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Article

Multifunctional Dynamic Voltage Restorer for Power Quality Improvement

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Abstract: Power quality is a major concern in electrical power systems. The power quality disturbances such as sags, swells, harmonic distortion and other interruptions have impact on the electrical devices and machines and in severe cases can cause serious damages. Therefore it is required to recognize and compensate all types of disturbances at an earliest to ensure normal and efficient operation of the power system. To solve these problems, many types of power devices are used. At the present time, one of those devices, Dynamic Voltage Restorer (DVR) is the most efficient and effective device used in power distribution system. In this paper, design and modeling of a new structure of multifunctional DVR for voltage correction is presented. The performance of the device under different conditions such as voltage swell, voltage sag due to symmetrical and unsymmetrical short circuit, starting of motors, and voltage distortion are described. Simulation result shows the superior capability of proposed DVR to improve power quality under different operating conditions. The proposed new DVR controller is able to detect the voltage disturbances and control the converter to inject appropriate voltages independently for each phase and compensate to load voltage through three single- phase transformers.

Keywords: compensation techniques; dynamic voltage restore; harmonic distortion; power quality; short circuit; voltage sag; voltage swell

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1. Introduction

With the increasing amount of sensitive devices (power electronic devices) that are quite sensitive to power quality disturbances in the supply network, the problem of compensation of power quality disturbances is ever increasing. Power quality disturbances are categorized into voltage sags, voltage swells, transients, harmonics, interruptions. It can cause many technical problems (such as extra heating, mis-operation, early aging of the devices etc.) and financial losses to the power system operators and the customers. There are different ways for improvement of power quality such as Distribution STATic synchronous COMpensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Active Filter (AF), Unified Power Quality Conditioner (UPQC), etc. Among these, the DVR is one of the most effective and cost-efficient devices, which can used in power distribution system.

Using DVR in the distribution system for power quality improvement has been analyzed and proposed through many publications [1]-[18]. However, these research consider the solution for each case, for example for mitigating voltage sags due to starting motors [9], or short circuits [4], [5], [6], [13], mitigating balanced voltage sags and swells [6], compensating fluctuations and distortions of voltage [2]. In this paper, the DVR is used for power quality improvement of any type (multifunctional DVR), providing the solution for all cases above. The detailed configuration of DVR is described in Section 3, and the multi-loop controller using PI (Proportional- Integral) controller

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developed on the rotating coordinate system is presented in Section 4. A multifunctional DVR is modeled using MATLAB-Simulink and tested for voltage swell, voltage sag due to starting motor, symmetrical and unsymmetrical short-circuit and voltage distortions. Simulation results show the capability of the DVR to control the fault and disturbance conditions of the distribution system.

2. Most Common Power Quality Problems

Although the problems described in this section are well known, for the sake of completeness, we review shortly here the fundamentals of power quality problems. Power quality can be defined as the ability of the power system to provide their customers with an uninterrupted flow of energy at ideal sinusoidal waveform. Various power quality problems can be categorized as voltage sags, swells, harmonics, transients, interruption considered are the most common power quality problems in electrical distribution systems. Common Power quality problems are described briefly below, following [2], [14], [15].

Voltage sag or a dip is short duration reduction of amplitude, it occurs when the RMS of voltage decreases between 10 to 90 percent of nominal voltage for one-half cycle to one minute. It is one of most frequent disturbance in the distribution system. It is caused by faults in the power system, transformer energizing or by the starting of a large induction motors, among other causes..

Voltage swell is the opposite to voltage sag, it happens when the RMS of voltage increases between 10 to 80 percent of nominal voltage for one-half cycle to one minute. It is not as common as voltage sag. The main causes for voltage swells are switching of large capacitors or start/stop of heavy loads, among other causes.

Interruption is defined as a reduction in voltage or current to less than 10 percent of nominal, not exceeding 60 seconds in length. Sustained interruption happen when the supply voltage or current falls to zero for more than 1 minute. These are the result of faults, equipment failure, control malfunction or improper breaker tripping.

Harmonics are the waves with frequencies that are the integral multiple of the frequency of reference wave (at which supply system is designed to operate).

Transient is defined as a short duration surge of electrical energy in power system caused by a sudden change of state. There are two types of transients: impulse and oscillatory. The main causes for harmonic distortion are rectifiers and, in general, all non -linear loads.

