Modeling and Performance Analysis of a DVR for Non-Linear Load

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ABSTRACT

Dynamic voltage restorer (DVR) can provide the most commercial solution to mitigate voltage sag by injecting voltage as well as power into the system. This paper describes the effectiveness of using dynamic voltage restorers (DVRs) in order to mitigate voltage sags in power distribution systems at critical loads. The DVR is a power electronic based device that provides three-phase controllable voltage source, whose voltage vector(magnitude and angle) adds to the source voltage during sag event, to restore the load voltage to pre-sag conditions. The DVR can restore the load voltage within few milliseconds. A control technique based on a proportional–integral (PI) controller and a selective controller is used. The controller is designed in asynchronously-rotating reference frame. In fact, three independent controllers (homo polar component, d-axis component and q-axis component) have been used to tackle balanced and unbalanced voltage supplies. Simulation results using Simulink' Sim Power System Toolbox is presented to illustrate the principle and performance of a DVR operation in load voltage compensation.

Keyword : - *FACTS, DVR, DQ transformation, power quality, voltage sags*

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1. INTRODUCTION

At the present, with the increasing demand for electrical energy and rapidly growing number of new production technologies, the voltage quality requirements are becoming stricter. In order to evaluate the level of power quality, STN EN 50160 standard was introduced, which stipulates the limits for voltage quality [1].

1.1. Voltage quality in electrical power system

The most severe power quality problems are voltage sags, swells, interruption, harmonics and flickers [2]. Failures due to such disturbances cause a huge impact on production cost. Especially, modern industrial equipment is more susceptible to power quality problems. STNEN 50160 defines a voltage sag as a short term reduction in voltage magnitude to a value in the range 5 to 90% of the supply voltage. A voltage sag means that the required energy is not being delivered to the load and this can have serious consequences depending on the type of load involved. Reference [2] defines power quality problems as follows: computers or other electronics damage, lights dim and flickers, loss of synchronization of processing equipment, motors or other process equipment malfunctions, transformers and cables overheating, problems with power factor correction equipment, noise interference to telecommunication lines and many more. Since the whole electrical power network represents a very complex structure, there is no way to control it without any faults and disturbances. Thus, companies are often forced to save its facilities on their own. One of the options for power quality and system stability improvement is to introduce FACTS devices [3].

1.2. FACTS controllers

FACTS (*Flexible Alternating Current Transmission systems*) are alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability [4].

The major advantages of FACTS are [5]:

- power lines transmission capabilities improvement,

- power flow control,
- static and dynamic stability enhancement,
- secure interconnections between neighboring utilities.

FACTS controllers are able to control and regulate one or several key parameters in power transmission, such as current, voltage, active, reactive power, frequency or phase angle. Reference [5] divides FACTS into four basic types – series connected, shunt connected, combined series-series and combined series-shunt controllers. The main disadvantage of implementing FACTS is very a high price of these devices and economic requirements. The series controller can be a variable impedance, such as capacitor and reactor, or a power electronics based variable voltage source. In general, all series controllers inject voltage in series with the line. They are able to compensate voltage sags or swells and eliminate harmonic distortion as well. These are static synchronous series controller (SSSC), thyristor-controlled series capacitor (TCSC) or dynamic voltage restorer (DVR). As in the case of series controllers, the shunt controllers may be variable impedance, variable source, or a combination of these. In basic principle, all shunt controllers inject current into the system at the point of connection. These are static thyristor controlled reactor (TCR), synchronous controller (STATCOM) or static var compensator (SVC). Combined series-shunt controllers are the most flexible and sophisticated FACTS devices. They are able to regulate and affect many different parameters at the same time. One of these devices is unified power flow controller (UPFC).

2. DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer (DVR) belongs to series connected FACTS controllers. The primary function of a DVR is to compensate voltage sags and swells but it can also perform tasks such as harmonics elimination, reduction of voltage transients and fault current limitation [6]. DVR is usually installed between a source and a critical load that should be protected. Even the shortest voltage sag can cause serious equipment damage, interruption of production cycles and thus financial losses as well.

