A Dynamic Voltage Restorer (DVR) For Protecting Hybrid Grids

Khodakhast Nasiriani1* and Mohsen Pasandi2

1Department of Electrical Engineering, Marvdasht Azad University, Marvdasht, Iran.
2Department of Electrical Engineering, Clausthal University of Technology, Germany.

ABSTRACT

Dynamic Voltage Restorer (DVR), for some important reasons, is utilized in Power Distribution for protecting loads especially critical loads against some power quality issues like sag, swell, harmonics and faults. Fast transient response for compensating voltage quality is an unavoidable factor. Different control topologies have been applied to this device. In this project, a DVR is deployed to preserve a critical load which is connected in parallel with grid and A wind turbine. Several situations of power quality issues have been considered. The simulation results of a proposed system which has been implemented in MATLAB/Simulink show how DVR is effective for protecting loads.

Keywords: Power quality; dynamic voltage restorer; hybrid systems; interconnected systems.

1. INTRODUCTION

In line with the design and development of electronic power systems, electric power research institutions have defined the concepts of FACTS in transmission systems and Custom Power in distribution systems. Custom Power devices have the same physical arrangement as the FACTS arrangement, but their application and control are completely different with FACTS devices [1-3]. Therefore, the use of power electronic devices is introduced to improve the quality of power in distribution systems called Custom Power. Custom Power Equipment is designed to improve the reliability and quality of power or specific voltage in distribution networks [3-5].

An example of this equipment is the Dynamic Retrieval of Voltage (DVR), which has received a lot of attention in recent years and has been introduced as the best voltage recovery equipment. The factors that have created the voltage shortage is one of the issues of power quality as well as the relations related to its calculation and modification techniques in the distribution networks, are expressed mainly for several faults conditions such as three-phase balanced faults, two-phase unbalanced to ground fault and single-phase fault. The methods which
are used to compensate it are often power-based electronic devices. Some of these solutions are using SMES, D-Statcom, UPQC, and so on [5-8].

Various types of custom power equipment and their tasks and applications which includes two categories are presented. The first group is those which do not need a DC power source and are used to change the network structure. This equipment is mainly used as static breakers in the systems, and they have the role of ordinary mechanical breakers. Generally, this equipment is a subset of solid-state breakers (SSBs) or fast-disconnected semiconductor circuits. The second category includes devices that come with a DC power source and is used for compensating purposes, the most widely used are DVR, D-Statcom and UPQC [9-11]. UPQC is a series-parallel which can compensate major power quality such voltage quality (sag, swell, harmonic, and unbalance voltage), and injected harmonics by non-linear loads to the grid current. A similar application of the series-parallel topology is given in [12].

The DVR has been introduced as an appropriate device for protecting sensitive loads against disturbances in the distribution network and in terms of its application to correct the voltage shortage in the network, the voltage has been calculated by the DVR to compensate for the voltage deficiency based on the injection power [13].

Fault detection and determining signal reference are two main parts of a control system in a DVR. The fault detection part is the first step in which the voltage grid will be measured and analyzed base on the method which has been used. The harmonic and disturbances in voltage can be recognized. Several detection methods like peak measurements, RMS measurement, dq0 components, positive sequence, using Kalman filter for estimating phasor components, or Fourier Transformation have been reported in papers. In the second part, the method for determining the reference signal of series injected voltage is related to the Energy Storage Unit. Several controllers such as PI, fuzzy, Neural Networks have been used in DVR [11,12,14,15].

Renewable Energies such as wind energy have several merits and using them is increasing significantly. Several aspects like protection, stability load management, and power quality should be considered for them. Power quality issue is a very important issue for them. Sometime during the fault condition, the wind system is separated from the grid. But by using DVR, the system can be protected without separation. Forecasting is a decision-making technique employed by many to help in budgeting, planning and estimating the future. In the simplest terms, forecasting is an effort to predict future outcomes based on past events and management insight. Different types of Forecasting are widely used in business, finance, engineering, and other science. The time-series econometrics model, applying statistical methods to economic data, is commonly used in economics and business (see [16]). The time series model also used in electrical engineering to predict price, load and wind speed (see [17]).

A solar system with P&O Maximum Power Point Tracking has been used in this research for the hybrid system. Several essential aspects of the wind turbine should be investigated more. Forecasting of wind speed can play a significant role in the planning and operating of the wind turbine. The weak effect is another essential item that can be considered more [18]. DVR control strategies can be considered in three categories: an open-loop, closed-loop, and the improvement of the control strategy. Implementing an open loop is easy but it does not have enough precision. Therefore, closed-loop control can improve control precision and stability.

