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DYNAMIC VOLTAGE RESTORER FOR EFFICIENT DETECTION AND COMPENSATION OF VOLTAGE SAG USING ANN BASED LMS AS A NEW CONTROL STRATEGY

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Abstract

Nowadays, innovations in the world of electrical and electronics exponentially increase sensitivity of electronic devices and control systems in daily use. Sensitivity of the devices and more dependency of industries on power systems make them more vulnerable to power quality issues such as voltage sags, spikes, interruptions, harmonics, power factor, and voltage and current unbalances. These power quality problems can lead the whole power systems towards malfunctioning, interruptions or in severe cases can damage the whole system. Whereas by IEEE reports, voltage sags are found to be most crucial and common power quality issue among all other power quality problems. Dynamic Voltage Restorer (DVR) is a cost effective, flexible and efficient compensating device for voltage related issues especially for voltage sags. This paper proposes an Artificial Neural Network (ANN) based on Least Mean Square Estimation Method (LMS) control system strategy; for detection and compensation of voltage sag with faster response time and accuracy for DVR. The proposed DVR is implemented in MATLAB-SIMULINK and tested under different power quality problems such as balanced and unbalanced voltage sags, swells and also for compensation of limited harmonics contamination with frequency shift. The achieved results validated the efficiency and performance of the system and further analysed in comparison with previous research works.

Keywords: Custom power devices (CPD), Voltage sag, Power quality.

1. Introduction

Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage. Among growing concerns of power quality mainly

Nomenclatures

n	Number of samples of voltage componen
$p.u.$	Per unit
$Vinj$	Injection voltage
V_{est}	Estimated voltage signal
V_{load}	Load voltage
V_S	Source voltage
V_{sag}	Sag voltage
V_{out}	Load voltage after compensation
W	Weight matrix
W-H	Widrow-Hoff (W-H) weights-updating algorithm
Y	Sine and cosine vector

Greek Symbols

$\propto$	Learning rate
Δt	Sampling time
ω	Fundamental frequency
ω_{1n}	Amplitude of sine
ω_{2n}	Amplitude of cosine

include voltage sags, swells and voltage imbalances, which may affect the operational ability of the power systems and can cause system destruction and malfunctioning. As a result of these vulnerabilities in power quality, most industrial and commercial facilities are at threat about their safety; that has compelled them to invest a lot on research and development of sophisticated equipment for compensation of power quality issues [1].

Recent research works have concluded that voltage sags are the most apparent and crucial power quality events which commonly take place, while approximately 85% of all power quality problems are attributed to the faulty connections which include mainly voltage sags and swells and interruptions. These can be originated in number of ways and may pose different impacts on power systems depending on the nature of sensitive load and origin of power quality problem [2]. According to IEEE standard; voltage sag is an abrupt decrease in nominal voltage from 0.1 and 0.9 p.u. which may remain for the duration of half a cycle to less than a minute [3].

A power system fault is a distinctive reason for the generation of voltage sag. Power faults typically occur in Extra High Voltage transmission lines (EHV), sub High Voltage transmission lines (HV), Medium Voltage (MV), and Low Voltage (LV) systems and voltage sag propagates throughout the power system. Furthermore, the proliferation of non-linear sensitive loads with large rated power has increased the contamination level of voltages and currents waveforms in transmission lines. Forcing to improve the compensation characteristics is required to satisfy more stringent harmonics standards [4].

In the past research works and those which are still in progress, are purposely to overcome and compensate the power quality issues for more efficient and optimized used of available energy resources and also for the safety and protection of the power systems from any sort of voltage and current related faults

[5]. These efforts have resulted in the creation of active power filters [6], passive filters [7], hybrid filters [8], Flexible Distribution Generation (FDG) [9] and custom power devices [10] for compensation and improvement of power quality problems. Under custom power devices, Dynamic Voltage Restorer (DVR) is among preferable one due to its cost effective, flexible and efficient compensating ability [11].