In general a DVR consists of three parts (Fig. 1.):

- measuring unit
- control
- power circuit

The measuring unit provides voltage and current measurements. The outputs are voltage and current analog signals (*u*, *i*), which enter the control unit. The control unit converts these signals to their digital representation using A/D converter so that they can be processed by a microprocessor (DSP – *digital signal microprocessor*). Next part is a voltage sags detection algorithm followed by compensating voltage calculation *U_com*, which is the voltage needed to be injected into the system in order to remain the load side voltage of purely sinusoidal waveform. Power section consists of a voltage source converter (VSC) equipped with a LC filter to smooth the output voltage, a DC energy storage and an injection transformer (TR) – *booster*.

The basic principle of DVR function is to inject or draw the compensating voltage *U_inj* to or from the supply voltage *U_s* in order to mitigate voltage sags or swells on the load side *U_load*. At every moment the control algorithm compares desired voltage and actual measured voltage. The difference between these two signals is considered as a compensating voltage signal (control signal) *U_com*, which is directly proportional to compensating voltage *U_inj* (power circuit). *U_com* is a digital input signal for a pulse width modulation (PWM) to control the voltage source converter. The VSC converts DC energy stored in an energy storage device (such as batteries or supercapacitors) to injecting AC voltage that is to be superimposed to the source voltage. DVR power output depends on the amount of energy that can be stored in the energy storage unit.

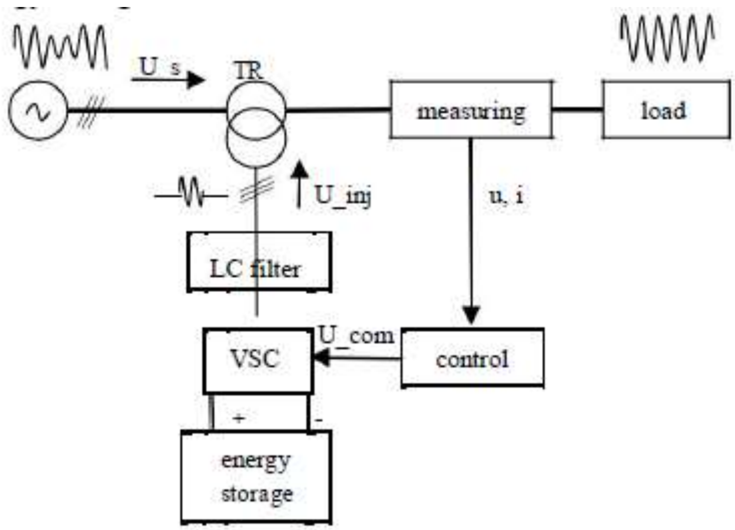

Fig. 1 Simplified Scheme of DVR

DVRs are normally installed to protect large electrical energy consumers with the sensitive technologies and devices (2 MVA or more) connected at distribution voltage [9].

3. VOLTAGE SAGS DETECTION METHODS

One of the most important requirements for DVR is that the controller should be able to operate in real-time manner. It means that the whole compensating process is carried out immediately, after a failure occurs, without any delay. The very important factor that influences the DVR speed most is the reaction time of the implemented voltage sag detection algorithm. The best DVR systems are able to react within 1 ms.

There are several voltage sags detection techniques, which can be used in DVRs, such as:

- peak value method,
- missing voltage method,
- RMS method,
- discrete Fourier transformation,
- DQ transformation,
- Hybrid methods.

