Machine Learning Techniques for Power Quality Enhancement of Power Distribution Systems with FACTS devices

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ABSTRACT

The power quality problem refers to the issues caused by the sudden rise of nonstandard voltage, current, or frequency. The problems that emerge from poor power quality due to non-linear loads are voltage sag, swell, interruptions, harmonics, and transients in distribution systems. Various compensation devices are used nowadays to improve power quality. The advances in power electronic technologies improve the reliability and functionality of power electronic based controllers, resulting in increased applications of FACTS devices like DSTATCOM and Dynamic Voltage Restorer (DVR) which are fast, flexible, and efficient solutions to the power quality problems. These devices are used to restore the source, load voltage, and current disturbances caused by different loads and faults. These devices were tested in a standard IEEE 14-bus system for Total Harmonic Distortion (THD) minimization while utilizing PI-based Artificial Neural Networks (ANNs) and Linear Regression (LR). The results were analyzed and compared.

Keywords-power quality; FACTS devices; types of faults; IEEE 14 bus system; linear load; non-linear load; THD; ANN; linear regression

I. INTRODUCTION

Power quality is rather the quality of the voltage than that of power. A good power distribution system provides an uninterrupted flow of energy and a lossless voltage to its customers. But, in practice, the distribution systems have a number of linear (balanced and non-balanced) and nonlinear loads (diode bridge and induction motor), which affect significantly the quality of supplied power [1, 2]. Power quality disturbance can be defined as the deviation of the voltage and current from their ideal values. Faults occur at either the transmission or distribution levels and may cause voltage sags or swells in the entire system or a large part of it. Under heavy load conditions, a significant voltage drop may occur in the system, whereas under light load conditions, the voltage raises significantly, while the electrical devices are becoming more and more sensitive to power quality deviations [3, 4]. Power quality problems [5-7] have a wide range of disturbances such as voltage sags/swells, flicker, harmonics variation, impulse transient, and interruptions. Voltage sags/swells occur more frequently than any other power quality phenomenon. Sags and swells are the most important power quality problems in the power distribution system. In order to resolve these problems, various compensating devices are used, such as DSTACOM and DVR. These devices help in mitigating major power quality problems like sags and swells and other power quality problems like flickers, harmonics, transients etc. [8]. A variety of control strategies has been proposed for load voltage control using these two devices.

In DSTATCOM, reactive power compensation and voltage-control operations take place [9]. DVR includes open-loop and closed-loop load voltage-control methods, and active, reactive power compensation is conducted. The closed-loop voltage-control mode operation of the two devices is considered the best, most precise, and fast control against sudden variations in the supply voltage and the load voltage. Both compensators are used under closed-loop voltage-control mode.

In this paper, various power quality problems like voltage sags, swells, and interruptions are effectively tackled with the use of different combinations of FACTS devices like DVR and DSTATCOM in conjunction with the different types of loads [10-12]. FACTS devices are based on power electronics and are used in order to improve the control of electric power transmission systems in both steady and transient state conditions. It has been observed that, in industries, most of the conditions that can disturb the process are generated within the load area itself [13]. For example, most of the non-linear loads cause transients, which can affect the stability, quality, and reliability of the power supply. A few abnormal conditions that can disturb the healthy operation of a Transmission and Distribution (T&D) system are:

- Voltage sag: Very short time disturbance/interruption
- Voltage spike/swell: Long time disturbance/interruption
- Voltage fluctuation and unbalance: Harmonics distortion and noise.

Depending on the type of connection to the network FACTS controllers can be classified as:

- Shunt connected controllers: connected in shunt with the power system (shunt compensation).
- Series connected controllers: connected in series with the power system (series compensation).
- Combined series-series controllers connected in series with the power system.
- Combined shunt-series controllers connected in both series and shunt with the power system.

A. DSTATCOM

Among the various FACTS controllers, DSTATCOM is a shunt compensator with the capability to solve power quality problems faced by distribution systems [13]. DSTATCOM has effectively replaced the Static VAR Compensator (SVC), which requires large response time and relates to the passive filter banks and is capable for only steady state reactive power compensation. A DSTATCOM is a Voltage Source Inverter (VSI)-based FACTS controller sharing similar concepts with a STATCOM used at the transmission level [14, 15], with the difference that a STATCOM at the transmission level handles only fundamental reactive power and provides voltage support while a DSTATCOM is employed at the distribution level or at the load end for power factor improvement and voltage regulation. DSTATCOM has similar functionality with a shunt active filter, it can even work as a shunt active filter to eliminate unbalances and distortion in the source current and supply voltage [16-18].