For voltage sag detection in DVR, different algorithms have been explored such as Adaptive Linear combiner (ADALINE), Fast Fourier Transform (FFT), Fuzzy Logic (FL), Kalman Filter (KF), and space vector pulse width modulation (SPVWM) [11, 12].

This paper presents a new optimized approach for DVR control system which can provide better response time and optimized compensation of voltage sag. Artificial neural network (ANN) based on Least Mean Square (LMS) estimation method, also known as Delta rule or Widrow-Hoff (W-H) weight updated algorithm, is used for detection of voltage sag and generation of compensation signal. ANN has a flexible, adaptive and self-organizing capability which empowers it with better accuracy and precise detection of voltage sag by interpolation using its inherited ability of self-learning in comparison with fuzzy logic controllers (FL) and space vector pulse width modulation (SVPWM). In fuzzy logic specifically, it requires complex calculation and mathematical work for more accurate performance [13, 14].

2. Custom Power Devices

Custom Power Devices (CPD) are generic power devices meant to be for the customer or group of customer for compensation of current and voltage related to power quality problems. Custom power devices can be categorized into two main classes; network configuring type and compensating type. The network configuring type devices are used for power quality enhancement in power system networks such as Solid State Current Limiter (SSCL), Solid State Circuit Breaker (SSCB) and Solid State Transfer Switch (SSTS) [1].The compensating type devices are mainly used for active filtering of current harmonics, load balancing, power factor correction and voltage regulation. The compensating devices are of three types such as Distribution Static Compensator (DSTATCOM) [15], dynamic voltage restorer (DVR) [4] and Unified Power Quality Conditioner (UPQC) [16], however, DVR is the most preferred and flexible compensating device for its cost effectiveness and performance in compensation of voltage related issues especially voltage sags. General configuration for CPDs can be seen in Fig. 1.

DSTATCOM is a custom power device for compensation of current related power quality issues. It connects with a power system in a shunt configuration for mainly compensation of current unbalances, harmonics and power factor correction. DVR is a series type compensating device for compensation of voltage related problems, and most commonly used for voltage sags and voltage unbalances. It injects compensation voltage in phase with supply line voltage using series injection transformer. Whereas UPQC is hybrid of shunt (DSTATCOM) and series (DVR) type device for compensation of current as well as voltage related to power quality issues. Because of its configuration and hybrid capability, it is very expensive and complex for implementation in distribution networks on a large scale [17].

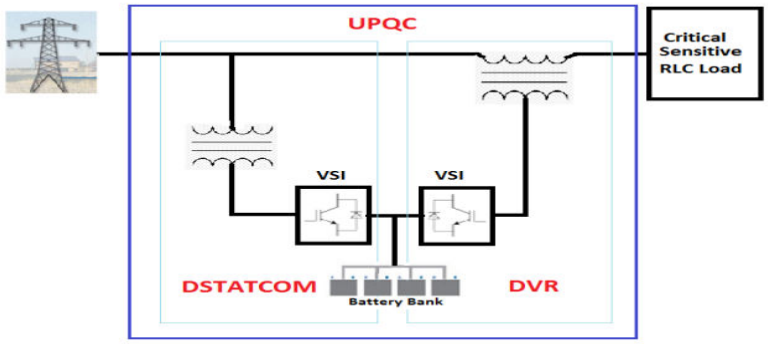

Fig. 1. Configuration of DVR, DSTATCOM and UPQC in the Power Distribution System.

3. Proposed Control Strategy for Dynamic Voltage Restorer

Dynamic voltage restorer is a series compensator which delivers technical and economical advanced mitigation solution for compensation of voltage sag. DVR is very attractive compensating device because of its fast dynamic response in detection and compensation of voltage sag. It is considered as a one of the most efficient and effective mitigation devices for use in power distribution networks. DVR injects a dynamically controlled voltage ($Vinj$) into the system through a series injection transformer by using active power from energy storage. The general structure of a DVR comprises three main parts, the Voltage Source Inverter (VSI), control system unit and voltage in the energy storage bank (VDC) for active compensation of voltage sag. The proposed configuration of DVR is given in Fig. 2.