In this paper the modeling of a DVR is proposed. Its control algorithm is based on DQ transformation. DQ transformation (dq0 – *direct-quadrature -zero*) is a mathematical transformation used to simplify the analysis of three-phase circuits [8]. d and q quantities represent rectangular two axis system, which rotates with angular frequency ω [7]. In the case of symmetric three-phase system, introducing of the dq0 transformation reduces three AC quantities (pu) to two DC quantities (d=1, q=0) . Any deviations from the steady state condition in abc system reflect in changes of dq0 values in real-time. For unbalanced and asymmetric three phase system applies d≠0, q≠0, 0≠0. According to this presumption it is possible to obtain the difference between desired and instant values dynamically. Therefore, the output compensating voltage can be controlled by PID regulators [3]. The resultant signal is converted back to abc values. DQ transformation can be applied in the case of three-phase system and there is a phase-locked loop (PLL) required to lock the synchronization of the compensating voltage in phase with the line voltage before the fault.

4. SIMULATION MODEL OF A DVR IN SIMULINK

In order to confirm the correct function of the proposed control algorithm it was necessary to create simulation model. For this purpose Simulink was used. The model is presented in Fig. 2. It consists of a *0.38 kV electrical source*, which represents a 0.38 kV distribution network, a *power line*, a distribution transformer (*TR 1*) which feds the sensitive load. There is DVR connected to the line right before the load that is protected. The different faults are generated by the block "*fault*". The variable *U_bef* is the voltage which is measured before the point of connection of the DVR and voltage *U_load* is the load side voltage that is measured at the load terminals. The lower part of the simulation model is DVR. It consists of measuring unit (*U_load*), control and power unit (voltage source converter, LC filter, series transformer and energy storage). When DVR is idle, the energy storage device is being recharged. The maximum amount of energy stored at the rated voltage 380 V.

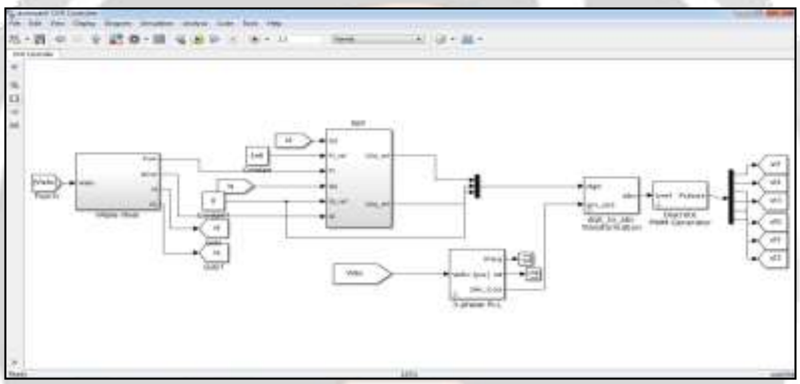

Fig.2 Proposed control scheme in Simulink

Fig. 2 shows the proposed control algorithm that is used for DVR automatic regulation of compensating voltage. It starts with measured three-phase load voltage U_load. These values are transformed to dq0 system and they are compared with references values. The difference enters PID regulator. PID controller regulates compensating voltage U_com, which is transformed back to abc system and the resultant voltage is sent to PWM module. And thus VSC is controlled by means of IGBTs' switching pulses.

5. SIMULATION RESULTS

The simulation model of DVR is designed to mitigate voltage sags and phase angle changes as well. It implements compensation method *pre-sag* which means that DVR is able to correct phase angle changes during a fault. Phase angle of voltage waveform is kept constant at the value as it was before the sag. Many different simulations with various types of sags have been tested.

5.1. Three-phase sag

First of all, three-phase sag mitigation is presented. Fig. 4 illustrates three different pictures. First waveform depicts the voltage before DVR (*U_bef*), the second one is compensating voltage *U_com* and the third one shows load voltage *U_load*.