In this paper, five control strategies were implemented to compensate the required reactive power at the load side. Phase control method has been used for the enhancement of power transmission system performance. The single line diagram of DSTATCOM is shown in Figure 1. DSTATCOM [19] consists of a DC capacitor, one or more converter modules, an L-C filter, a distribution transformer and a PWM control module as shown in Figure 1.

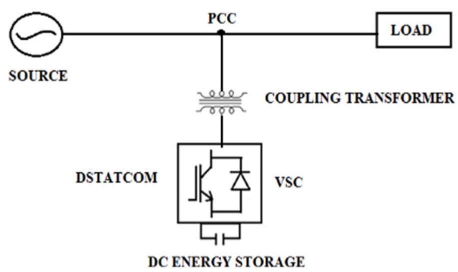

Fig. 1. Schematic diagram of DSTATCOM.

The main principles of DSTATCOM are:

- $V_i > V_M$ (DSTATCOM will supply the reactive power)
- $V_i < V_M$ (DSTATCOM will absorb the reactive power)
- $V_i = V_M$ (DSTATCOM will not exchange reactive power which is a balanced condition)

where V_i is the inverter voltage, V_M is the Point of Common Coupling (PCC) voltage, and V_s is the source voltage.

Each control algorithm calculates the compensated current to supply or absorb the reactive power. The compensated current is given by:

$$Ic = I_L = Is \quad (1)$$

where Ic is the compensated current, I_L the load current, and Is the source current.

In this configuration, the VSC is used with the DC storage capacitor. Two IGBT switches are used in one leg and three legs are connected in parallel with the DC capacitor. Interfacing of filter resistance R_f and inductance L_f are used to filter the high frequency components of the compensating current. The value of inductance L_f controls the switching frequency of the converter as shown in Figure 2.

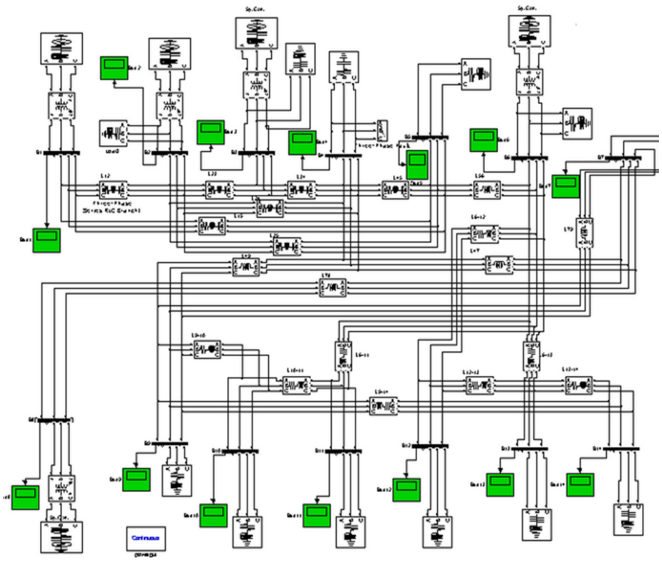

Fig. 2. Simulation model of the DSTATCOM for the IEEE 14-bus system.

B. DVR

The DVR is a static device that has seen applications in a variety of transmission and distribution systems [20-22]. It is a series compensation device, which protects sensitive electric load from power quality problems such as voltage sags, swells, unbalance, and distortion through power electronic controllers that use VSCs. Generally, it employs Gate Turn Off (GTO) thyristor solid state power electronic switches in a Pulse Width Modulated (PWM) inverter structure as shown in Figures 3 and 4.

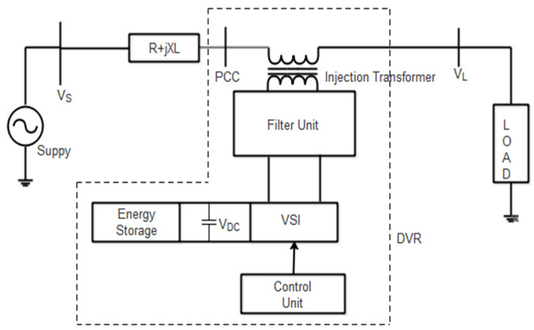

Fig. 3. Schematic diagram of the DVR.

A DVR injects a voltage in series with the system and a D-STATCOM implants current into the system to correct voltage sags, swells, and interruptions [23, 24]. Two-level and three-level MLIs with SPWM are controlled by two control strategies for THD minimization, i.e. stationary reference frame and rotating frame. For DSTATCOM and DVR with different loads, the THD is obtained with FFT analysis.

Tables I and II show the simulation results of utilizing DSTATCOM and DVR with and without load, whereas Table III shows the comparison of the performance of the utilization of DSTATCOM and DVR for both considered types of nonlinear load.