In this project, a DVR is used to protect a hybrid system including solar, and a constant speed wind turbine against voltage fluctuations. The DVR will keep the voltage on the busbar for load and wind systems almost constant. The simulation results of a proposed system that has been implemented in MATLAB/Simulink show how DVR is effective for protecting loads.

2. POWER QUALITY

Two of the most important problems of power quality is voltage sag and voltage swell, which are of the most important challenges faced by power distribution companies in dealing with advanced industries, and about 80% of the quality problems of the system are included. Different Standards have different definitions of voltage quality. In the IEEE-1159-1995 standard, the voltage sag is defined as: "A sudden decrease in the effective value of a voltage of 10% to 90% at a nominal frequency and within a time interval of half-cycle to 1 minute." In this definition, the voltages below 10% of the nominal voltage are considered as voltage interruption or
Fig. 1. Overview of the DVR

Voltage cottage. In the IEEE-1159-1995 standard, the voltage swell is defined as: "The sudden increase in the effective value of the voltage over 110% at the nominal frequency and in the period from half-cycle to 1 minute." If voltage swell exceeds one minute, it is overvoltage, and over-voltage of less than half a cycle is considered transient. In this definition, for both the maximum and minimum voltage, a threshold is considered. Fig. 1 illustrates the definition of deficiency and voltage overvoltage in IEEE-1159-1995 [5] Fig. 1. Definition diagram for voltage sag and swell by IEEE-1159-1995 standard [3].

3. DVR COMPONENTS

In this chapter, the DVR in terms of the structure of the circuit, its components, and how it is designed and the factors which are effective in its design are described. Fig. 1 shows the overall structure of the DVR, which includes the following units: Fig. 2. Dynamic Voltage Restorer structure

Energy Storage Unit: For low voltage sag, load voltage magnitude just by injecting reactive power can be compensated. But, for compensating deep voltage sag, in addition to reactive power injections, the injection of active power is also required.

Voltage Source Inverter (VSI): The main task of the Voltage Source Inverter (VSI) or inverter is to convert the DC voltage provided by the energy source to the AC voltage.

Passive filters: Low-Pass passive filters are used to convert the PWM pulse waveform into a sinusoidal waveform.

Voltage injection Transformers: The main task of the transformer is to increase the voltage supplied by the VSI to the desired level and isolate the DVR circuit from the distribution network.

By-Pass Switch: This switch is used to protect the inverter from high currents. When a fault occurs on the downside, the by-pass switch will be active and as a result, DVR changes the situation to By-Pass and protect (VSI) from high current.

DVR Control System: In general, the DVR control system has the following functions:
- Error detection
- Calculate and determine the voltage required for compensation
- Production of trigger pulses for VSC and serial voltage injection
- Termination of triggered pulses when the error is resolved.
- Control the security Breakers and disconnect the DVR to the network.

It is also possible to use a control system to change the DC-AC inverter to a rectifier (rectifier)
mode for charging capacitors in a DC power link in the absence of an error [2,4].

4. WIND TURBINE MODELING

Using wind energy started in the 19th century. At first it was so expensive. But today by improving technology is getting cheaper and cheaper. It can be a good replacement for fuel resources. Several kinds of generators are utilizing in wind systems as following:

1. DC Generators
2. AC Synchronous Generators
3. AC Asynchronous Generators
4. Switched Reluctance Generators

The induction generators are categorized into two categories: fixed-speed induction generators (FSIGs) (Fig. 2) with squirrel cage rotors, and doubly-fed induction generators (DFIGs) with wound rotors [19-20].

Based on the design, the rotor dimension, and other parameters the generated power can be different. The extracted power from a wind turbine can change based on below equations [21-22]:

\[ P_m = C_p P_w \]
\[ P_w = \frac{1}{2} \pi \rho R^2 V_w^3 \] \hspace{1cm} (1)

PM is mechanical power, \( P_w \) is wind power, \( \rho \) air density, \( R \) is the radius of the turbine blades, \( V_w \) wind speed, and \( C_p \) is the Performance coefficient. In this research, an induction generator for a wind generator is used. The below equations show how the generator is formulated. This model is shaped based on the DQ rotating frame without zero component.

\[
\begin{bmatrix}
\lambda_{ds} \\
\lambda_{qs} \\
\lambda_{mr} \\
\lambda_{qr}
\end{bmatrix}
=
\begin{bmatrix}
I_{ds}+I_{m} & 0 & I_{mr} & 0 \\
0 & I_{ds}+I_{m} & 0 & I_{qr} \\
I_{m} & 0 & I_{mr}+I_{m} & 0 \\
0 & I_{m} & 0 & I_{qr}+I_{m}
\end{bmatrix}
\begin{bmatrix}
I_{ds} \\
I_{qs} \\
I_{mr} \\
I_{qr}
\end{bmatrix}
\] \hspace{1cm} (2)