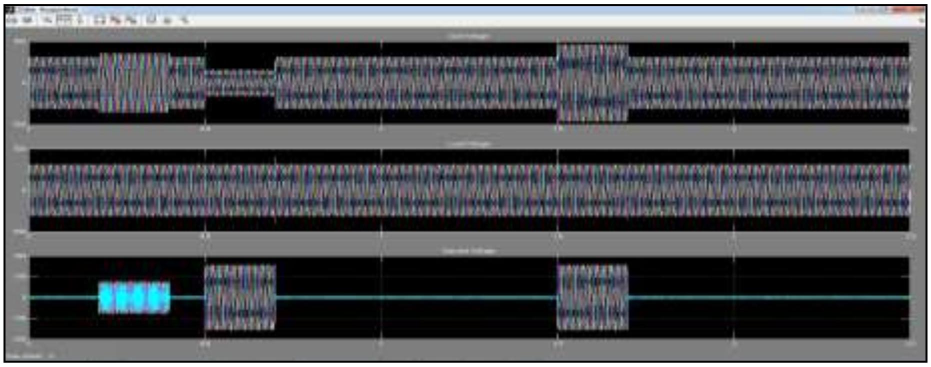

Fig.3 DVR output, Load side Wave

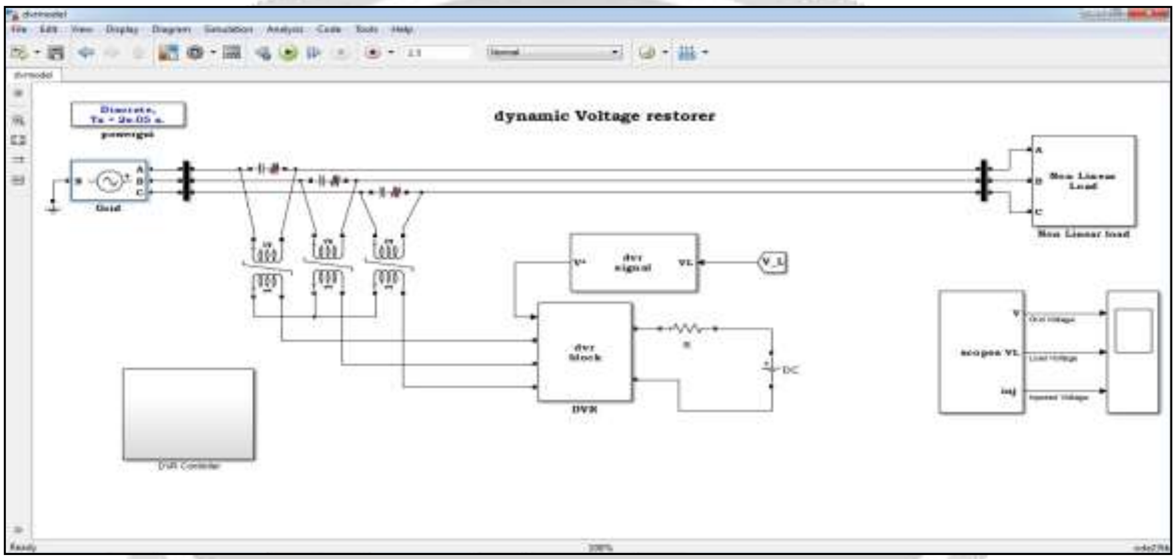

Fig. 4 Proposed MATLAB Model of DVR

6. CONCLUSION

To sum up, the presented DVR simulation model is based on a DQ transformation control algorithm. The main advantages of this control technique are high speed, simplicity and it can be used even during distorted supply voltage waveform. On the other hand the disadvantages are that DQ transformation can be only applied on a three phase system and a reference sinusoidal signal is required (PLL) synchronized with the voltage before the fault. The entire DVR model was created in Matlab/Simulink and its correct function was verified by several simulation tests. The obtained results showed that, the proposed DVR mitigates voltage sags and harmonics very fast and reliably. Many other parameters and conditions influence the DVR operation. They are: sampling frequency, speed of the regulators, dynamic behavior of energy storage device, converter switching speed

and the type of the disturbance. The right choice of a reliable voltage sag detection method and a proper design of the whole system is the very first step in the developing of a DVR. Thus, the proposed simulation model can support the next research in the field.

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