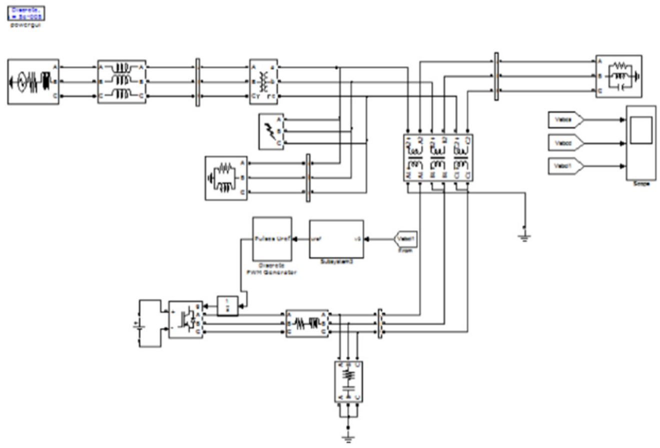

Fig. 4. Simulation model of the DVR.

TABLE I. THD RESULTS WITH DSTATCOM AND DVR WITHOUT LOAD

FACTS device (without load)	Voltages THD (%)			Avg Voltage THD (%)
	Phase a	Phase b	Phase c	
DVR	1.88	1.59	1.61	1.693
DSTATCOM	4.84	3.38	4.58	4.26

TABLE II. THD RESULTS WITH DSTATCOM AND DVR WITH LOAD

FACTS device	Type of Load	Voltage THD (%)
DSTATCOM	Linear Load - Balanced	0.28
	Linear Load - Unbalanced	0.40
	Non-Linear Load – DB	1.20
	Non- Linear Load – IM	3.6
DVR	Linear Load - Balanced	1.94
	Linear Load - Unbalanced	9.3
	Non-Linear Load – DB	13.69
	Non- Linear Load – IM	14.75

TABLE III. THD WITH DSTATCOM AND DVR

FACTS device	Type of Load	Type of MLI	Voltage THD (%)
DSTATCOM	Non-linear – diode bridge	Two-level	2.91
		Three-level	8.92
	Non-linear– induction motor	Two-level	4.25
		Three-level	6.23
DVR	Non-linear – diode bridge	Two-level	8.94
		Three-level	19.21
	Non-linear– induction motor	Two-level	14.45
		Three-level	9.44

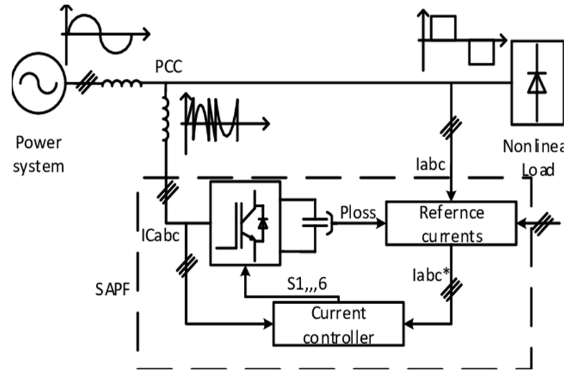

Fig. 5. Schematic diagram of a shunt active power filter.

II. MACHINE LEARNING TECHNIQUES

Electric power utilities have launched comprehensive data collection programs to evaluate the Power Quality (PQ) problems in their systems [22]. A Machine Learning (ML)-based classification and characterization of the power system data will help to deal with the voluminous quantities of the monitored data. The ML techniques considered in this paper are Artificial Neural Networks (ANNs) and Linear Regression (LR). Simulations were conducted in Matlab and the results are shown in Figures 6-8 [25-30].

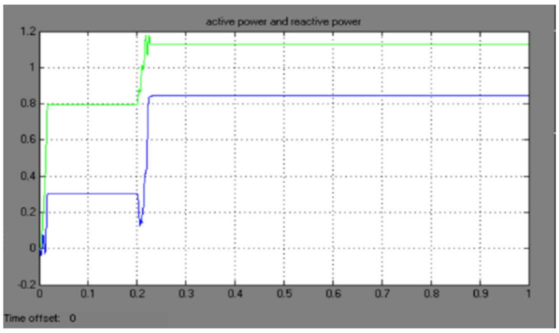

Fig. 6. Active and reactive power versus time (s).