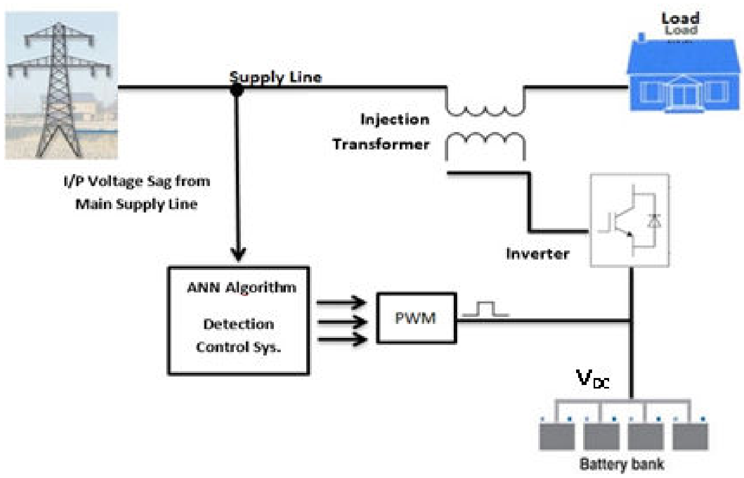

Fig. 2. Proposed Configuration of DVR.

ANN based Least Mean Square Estimation Method (LMS) is used for the detection of voltage sag. LMS is an advanced online estimation and real time detection technique used for minimizing square estimation and it is also known as

Delta rule or Widrow-Hoff (W-H) weight updated algorithm. ANN with W-H algorithm for minimizing error estimation is its flexibility with learning rate for quick detection of voltage sag.

For detection of voltage sag, line voltage can be measured using voltage sensors where it can be defined as a fundamental component of voltage signal in proportion with supply voltage $V_S(k)$ in the form sine and cosine as follows

$$V_S(k) = \sum_{n=1,2,3,4,....}^{N}[\omega_{1n}\sin(n\omega k\Delta t) + \omega_{2n}\cos(n\omega k\Delta t)] \\ = \omega_{11}\sin(\omega k\Delta t) + \omega_{21}\cos(\omega k\Delta t)] + \\ \sum_{n=2,3,4,....}^{N}[\omega_{1n}\sin(n\omega k\Delta t) + \omega_{2n}\cos(n\omega k\Delta t)] \tag{1}$$

where,

$\omega = 2\pi f$,
$\Delta t =$ sampling time,
$n =$ number of samples of voltage component, and
$f =$ fundamental frequency of the supply line.

ω_{1n} and ω_{2n} are amplitudes of sine and cosine components of the measured power supply line voltage and k represents each sample operation for detection of voltage sags. For detection of voltage sag, it is a change in nominal value of voltage value, and voltage sample amplitude of every cycle is sufficient to detect voltage sag by subtracting measured supply voltage with the estimated voltage signal. As the main idea for measuring voltage sag V_{sag} is the difference between amplitude of supply voltage V_s with the estimated voltage signal V_{est}, thus

$$V_{sag} = V_S - V_{est} \tag{2}$$

As the voltage sag can be defined as,

$$0.1\,p.u. < V_{sag} < 0.9\,p.u. \tag{3}$$

If the measured V_{sag} from Eq. (2) satisfies the condition in Eq. (3), then the detected V_{sag} will generate compensating signal using PWM which will be fed to Voltage Source Inverter (VSI) for supplying injection voltage V_{inj} in the main supply line connected to power system load using injection transformer as in below:

$$V_{load} = V_S + V_{sag} \tag{4}$$

Before injection transformer, a passive filter is used to compensate high frequency harmonics generated from IGBTs in VSI. At the end, the compensated voltage is being injected in phase with supply voltage with high efficiency, quick response time and accuracy.

