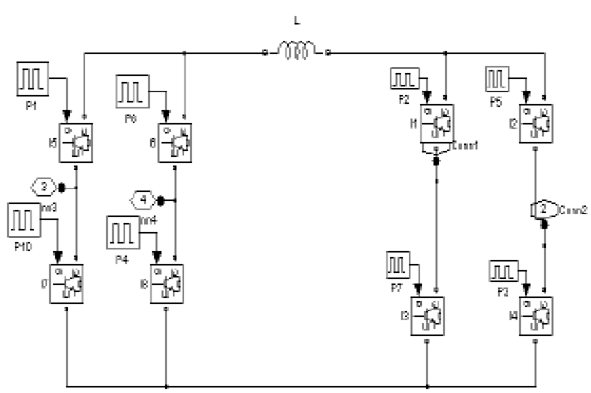

Figure-2. Circuit model of the IDVR.

3. ADAPTIVE ANN BASED VOLTAGE FLICKER MITIGATION

The voltage waveform at PCC and rms voltage at PCC are shown in Figure-3 as a sample when loads like arc furnace and welding machine are connected to the system.

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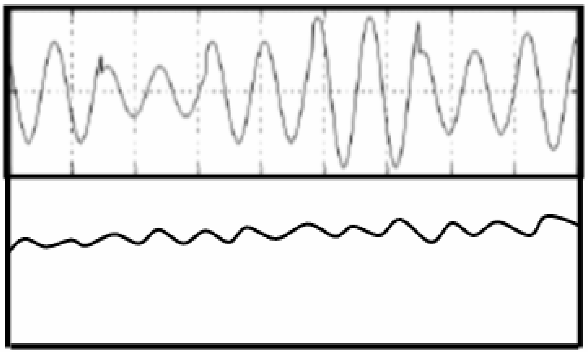

Figure-3. Sample disturbed voltage waveform and rms voltage at PCC.

This type of disturbed voltage waveforms due to flicker can be represented as:

$$V(t) = \sum_{n=1}^{N} V_n \sin(n\omega t + \theta_n) \qquad (1)$$

The above equation can be expanded as follows.

$$V(t) = \sum_{n=1}^{N} (V_n \sin n\omega t \cos\theta_n + V_n \cos n\omega t \sin\theta_n) \qquad (2)$$

$$V(t) = (V_1\cos\theta_1 \sin\omega t + V_1 \sin\theta_1 \cos\omega t + V_2\cos\theta_2 \sin 2\omega t + \sin\theta_2 \cos 2\omega t + \ldots V_N \cos\theta_N \sin N\omega t + V_N \sin\theta_N \cos N\omega t) \qquad (3)$$

The term sinωt and cosωt corresponds to fundamental frequency and, V_1 and θ_1 gives its magnitude and phase angle respectively. Similarly sinNωt and cosNωt corresponds to frequency equal to 'N' times of fundamental frequency and, I_N and θ_N gives its magnitude and phase angle. Equation (3) can be written as:

$$V(t) = W_1 \sin\omega t + W_2 \cos\omega t + W_3 \sin 2\omega t + W_4 \cos 2\omega t + \ldots\ldots\ldots + W_{2N-1} \sin N\omega t + W_{2N} \cos N\omega t \qquad (4)$$

Where,

$$W_1 = V_1 \cos\theta_1$$
$$W_2 = V_1 \sin\theta_1$$
$$W_3 = V_2 \cos\theta_2$$
$$W_4 = V_2 \sin\theta_2$$
$$W_{2N-1} = V_N \cos\theta_N$$
$$W_{2N} = V_N \sin\theta_N$$

The weight vector is:

$$[W]^T = [W_1 W_2 \ldots\ldots. W_{2N}] \qquad (5)$$

The input vector is:

$$[X]^T = [\sin\omega t \cos\omega t \sin 2\omega t \cos 2\omega t \ldots\ldots.. \sin N\omega t \cos N\omega t] \qquad (6)$$