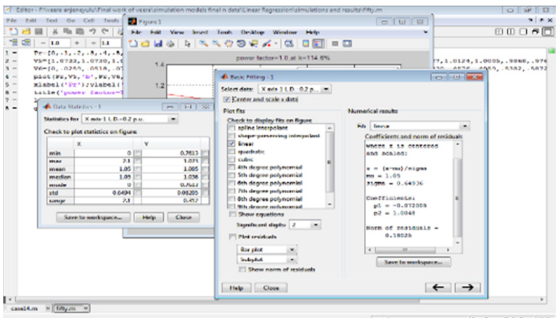

Fig. 7. ANN and LR analysis for MLP estimation.

A voltage sag occurred, at bus 14 of the IEEE 14-bus system and was mitigated by back propagation ANNs with varying number of hidden layers. Table IV shows the results, of the Mean Square Error (MSE) and Regression coefficient R (accuracy) metrics. It can be observed (Table IV) that the DSTATCOM with two-level MLI has less THD than that of the three-level MLI. Based on the simulation models and results, it is observed that the DSTATCOM device can be used for mitigating voltage sags in the IEEE standard 14-bus system. Table V shows the results, of RMSE and R metrics for basic curve and full quadratic fitting of the LR method. Table VI shows the performance comparison results of DSTATCOM DVR utilizing either ANN or LR for both considered types of nonlinear load.

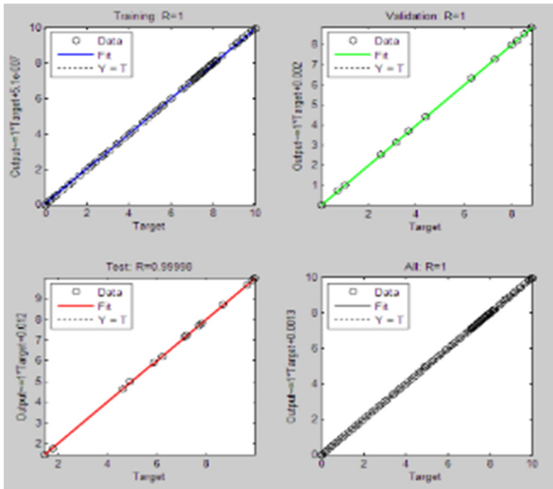

Fig. 8. MSE value comparision with ANN and LR.

TABLE IV. VOLTAGE SAG RESULTS WITH THE ANN

Hidden layers	MSE	R (Accuracy)	Voltage at bus 14 (pu)
1	$6.40e^{-6}$	0.99544	0.82
2	$3.074e^{-5}$	0.99688	0.85
5	$1.13e^{-4}$	0.99999	0.76
8	$5.45e^{-5}$	0.98088	0.78
10	$1.00e^{-5}$	0.9969	1.07
15	$4.18e^{-3}$	0.513	1.02

TABLE V. RMSE, R, AND VOLTAGE COMPARISON OF BUS 14 VARIATION WITH LR

Method		RMSE	R	Voltage at bus 14 (pu)
LR	Basic curve fitting	0.0403	0.7706	0.89
	Full quadratic	0.01952	0.9502	0.92

TABLE VI. PERFORMANCE COMPARISON

Device	Type of load	ML method	Voltage THD (%)
DSTATCOM	Non-linear – diode bridge	LR	3.45
		ANN	1.53
	Non-linear – induction motor	LR	4.4
		ANN	1.28
DVR	Non-linear – diode bridge	LR	4.36
		ANN	1.99
	Non-linear – induction motor	LR	3.98
		ANN	1.48

To maintain the present-day electrical grid network's stability, reliability, and flexibility by combing with Renewable Energy Sources (RES), energy storage devices, and loads, some type of smart control is required. The quality of power generated is adversely affected by nonlinear loads, and harmonic injections. So, maintaining controlled regulation of PQ and delivering compensation at all levels of power is a vital issue. In this regard, a meticulous survey of numerous PQ mitigation techniques such as filters, controllers, FACTS, OTs, compensators, conditioners, and ML tools for enhancing the quality of the electrical power delivered to the distribution systems has been carried out and highlighted in detail in this article.

III. CONCLUSIONS

In this paper, the IEEE standard 14 bus distribution system was studied considering different loads, different FACTS devices, and different multi-level inverters which were discussed and a comparative study among all PQ improvement techniques from technical and economic aspects was presented. A detailed study covering almost all challenges was been cited, and possible solutions in the future for hassle-free PQ improvement were suggested.

Two-level inverters have low THD and a reduced number of switches over three-level inverters for linear and non-linear loads. The performance of the PQ compensator under varying loads and non-ideal source conditions relies on the control strategy. In this paper, ML techniques were used to mitigate a voltage sag obtained at bus 14 of the IEEE standard test system. From the simulation results, it was observed that the Voltage THD the ANN system is approximately 45% less than that obtained by the full quadratic LR technique.

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