3. Multifunctional Dynamic Voltage Restorer

3.1. Configuration and components

The DVR is a power-electronic-converter-based device capable of protecting sensitive loads from most supply-side disturbances [11]. A DVR is installed in a distribution system between the supply and a sensitive load feeder at the so-called point of common coupling (PCC). Its primary function is to rapidly inject/absorb additional energy in the system in order to avoid any power disruption to that load event of disturbances in the system. The general structure of a DVR consists of a booster transformer, a harmonic filter, a voltage source converter (VSC), and an energy storage (Fig. 1).

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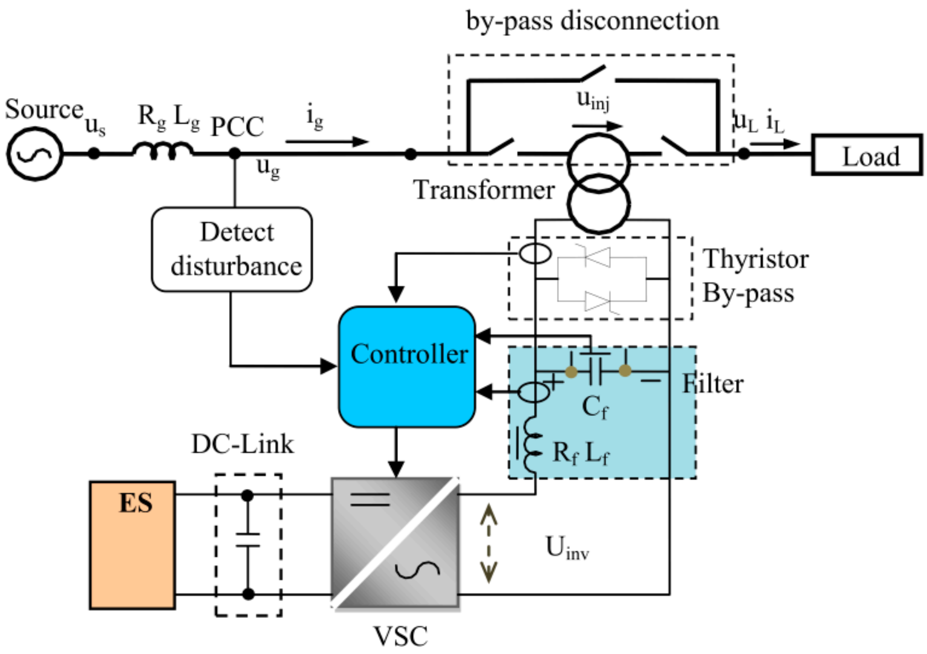

Figure 1. Configuration of DVR in the Power Distribution System.

3.1.1. Injection/booster Transformer

The injected voltage is supplied into the distribution system through an injection transformer. It connects the DVR to the distribution system via HV- winding and transforms the injected compensating voltage generated by the Voltage Source Converter (VSC) to the supply voltage after the detection of any disturbance by the controller. In addition, the injection transformer serves the purpose of isolating the DVR circuit from the system. For compensating unbalanced voltage sags, three single-phase transformers can be used, however, this increases the size and cost of the DVR. To select a suitable injection transformer into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short–circuit impedance values of transformers are required.

3.1.2. Harmonic Filter

The main task of the harmonic filter is to keep the harmonic voltage content generated by the VSC at the permissible level. The filter is placed to damp the switching harmonics generated by the PWM control of VSC.

3.1.3. DC- link and Energy Storage Unit

The main function of these energy storage units is to provide the desired real power during the voltage sag. Two types of systems are considered; the first where energy is taken from the incoming supply through a shunt converter, and the second where energy storage devices such as flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors are used [3]. The energy storage devices have the advantage of fast response.

3.1.4. The Voltage Source converter

A VSC is a power electronic system that consists of a storage device and switching devices, which converts the dc voltage from the energy storage unit to a controllable three phase ac voltage. The inverter switches are normally fired using a sinusoidal Pulse Width Modulation (PWM) scheme. In multifunctional DVR, the VSC can be operated with unbalanced switching functions for three phases, and deal with each phase independently. Normally the VSC is not only used for voltage sag/swell compensation, but also for other power quality issues, e.g. flicker and harmonics [3].

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3.2. Compensation Techniques

For the proposed DVR, the pre-sag compensation method is chosen because it is the best compensation strategy to restore controlled pre-sag magnitude without phase change. The magnitude and the angle of the injected voltage are

$$\left|V_{inj}\right| = \sqrt{V_L^2 + V_S^2 - 2V_L V_S \cos(\theta_L - \theta_S)} \quad (1)$$

$$\theta_{inj} = \tan^{-1}\left(\frac{V_L \sin\theta_L - V_S \sin\theta_S}{V_L \cos\theta_L - V_S \cos\theta_S}\right) \quad (2)$$

However, the disadvantage of this method is that the injected active power is not controlled so high capacity energy storage is required.