The block diagram of adaptive ANN control algorithm and Adeline used for flicker extraction are shown in Figure-4 and Figure-5, respectively. The input to the ANN is voltage waveform sampled at regular intervals. If the current wave form is having 'k' sampling intervals each having sampling time 't_s', then the current at the k^{th} interval is got by substituting t = kt_s in equation (4). Thus,

$$V(k) = W_1 \sin\omega k t_s + W_2 \cos\omega k t_s + W_3 \sin 2\omega k t_s + W_4 \cos 3\omega k t_s + \ldots\ldots.. W_{2N-1} \sin N\omega k t_s + W_{2N} \cos N\omega k t_s \qquad (7)$$

$$[X]^T = [\sin\omega k t_s \cos\omega k t_s \sin 2\omega k t_s \cos 2\omega k t_s \ldots\ldots. \sin N\omega k t_s \cos N\omega k t_s]$$

$$V(k) = [W]^T [X]$$

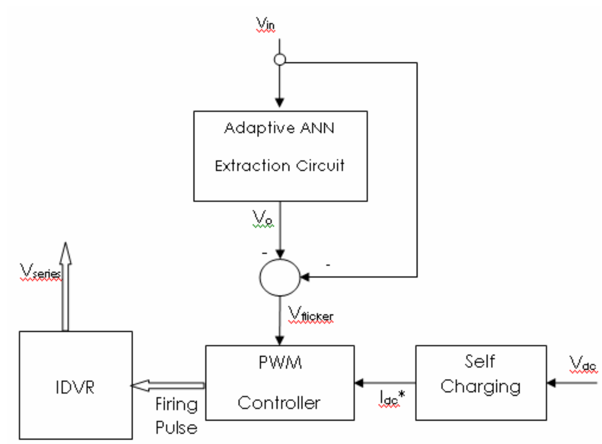

Figure-4. Control circuit for flicker mitigation using IDVR.

$$V(k) = W_1 \sin\omega k t_s + W_2 \cos\omega k t_s + \sum_{N=3,5,\ldots\ldots}^{2N-1} W_n \sin n\omega k t_s + \sum_{N=4,6,\ldots.}^{2N} W_n \cos n\omega k t_s \qquad (8)$$

ARPN Journal of Engineering and Applied Sciences

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Where $V_f(k) = W_1 \sin \omega k t_s + W_2 \cos \omega k t_s$

$$V_{flicker}(k) = \sum_{N=3,5,...}^{2N-1} W_n \sin n\omega k t_s + \sum_{N=4,6,...}^{2N} W_n \cos n\omega k t_s \quad (9)$$

V_f = Fundamental component of supply voltage

$V_{flicker}$ = Flicker component of supply voltage which is to be supplied by IDVR for flicker mitigation.

$$V_{flicker}(k) = V(k) - V_f(k)$$

The flicker component of supply voltage got as output of adaptive ANN is given as reference signal to PWM controller which produces firing pulses for IDVR to mitigate voltage flicker.

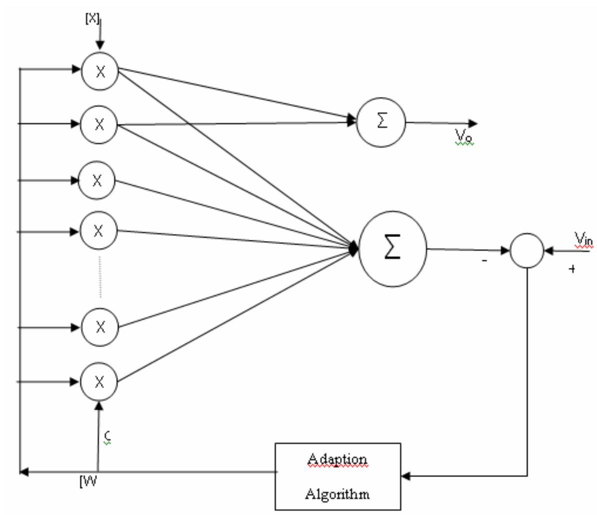

Figure-5. Adaptive ANN for flicker mitigation.

4. ADAPTIVE ANN BASED FLICKER ESTIMATION

Based on the weights of adaptive ANN the magnitude and angle of flicker components can be estimated. The angle of flicker components θ_N can be estimated from the elements of weight matrix using the formula,

$$\theta_N = \tan^{-1}\left(\frac{W_{2N}}{W_{2N-1}}\right) \quad (10)$$

The magnitude of flicker components V_N can be estimated using the formula,

$$V_N = \sqrt{W_{2N}^2 + W_{2N-1}^2} \quad (11)$$

The voltage flicker can be estimated using total flicker distortion (TFD) which can be calculated using equation (12).

$$\%TFD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots \ldots V_N^2}}{V_1^2} \quad (12)$$

The limits of flicker emission for an individual fluctuating load must be determined in order to assure that the total flicker injection from all types of loads does not exceeding the planning levels.