4. Simulation Results

The proposed control strategy for DVR is implemented in MATLAB-Simulink for single phase balanced and unbalanced voltage sags. The results are validated by comparing with previous research works. Single phase DVR uses ANN based LMS technique control strategy for detection of voltage sag. Whereas PWM is used to generate switching signal for voltage source inverter to inject compensating voltage in the power supply line. The parameters of the system are given in Table 1.

Table 1. Parameters for Proposed DVR.

Parameter	Value
Configuration Type	Series Type
Supply Voltage	230 V_{rms}
Frequency	50 Hz
DC Bus V_{DC}	400 V
Sampling Frequency	30 kHz
Switching Device	IGBT
Limiting Inductor	70 mH
Capacitor	5 μF
THD Limit	< 3%

Balanced voltage sag is applied for 0.8 p.u. from 0.12 s to 0.14 s and 0.5 p.u. from 0.14 s to 0.20 s. Figure 3 shows compensation of balanced voltage sags using proposed DVR in which V_s is source voltage, V_{Inj} is injected voltage and V_{out} is load voltage after compensation whereas Fig. 4 validates the efficiency of the proposed control system as measured THD is 0.85% which is less than the limit allowed by IEEE of 3%. In Fig. 3, vertical axis represents voltage and horizontal axis represents time in seconds. Secondly, variable unbalanced voltage sags are injected into the system at 0.12 s to 0.20 s whereas 30% of p.u. value voltage is added with contaminated harmonics from 0.14 s to 0.18 s. The proposed DVR successfully mitigates the unbalanced as well as injected harmonics with quick response and accurate injection of compensation voltage as shown in Fig. 5. Vertical axis represents voltage and horizontal axis represents time in seconds. Measured THD is 1.48% with response time of less than 1 ms as shown in Figs. 5 and 6.

The main advantage of using ANN with W-H algorithm for minimizing error estimation is its flexibility with learning rate for quick detection of voltage sag. Learning rate ∝ plays a key role in detection of voltage sag. It varies from 0 to 1, and when it is higher, the response is quicker but with less accuracy.

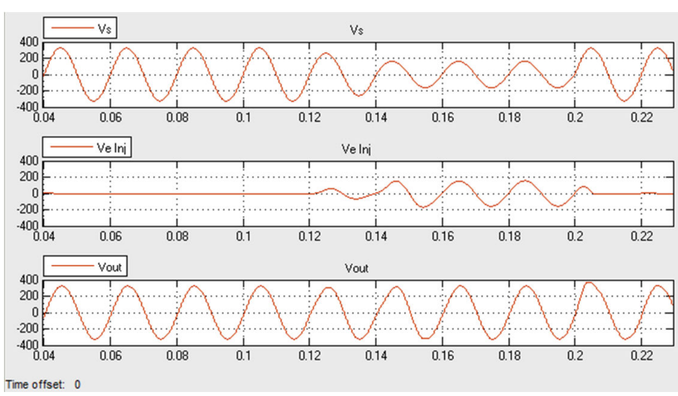

Fig. 1. Balanced Voltage Sag Compensation.

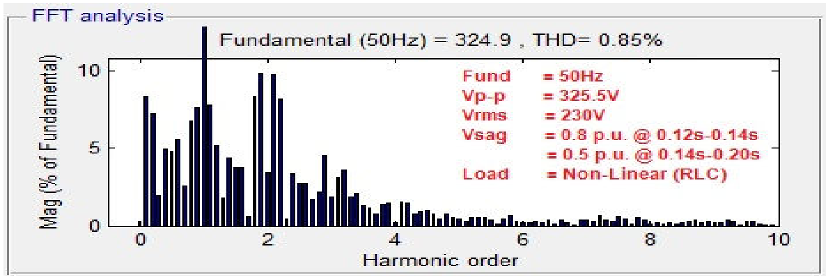

Fig. 4. THD for Balanced Voltage Sag Compensation.