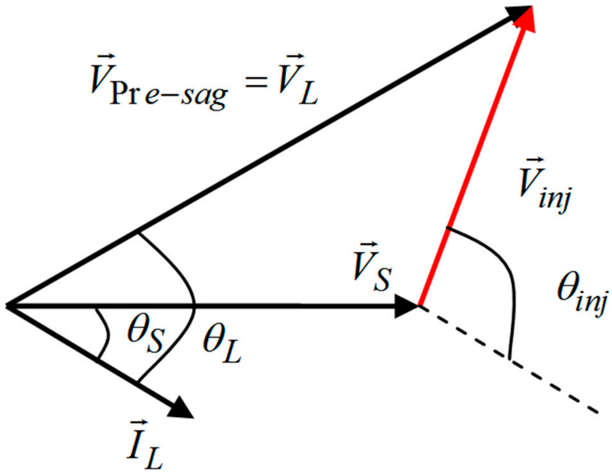

Figure 2. Phasor diagram of the pre-sag compensation technique.

3.3. Operation Modes of DVR

The DVR has three modes of operation: protection mode, standby mode (during steady state), and injection/boost mode (during sag/swell). In Protection mode, the DVR is protected from the over current on the load side due to short-circuit on the load or large inrush current. The DVR can be isolated from the system by using the by-pass switches as shown in Figure 1. In standby mode, no switching of semiconductors occurs and the load current will pass through the transformer primary winding. In boost (Injection) mode, when the voltage disturbance occurs in the supply is detected, the DVR will be injected a compensation voltage through the voltage injection transformer.

4. Control Techniques of DVR

In general, the process control of DVR includes 3 steps: 1. Detection of voltage sag/swell occurrence in the system, 2. Comparison with the reference value and 3. Generation of gate pulses to the voltage source inverter (VSI) to generate the DVR output voltages which compensates/absorbs the voltage sag/swell.

4.1. Grid Synchronization Techniques

Synchronization to the supply voltages is very important in order to control the DVR. It keeps an output signal synchronized with a reference input signal in frequency and phase. Synchronization methods have been developed and presented in many publications [16]-[18]. The most often used synchronization method in engineering applications, the phase-locked loop (PLL) has been used in this paper.

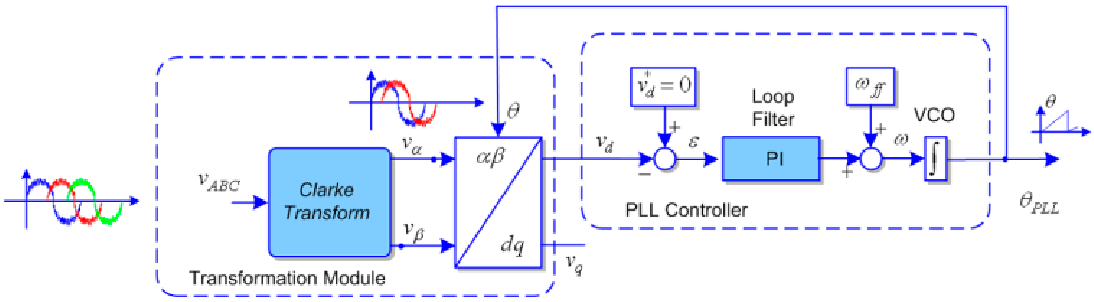

Figure 3. Phase locked loop to synchronize the DVR to the supply voltages.

Figure 3 shows the block diagram of three phase PLL. The voltages measured at PCC bus (V_{abc}) is transformed from three phase frame to αβ frame using Clarke's transform.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3}$$

and transformed from αβ frame to synchronously rotating *dq* frame using Park's transform

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{4}$$

The Loop Filter is a low-pass filter, it is used to suppress high frequency components. The Loop Filter provides controlled signal to voltage controlled oscillator (VCO) which work as an integrator.

Typically, this block is constituted of a first-order low-pass filter or a PI controller [16]. The output of the PI controller is the inverter output frequency that is integrated to obtain inverter phase angle θ. The PI regulator of the LF will set the angular position of the *dq* reference frame to make $V_d=0$ in the steady state, which means that the PLL will be active when the difference between grid phase angle and inverter phase angle is reduced to zero. The model of PLL in MATLAB-Simulink environment is present in Fig.4.