Below equations show that how the extended torque in the generator shaft and the angular velocity of the rotor are interrelated

\[ J_R \frac{d\omega_r}{dt} = T_g - T_{em} \] \hspace{1cm} (3)

4.1 Solar Cell Modeling

PV cell simulation includes obtaining characteristic (P-V) and (I-V) curves. The purpose of this work is to adapt the curves Characteristics of the Simulation Model with the Characteristic Curve of the actual Cell under various environmental conditions. The most common approach is to use an equivalent electrical circuit which is based on a diode model. Many models have been presented by several researchers. The simplest model is the single diode model. This model includes an independent current source, which has been connected parallel with a diode shown in Fig. 3. The mathematical equations which represent the performance of this model are expressed by [1].

![Fig. 2. fixed-speed induction generators (FSIGs)](image-url)
In this project the first method has been used. This algorithm perturbs the operating voltage to ensure maximum power. While there are several advanced and more optimized variants of this algorithm, a basic P&O MPPT algorithm is shown below.

\[ I = I_{pv} - I_D \]  \hspace{1cm} (4)

\[ I = I_{pv} - I_0 \left[ \exp \left( \frac{V}{kT} \right) \right] - 1 \]  \hspace{1cm} (5)

\[ V_T = \frac{kT}{q} * V * N_{cell} \]  \hspace{1cm} (6)

**Fig. 3. The ideal solar cell model**

**Fig. 4. Perturbation and observation (P&O)**
5. CONTROL SYSTEM

The below figure shows the circuit for the system.

![Circuit Diagram](image)

Fig 5. DVR circuit

Based on above figure, the following equation can be achieved:

\[ V_{Load} = V_{grid} - Z_{th}I_L + V_{dvr} \]  \hspace{1cm} (7)

Fig. 3 gives a view of the used control strategy for this system. The \( V_{load} \) is taken and given to a block to get a fundamental positive sequence. The taken value based on per unit will be sent to be compared with the reference value which is 1pu. The PI control will control the error to send the value to PWM. The output of PWM will be sent to the gate of VSC for controlling the system.

6. SIMULATION AND RESULTS

The below system is designed and simulated to protect the critical load and wind turbine against several voltage issues. The simulations have been done in MATLAB/Simulink environment. Table 1 shows the characteristics of the studied system.

![Simulation Diagram](image)

Fig. 7. Simulated system in MATLAB
Table 1. System characteristics

| Characteristic          | Value          |
|-------------------------|----------------|
| Voltage L_L             | 20 KV          |
| Frequency               | 50 HZ          |
| Transformer             | 20kv/400v Yg-Yg|
| Load Active Power       | 20 KW          |
| Load Reactive Power     | 15 KAR         |
| Wind turbine Voltage    | 400 V          |
| DVR filter L            | 50mh           |
| DVR filter R            | 0.005 oh       |
| DC voltage DVR          | 800            |

A. Case 1:

Fig. 9 shows applying two different stages of voltage sag 20% and 50% to the grid, respectively. Fig. 8 shows the good performance of the design DVR for two different levels of sag that are applied to the grid voltage. The simulation is designed for 1 sec. after 0.2 s a sag with 20% depth occurs. The second sag's depth occurs after 0.4 sec and it will be completed after 0.6 seconds.
B. Case 2:

To show the great performance of the modeled DVR, two various values of voltage swell are picked for utility. The simulation is designed for 1 sec. after 0.2 s a swell with 20% depth occurs. The second swell depth occurs after 0.4 sec and it will be finished after 0.6 second (see Fig. 8).

7. CONCLUSIONS

In this research, a new topology including wind and solar energy systems was presented. For protecting sensitive loads and renewable energies inverters against voltage quality issues such as voltage sag and voltage swell, Dynamic...
Voltage Restorer (DVR) as a series compensator was developed. This FACTS device solved the sag and swell problem by injecting the proper magnitude and phase to deliver a sufficient voltage to the load and inverters. The effectiveness of the proposed method was verified by simulation in the MATLAB/Simulink environment.

COMPETING INTERESTS
Authors have declared that no competing interests exist.

