Power quality enhancement using Artificial Neural Network (ANN) based Dynamic Voltage Restorer (DVR)

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Abstract. The power quality, which can affect consumers and their utility, is a key concern of modern power system. The sensitive equipment is damaged by voltage harmonics, sag and swell. Therefore, as usage of sensitive equipment has been increasing, power quality is essential for reliable and secure operation of the power system in modern times. The potential distribution flexible AC transmission system (D-FACTS) device, a dynamic voltage restorer (DVR), is widely used to address problems with non-standard voltage in the distribution system. It induces voltages to preserve the voltage profile and ensures continuous load voltage. In this paper, the voltage sag and swell is compensated by DVR with an artificial neural network (ANN) controller. For the generation of reference voltage for voltage source converter (VSC) switching, and for the voltage conversion from rotating vectors to stationary frame, synchronous reference frame (SRF) theory is applied. The DVR Control Strategy and its performance is simulated using MATLAB software. It is also shown a detailed comparison of the ANN controller with the conventional Proportional Integral controller (PI), which showed ANN controller's superior performance with less Total Harmonic Distortion (THD).

1 Introduction

Electrical energy is a universal commodity available throughout the world and regarded as a daily consumer need [1]. The sources of renewable energies like solar, wind, etc are used to support the primary demand of energy. The intermittency of the renewable sources, reactive power issues and harmonics stop the performance of the power system by causing problems of power system stability [2], [3]. Flexible AC Transmission Systems (FACTS) devices are commonly incorporated to compensate reactive power, regulate voltage stability and improve power quality [4], [5]. FACT devices, however, also change different system parameters [6], so as to study the quality of power and determine the causes and solutions to these issues of power quality. In power systems, power quality has a major role during supply of variable power to the load. Consequently, the customers of domestic and industrial with sensitive loads will get affected by poor power quality. When any disturbance occurs in load voltage, results in voltage transient, sag, swell, harmonics causing high distortions and faults causing Total Harmonic Distortion (THD). The DVR can control the voltage from these problems and protect against tripping and resulting losses. Various problems and solutions related to DVR were reported, such as

balanced voltage in a three-phase system and energy-optimized DVR control [7]. References [8], [9] give analysis of various control strategies for different voltage sag types. In [10] a comparison is presented for DVR between various topologies and control techniques. Paper [11] discusses the design of a DVR supported by a capacitor that protects distortions, sags, swells, or imbalances in supply voltages. The DVR's performance is discussed in [12] with a transformer of high frequency-link. This paper presents DVR's control and its performance with voltage source converter (VSC). In this paper synchronous reference frame (SRF) theory with artificial neural network (ANN) controller is used for DVR control.

The DVR is designed for balancing load side voltage with minimal injection of active power, even in the event of unbalanced disturbances compensation [9], through a cascaded H-bridge multilevel inverter. The use of DVR is a cost-effective way of mitigating sensitive load voltage sags and swells. The disadvantages of the existing method are solved through the application of the Artificial Neural Network (ANN) controller. The ANN controller is used for design and simulation of DVR to improve power quality and minimize harmonic distortions in sensitive loads [9]. DVR is utilized to increase the real power of the inverter in any disturbance. The DVR can be used as a voltage sag restorer and the voltage distortion compensator with

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ANN, to decrease the harmonics and voltage sag/swell produced with zero sequence components, using the Delta connected transformer between electricity supply and booster transformer.

ANN broadly emulates animal brains, is a connection of various nodes acts as neurons, organized in different layers. Each node upon receiving information forwards to the next node, after doing necessary process. Any input is processed by all the layers generating an output. For any specific task to be performed by ANN all the nodes need to be trained with relevant data. A back propagation optimization is carried out to train a feed forward ANN and uses transfer functions in layers. The training data is summarized and randomly selected to prevent excessive training and consists of the history of

faults and possible disturbances. It is a robust ANN approach, due to its adaptive nature and its ability to be trained on all possible cases [16] – [20]. The presented work is simulated in MATLAB/Simulink software.