5. ADAPTION ALGORITHM FOR ANN

The algorithm which imparts adaptive nature to ANN is based on Newton-Raphson method.

Based on equation (7), the equation for k[th] sample of disturbed voltage is:

$$V(k) = W_1 \sin\omega k t_s + W_2 \cos\omega k t_s + W_3 \sin 2\omega k t_s + W_4 \cos 2\omega k t_s + \ldots\ldots\ldots + W_{2N-1} \sin N\omega k t_s + W_{2N} \cos N\omega k t_s$$

Differentiating the above equation with respect to weights,

$$\frac{\partial V(k)}{\partial W_1} = Sin\omega k t_s$$

$$\frac{\partial V(k)}{\partial W_2} = \cos \omega k t_s$$

Similarly, $\frac{\partial V(k)}{\partial W_{2N-1}} = SinN\omega k t_s$ and $\frac{\partial V(k)}{\partial W_{2N}} = CosN\omega k t_s$ (13)

If 'F' denotes iteration count then

$$[V(F)] = \begin{bmatrix} V(t_s) \\ V(2t_s) \\ : \\ : \\ V(Kt_s) \end{bmatrix}. \quad (14)$$

The size of $[V(F)]$ matrix is $(k \times 1)$ where K denotes number of samples.

The sampled output vector is:

$$[V_R] = \begin{bmatrix} V_{R1} \\ V_{R2} \\ : \\ : \\ V_{Rk} \end{bmatrix}. \quad (15)$$

Equation (14) can be calculated using equation (7).

The size of $[V_R]$ matrix is $(k \times 1)$.

The error vector is:

$$[E(F)] = [V_R] - [V(F)]. \quad (16)$$

The size of [E (F)] matrix is also $(k \times 1)$.

The size of [W (F)] matrix is $(2N+1) \times 1$

ARPN Journal of Engineering and Applied Sciences

The fundamental frequency ω which is included in weight vector is also updated.

$$[W(F)] = \begin{bmatrix} W_1 \\ W_2 \\ : \\ : \\ W_{2N-1} \\ W_{2N} \\ \omega \end{bmatrix}. \quad (17)$$

Differentiating equation (7) with respect to ω,

$$\left[\partial V(k) \big/ \partial\omega \right] = \begin{bmatrix} kt_s(W_1 \cos\omega kt_s - W_2 \sin\omega kt_s + 2W_3 \cos 2\omega kt_s \\ -2W_4 \sin 2\omega kt_s ...... \\ + NW_{2N-1} \cos N\omega kt_s - NW_{2N} \sin\omega kt_s) \end{bmatrix} \quad (18)$$

The sub matrix $\frac{\partial V(F)}{\partial W}$ is given by:

$$[M] = \begin{bmatrix} Sin\omega t_s Cos\omega t_s ....SinN\omega t_s CosN\omega t_s \\ Sin2\omega t_s Cos2\omega t_s ......Sin2N\omega t_s Cos2N\omega t_s \\ Sin3\omega t_s Cos3\omega t_s ......Sin3N\omega t_s Cos3N\omega t_s \\ : \\ : \\ : \\ Sink\omega t_s Cosk\omega t_s ....Sin3Nk\omega t_s Cos3Nk\omega t_s \end{bmatrix} \quad (19)$$

The size of [M] sub matrix is $k \times 2N$

The elements of [M] sub matrix are got using equation (13).

The sub matrix $\frac{\partial V(F)}{\delta\omega}$ is given by:

$$[N] = \left[\frac{\partial V(F)}{\partial\omega} \right] = \begin{bmatrix} \frac{\partial V(t_s)}{\partial\omega} \\ \frac{\partial V(2t_s)}{\partial\omega} \\ : \\ : \\ : \\ \frac{\partial V(Kt_s)}{\partial\omega} \end{bmatrix}. \quad (20)$$

The size of [N] sub matrix is $k \times 1$.