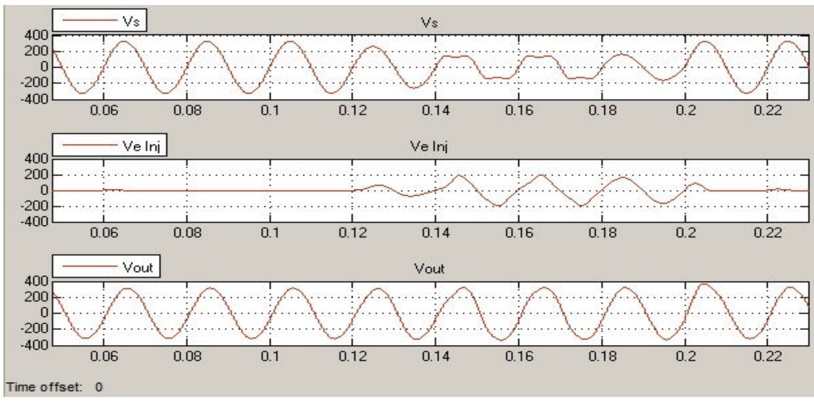

Fig. 5. Unbalanced Voltage Sag Compensation.

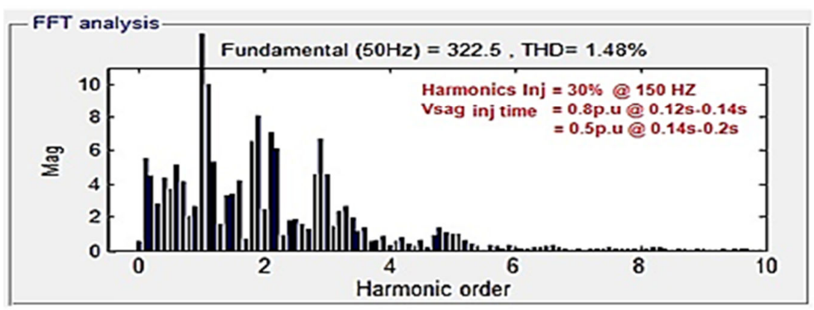

Fig. 6. THD for Unbalanced Voltage Sag Compensation.

W-H weight algorithm is implemented for weight updating in fundamental component of $\sin(n\omega k\Delta t)$ and $\cos(n\omega k\Delta t)$ using below Eq. (1)

$$\bar{W}(k+1) = \bar{W}(k) + \frac{\alpha\, e(k)\bar{Y}(k)}{\bar{Y}^T(k)\bar{Y}(k)}$$
$$\bar{W}^T = [\omega_{11}\omega_{21}] \text{ and } \bar{Y} = \begin{bmatrix}\sin(n\omega k\Delta t)\\ \cos(n\omega k\Delta t)\end{bmatrix} \tag{4}$$

Table 2 shows the effectiveness of LR with response time and THD achieved by the proposed DVR.

Table 2. Learning Rate Performance.

Condition	Balanced Voltage Sag		Unbalanced Voltage Sag	
Learning Rate (LR)	**Response Time (ms)**	**THD (%)**	**Response Time (ms)**	**THD (%)**
0.002	3	1.21	4	1.71
0.003	3	0.90	3	1.56
0.004	3	0.81	3	1.57
0.005	2	0.89	3	1.52
0.006	2	0.78	2	1.48
0.007	2	1.02	2	1.57
0.008	2	1.23	2	1.64
0.009	2	1.33	2	1.69
0.010	2	1.41	2	1.74
0.020	2	1.75	2	2.01

5. Conclusion

The proposed DVR with its optimized new control strategy using ANN based LMS method validates its quick responsiveness of around 1 ms and compensation accuracy with optimized detection and compensation of voltage sags for single phase power system. A new modified control strategy is successfully able to detect voltage sag and PWM is used as switching technique for VSI for generating compensating signal. The designed ANN technique successfully improves the quick response of DVR and also enhances its efficiency by injecting same phase of supply voltage with minimum THD.

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