This paper presents Dynamic Voltage Restorer to reduce the voltage sag and swell in the distribution system by ANN controller. The synchronous reference frame (SRF) theory is used for the control of the DVR with ANN controller. The simulation results based on the MATLAB/SIMULINK model were presented here, over conventional methods, for validation of the effectiveness of the proposed ANN control method together with DVR over conventional method. Figure 1 shows the block diagram of the proposed system.

Fig. 1. Block diagram of the proposed system

Fig. 2. System configuration of a three-phase dynamic voltage restorer

2 DVR operation principle and its control

The main aim of the DVR is to reduce most of the voltage-based problems, including PCC voltage harmonics. Even for linear loads with self supporting DC-bus, the DVR supplies sinusoidal balanced voltages with the injection of required voltages between PCC and load. The DVR's objective is achieved independently or in combination in accordance with the configuration, requirements and control strategy as necessary for appropriate selection. Figure 2 shows the DVR's basic circuit for a three-phase AC system. DVR is the combination of a voltage source converter (VSC) based on IGBT and a DC bus capacitor. The VSC as a DVR estimates the reference voltages and manages the sensed voltages directly by a control algorithm near the reference voltages.

2.1 DVR operation principle

A three-phase VSC converter in series connected to 3-phase supply via three single-phase coupling transformers is included in the circuit diagram of the DVR. A DVR with a DC bus capacitor is considered to be three-phase VSC. Across each transformer, an RC filter with a small rating is connected, to remove ripples of high switching at the DVR injected voltage. In order to remove voltage harmonics across linear or non linear loads, a series filter has been installed at PCC. But if short circuit takes place in the utility line, more protection is needed for this configuration.

DVR shall be controlled directly to inject the required voltage into the supply in case of voltage sensitive loads, where voltage harmonics are eliminated and zero voltage control is maintained at PCC. Thus, the sum of the supply voltage and the voltage injected are sinusoidal across the load. The DVR is controlled as a harmonic voltage controlled source and acts as a highly valued resistor for harmonic voltages at ac mains, presenting low impedance at fundamental frequency. This satisfies the need for harmonic load voltages and prevents the harmonic voltages from flowing into the AC source.

2.2 Dynamic voltage restorer control

The main function of a DVR control algorithm is to estimate the reference voltages with feedback signals based on their applications. In PWM (pulse-width modulated) generators PWM gating signals for VSC IGBTs are obtained by the reference voltage with a corresponding sensed voltage. DVR control reference voltages must be obtained accordingly, and these signals are estimated by means of control algorithms. The different DVR control algorithms are categorized as frequency-domain and time-domain control algorithms

that are easy to modify. Here SRF is used for the estimation of signals.

2.2.1 Control algorithm for elimination of voltage harmonics

Fig.3 shows the control algorithm of DVR which uses the SRF theory for controlling a self-supported DVR. The voltages at PCC are transformed by Park's transformation into a rotating reference frame. The harmonics and the oscillating components of the voltages are removed by means of Low-Pass Filters (LPFs). The d-axis and q-axis voltage components are

$$V_{sd} = V_{dDC} + V_{dAC} \quad (1)$$

$$V_{sq} = V_{qDC} + V_{qAC} \quad (2)$$

In the compensation method, the voltage at the load end should be at rated magnitude and undistorted in nature for compensating for problems of voltage quality. The DC bus voltage of the self-supported VSC Capacitor can be maintained using the PI controller of the DVR.

The direct axis load voltage reference is therefore

$$V_d^* = V_{dDC} - V_{loss} \quad (3)$$

The load terminal voltage amplitude (VL) is controlled at its reference voltage (V*L) with another PI controller. For the voltage control across the load terminal, the output of the PI controller is the reactive voltage component (vqr).

The quadrature-axis reference load voltage is

$$V_q^* = V_{qDC} - V_{qr} \quad (4)$$

Reference loads in the abc framework .v*La, v*Lb,v*Lc. are obtained through reverse park's transformation. A PWM controller generates the gating pulse of the DVR using the errors between the sensed load voltages (vLa, vLb, vLc) and the references load voltages v*La, v*Lb, v*Lc.