The elements of [N] sub matrix can be calculated using equation (18)

The Jacobian matrix is given by:

$$[J] = [M\,N]. \quad (21)$$

M and N are the sub matrix of [J].

$$[L] = \begin{bmatrix} \Delta W_1 \\ \Delta W_2 \\ : \\ : \\ : \\ \Delta W_{2N-1} \\ \Delta W_{2N} \\ \Delta\omega \end{bmatrix}. \quad (22)$$

The size of [L] matrix is $(2N+1)\times 1$

The [L] Matrix can be calculated using the equation given below:

$$[E(F)] = [J][L]$$
$$[L] = [J]^{-1}[E(F)]. \quad (23)$$

Steps to be followed are:

(a) Set the error tolerance value '$\in$' and iteration count F= 0.

(b) Initialize $[W(F)]$matrix given in equation (17).

(c) Calculate $[V(F)]$matrix given in equation (14) using equation (7).

(d) Calculate $[E(F)]$ matrix using equation (16).

(e) Check whether the largest element of $[E(F)]$ is less than '$\in$'.

If yes, go to Step-(10). Else go to next step.

(f) Calculate the Sub Matrices [M] and [N] of [J] using equations (19) and (20) and form [J] matrix as per equation (21).

(g) Calculate [L] Matrix using equation (22).

(h) Update $[W(F)]$matrix using equation

$[W(F)] = [W(F)] + [L]$

(i) Set iteration count F=F+1 and go to Step - 3.

(j) Using the element of [W (F)] calculate current reference.

6. SELF CHARGING CIRCUIT FOR MAINTAINING DC BUS VOLTAGE

To regulate the dc link capacitor voltage at the desired level, real power has to be drawn by the IDVR from the supply side to charge the capacitor. The configuration of three-phase self charging current is shown in Figure-7. The simple control algorithm is developed which does not use PI controller. To regulate the dc capacitor voltage at the desired level, an additional real power has to be drawn by the adaptive shunt active filter from the supply side to charge the two capacitors. The energy 'E' stored in each capacitor can be reprinted as

$$E = \frac{1}{2} C V_{dc}^{\ 2} \quad (24)$$

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ARPN Journal of Engineering and Applied Sciences

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Where 'C' is the value of each capacitor and V_{dc} is the voltage of each capacitor. If the desired level of voltage across each capacitor is $V_{dc(ref)}$, the energy for capacitor is:

$$E' = \frac{1}{2} C V_{dc(ref)}^{2} \tag{25}$$

The difference between E¹ and E represents the additional energy required by capacitor to reach the desired voltage level. Thus

$$\Delta E = E^{\prime} - E = \frac{1}{2} C \left\{ V_{dc(ref)}^{2} - V_{dc}^{2} \right\}$$

On the other hand the charging energy E_{ac} delivered by the three phase supply side to the inventor of each capacitor will be:

$$E_{ac} = 3pt$$

$$= 3(V_{rms} I_{dc(rms)} \cos\Phi)t. \tag{27}$$

p = Additional real power required

V_{rms} = RMS value of the instantaneous supply voltage

$I_{de(rms)}$ = RMS value of the instantaneous charging current

t = Charging time

ϕ = Phase deference between the supply voltage and charging current

Here't' can be defined as T/2 since the charging process only takes place for half a cycle for each capacitor, where 'T' is the period of supply frequency. By using Phase Lock Loop (PLL) the charging current is made in phase with the supply voltage. Thus, power factor $\cos\phi = 1$. Also the RMS value can be expressed in terms of maximum values. This result in

$$E_{ac} = 3 \frac{V}{\sqrt{2}} \frac{I_{dc}}{\sqrt{2}} \frac{T}{2}. \tag{28}$$

$$E_{ac} = \frac{3VI_{dc}T}{4} \tag{29}$$

Neglecting the switching losses in the inverter and according to the energy conservation law the following equation holds:

$$\Delta E = E_{ac}$$

$$\frac{1}{2} C \left\{ V_{dc(ref)}^{2} - V_{dc}^{2} \right\} = \frac{3VI_{dc}T}{4} \tag{30}$$

$$I_{dc} = 2C \frac{\left\{ [V_{dc}(ref)]^{2} - [V_{dc}]^{2} \right\}}{3VT} \tag{31}$$