REFERENCES
1. Nielsen JG, Blaabjerg F, Mohan N. Control strategies for dynamic voltage restorer compensating voltage sags with phase jump. Proc. 16th Annu. IEEE Appl. Power Electron. Conf. Exp. 2001;2:1267–1273.
2. Ajaei FB, Afsharnia S, Kahrobaeean A, Farhangi S. A fast and effective control scheme for the Dynamic Voltage Restorer. IEEE Trans. Power Del. 2011;26(4):2398–2406.
3. Li JD, Choi SS, Vilathgamuwa DM. Impact of voltage phase jump on loads and its mitigation. Proc. 4th Int. Power Electron. And Motion Control Conf. 2004;3:1762–1766.
4. Sullivan MJ, Vardell T, Johnson M. Power interruption costs to industrial and commercial consumers of electricity. Proc. IEEE Ind. Commer. Power Syst. Tech. Conf. Rec. 1996;23–35.
5. Rauf AM, Khadkikar V. An enhanced voltage sag compensation scheme for dynamic voltage restorer. IEEE Trans. Ind. Electron. 2015;62(5):2683–2692.
6. Kanjiya P, Singh B, Chandra A, Al-Haddad K. SRF theory revisited to control self-supported dynamic voltage restorer (DVR) for unbalanced and nonlinear loads. IEEE Trans. Ind. 2013;49(5):2330–2340.
7. Dehnavi SD, Shahparasti M, Simab M, Mortazavi SM. Employing interface compensators to enhance the power quality in hybrid ac/dc microgrids; 2015.
8. Ebrahimzadeh E, Farhangi S, Imran-Eini H, Ajaei FB, Iravani R. Improved phasor estimation method for Dynamic Voltage Restorer applications. IEEE Trans. Power Del. 2015;30(3):1467–1477.
9. Ye J, Gooi HB, Zhang X, Wang B, Pou J. Simplified four level inverter-based dynamic voltage restorer with single dc power source. IEEE Access. 2019;7(137):461–137,471.
10. Wang B, Illindala M. Operation and control of a Dynamic Voltage Restorer using transformer coupled H-Bridge converters. IEEE Trans. Power Electron. 2006;21(4):1053–1061.
11. Babaee E, Kangarlu MF. Voltage quality improvement by a dynamic voltage restorer based on a direct three-phase converter with fictitious DC link. IET Gener. Transm. Distrib. 2011;5(8):814–823.
12. Dehnavi SD, Shayani E. Compensation of voltage disturbances in hybrid AC/DC microgrids using series converter. Ciencia e Natura. 2015;37:349.
13. Soenke Grunau, Friedrich W. Fuchs. Effect of wind-energy power injection into weak grids. Y. Zhou, D. D. Nguyen, P. C. Kjær, S. Sylors. Connecting wind power plant with weak grid –Challenges and solutions. PES. 2013;978-1-4799-1303-9/13/$31.00 ©2013 IEEE.
14. Pradhan M, Mishra MK. Dual p- q theory-based energy-optimized dynamic voltage restorer for power quality improvement in a distribution system. IEEE Transactions on Industrial Electronics. 2019;66(4):2946–2955.
15. Shirvani A. Stock returns and roughness extreme variations: A new model for monitoring 2008 market crash and 2015 flash crash. Applied Economics and Finance. 2020;7(3):78–95.
16. Taylor JW, McSharry PE, Buizza R. Wind power density forecasting using ensemble predictions and time series models. IEEE Transactions on Energy Conversion. 2009;24(3):775–782.
17. Shun-Hsien (Fred) Huang, John Schmall, Jose Conto, John Adams, Yang Zhang, Cathey Carter. Voltage control challenges on weak grids with high penetration of wind generation: ERCOT Experience, IEEE. 2012;978-1-4673-2729-9/12/$31.00.
18. Hui Ouyang, Peiqiang Li, Lin Zhu, Yuanzhao Hao, Changhong Xu, Chenguang He. Impact of large-scale wind power integration on power system transient stability. IEEE PES ISGT ASIA. 2012;1569526989
19. Morris Brenna, Federica Foiadelli, Dario Zaninelli. The impact of the wind
21. Strachan NPW, Jovicic D. Stability of a variable-speed permanent magnet wind generator with weak ac grids. IEEE Transactions on Power Delivery. 2010; 25(4):2779–2788.

22. Shariatpanah Hamid, Roohollah Fadaeinedjad, Masood Rashidinejad. A new model for PMSG-based wind turbine with yaw control. IEEE Transactions on Energy Conversion. 2013;28(4):929-937.

20. Najafi HR, Robinson F, Dastyar F, Samadi AA. Transient stability evaluation of wind farms implemented with induction generators. Universities Power Engineering Conference. UPEC. 43rd International; 2008.

generation connected to weak grids.