3 Artificial Neural Networks (ANN)

The controller is primarily interested in quickly detecting the disruptive signal with extreme accuracy and a high interactive response to the desired DVR compensation. Under conditions of parameter change, disturbance in the load and non-linearity, etc., the traditional controller cannot operate correctly. A recent survey has shown that an ANN-based controller provides rapid dynamic responses while keeping the DVR stable over a wide range of operating conditions.

The ANN contains nonlinear elements referred as neurons which are interconnected. It generally represents a cluster of interconnected very simple nonlinear elements that have the capacity to learn and adapt. The main characteristics of neural networks are

their topology, their way of communicating with their environments, their manner of training and their capability in processing information.

A control system based on the multi-layer neural network is developed to maximize the DVR's performance characteristics. The ANN-based controller has three-layer components, one neuron input layer, 20 neurons hidden layer and one neuron output layer. In the MATLAB workspace, the data obtained from the PI controller are stored which is used for the neural network controller offline training. Here, that activation function used is TrainLM for input layer and hidden layers and pure linear for the output layer. Levenberg Marquardt back propagation (LMBP) is the used training algorithm in this study.

Fig. 3. Control scheme of a DVR for voltage harmonic elimination

The ANN controller's compensation performance is based on input and development. The configuration selected is equipped with two inputs and one output for dc link voltage reference, dc link voltage measured and a PI controller reference signal respectively. The training of neural network is done to receive a reference signal (PI controller output). To produce the necessary gating pattern, the signal received is sent to a hysteresis control.

4 SIMULATION RESULTS

MATLAB/SIMULINK is used to simulate the proposed DVR model. Two different control strategies have been simulated for the proposed system. The performance of the two controllers was simulated with MATLAB/Simulink. Fig.4 and fig.5 present the simulation results of conventional PI controller-based DVR for voltage sag and voltage swell.

Fig. 4. Source, Injected & Load Voltages of DVR for voltage sag with PI Controller

Fig. 5. Source, Injected & Load Voltages of DVR for voltage swell with PI Controller

Fig. 6. THD% of Load Voltage is 4.78%

Similarly, Fig.7 and fig.8 depict the simulated results of ANN control strategy-based DVR for voltage sag and voltage swell. The Total Harmonic Distortion (THD) analysis of DVR using both the control techniques PI and ANN are shown in fig.6 and fig.9 respectively.

Fig.4 shows the source voltage, injected voltage, and load voltage of conventional PI controller-based DVR for voltage sag. The sag occurs in between 0.2s to 0.3s which is compensated by the required injected voltage

via DVR using PI controller. The fig.5 includes the source voltage, injected voltage and load voltage of PI based DVR for voltage swell. Here the voltage swell is observed from 0.2s to 0.3s and is compensated by injecting voltage. The THD% of load voltage by PI controller method is described in Fig.6.

Fig.7 shows the source voltage, injected voltage and load voltage of ANN controller-based DVR for voltage sag. The sag occurs in between 0.2s to 0.3s which is compensated by the injected required voltage in line via DVR using ANN controller.

Fig. 7. Source, Injected & Load Voltages of DVR model for voltage sag with ANN controller

Fig. 8. Source, Injected & Load Voltages of DVR model for voltage swell with ANN controller

The fig.8 includes the source voltage, injected voltage and load voltage of ANN based DVR for voltage swell. Here the voltage swell is observed from 0.2s to 0.3s and is compensated by injecting voltage.

The THD% of load voltage by PI controller method is described in Fig.6. and Fig.9 describes an ANN controller load voltage THD%. The simulated results allow us to analyze the better performance of the ANN control scheme in comparison with conventional PI control system.

Fig. 9. THD% of Load Voltage is 1.67%

5 Conclusions

DVR has proved to be a useful and well-performing device to improve power quality. The structure and the operation of the DVR were explained. This paper proved the %THD of ANN controller is less when compared to PI controller. This paper presented the ANN application to DVR for improved performance in mitigating voltage sag and swell compared to the conventional controller. The SRF theory was used for the estimation of reference DVR voltages. The simulation of the proposed system with sensitive load is carried out using MATLAB/Simulink software. DVR performance has been shown by the simulation results during voltage disturbances. The proposed method was compared with the popular PI controller and proved to be the best option for restoring system voltage while reducing THD in the greater part.

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