To regulate the dc link capacitor voltage at the desired level, an additional real power has to be drawn by the IDVR from the supply side to charge the two capacitors. The configuration of three-phase self charging current is shown in Figure-7. The PLL synchronizes itself with the supply voltage of phase 'a' and outputs three sine waves which are 120° out of phase from each other. Three phase i_{dc} is obtained by multiplying these sine waves with the current I_{dc} which is calculated by the control algorithm. Thus, the three phase injection currents can be calculated as:

$$\begin{aligned} i_{inj,a} &= -I_{dc} \sin \omega t \\ i_{inj,b} &= -I_{dc} \sin(\omega t - 120) \\ i_{inj,c} &= -I_{dc} \sin(\omega t + 120) \end{aligned} \tag{32}$$

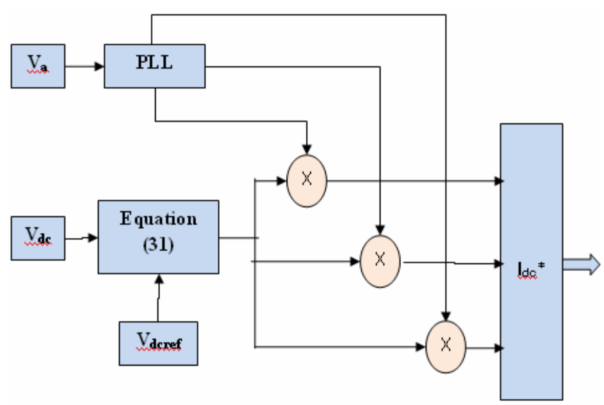

Figure-6. Three-phase self charging circuit

I_{dc}* denoted as output of self charging block in Figure-5 is given as I_{dc}*= [$i_{inj,a}$, $i_{inj,b}$, $i_{inj,c}$]

The minus sign indicates that the charging current i_{dc} flows into the IDVR. A PWM controller is used to control the switching of the IDVR.

7. SIMULATION STUDY

A detailed simulation has been carried out for a simple IDVR system consisting of two lines of 6.6 KV. The parameters of IDVR system are given in Table-1. Two lines are feeding equal loads of 1MVA with 0.8 PF lagging. Simulation results presented in this paper are for switching of welding machine in the load bus of line L_2. The total flicker distortion (TFD) of phase-A of the supply voltage of lines L_1 and L_2 are 2% and 40% respectively. The series converter of IDVR connected with lines L_2 operates in flicker mitigation mode and series converter of IDVR connected with L_2 are operated in self charging mode which replenishes dc link energy. The TFD of compensated load voltage of line L_2 is 11% which shows that, the load voltage tracks the desired reference accurately, without RMS tracking error. It also proves the effectiveness of the adaptive ANN control technology for voltage flicker compensation. The degree of mitigation and dynamic performances is within the acceptable limits.

Table-1. Parameters of the two-line IDVR system.

Parameter	Values
Supply voltage per phase (KV)	3.81
Load resistance (Ω)	35.0
Load inductance (mH)	83.0
Transformer resistance (Ω)	0.05
Transformer leakage inductance (mH)	1.0
Filter resistance (Ω)	0.05
Filter inductance (mH)	10.0
Filter capacitance (μF)	86
Common dc-link capacitance (μF)	14400

8. CONCLUSIONS

This paper proposes the concept of IDVR, which is an economical approach to improve multiline power quality. The IDVR considered in this paper consists of several DVRs which are electrically far apart, connected to a common dc link. When one of the DVRs compensates voltage flicker, the other DVRs are used to replenish the dc-link stored energy. The Interline Dynamic voltage restorer is used to mitigate voltage flicker caused by sudden switching of loads. This paper presents a new IDVR topology derived from current-source inverter. The control strategy adopted to mitigate flicker plays a key role for effective mitigation. In this paper, adaptive ANN is used for generating reference control signal for PWM controller to mitigate flicker using IDVR. A Newton-Raphson based algorithm is proposed for ANN to extract flicker components. Voltage flicker can also be estimated using the output of proposed adaptive ANN. Since the controls do not include any parameter which is dependent on network condition, the performance of such controller is robust with respect to network structure, flicker location and system loading. The control structure is decentralized and does not need any coordination with other compensating devices. The structure of proposed algorithm is easy to understand, easy to implement and attractive from a view-point of engineering. The performances of proposed IDVR system and its controller were tested with simulations using Matlab / Simulink. It was observed that the IDVR compensates the disturbance caused by the sag effectively.

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