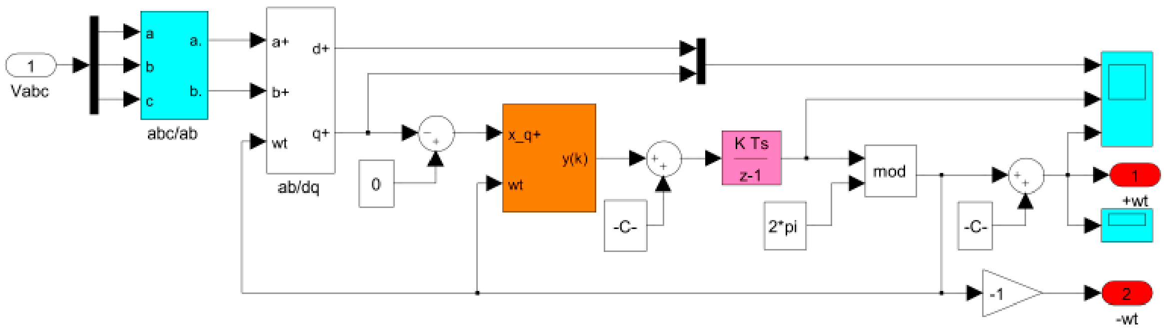

Figure 4. The MATLAB-Simulink model of PLL.

4.2. Sag/swell Detection Techniques

The voltage sag/swell phenomena are necessary to detect the starting point, the end point, sag depth and phase shift. There are many different methods for detecting voltage sag, swell, such as peak value, root mean square (RMS), Fourier transform, Wavelet transforms and Space Vector method. In the number of methods, Space Vector control is the most effective method which is used widely in DVR applications. In this method, the three phase voltages V_{abc} are transformed into a two-dimensional voltage V_{dq} which in turn can be transferred into magnitude and angle. The

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information of voltage magnitude and angle shift is compared with the reference value in the *dq* frame, which had to be transformed back to the three-phase frame.

$$\left|V_{err,dq}\right| = \sqrt{(V_{ref,d} - V_{PCC,d})^2 + (V_{ref,q} - V_{PCC,q})^2} \tag{5}$$

$$\left|V_{err,dq}\right| > V_{threshold} \tag{6}$$

If the voltage dip contains a phase jump, it will lead to a reduction in both the d- and q-component. Details of this case are described in [17]. Figure 5 shows the voltage sag/swell detector model of DVR in MATLAB-Simulink environment. The proposed method can detect the change in the state of the supply (the start, end points, and phase jump) with low time delay.

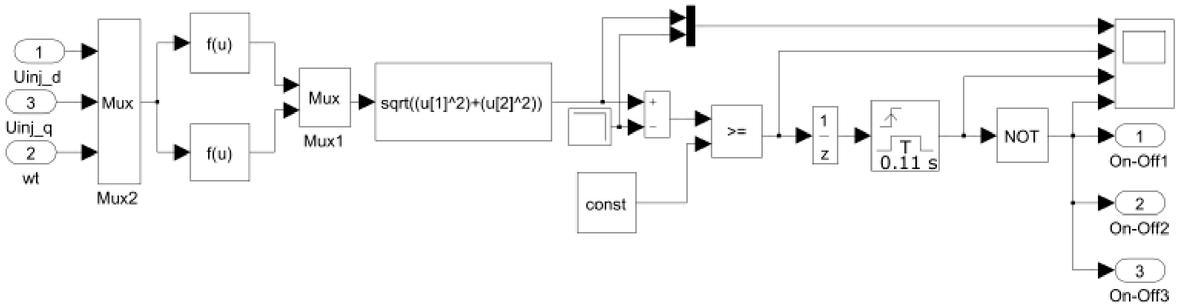

Figure 5. The MATLAB-Simulink model of the Detector.

4.3. Control Techniques

The control system is very important in DVR, with the requirements of fast response for of voltage sags and variations in the supplied load. The main purpose of the control system is to maintain the voltage magnitude of the sensitive load, where DVR is used, under system disturbances. There are three main voltage controllers used, the Feed-forward (open loop), Feedback (closed loop) and Multi-loop controller, and another controllers based on "artificial intelligence", such as Artificial Neural Networks (ANN), Fuzzy Logic (FL) and Space Vector Pulse Width Modulation (SVPWM) for special conditions. The Feed-forward voltage controller is the primary option for the DVR, because of its simplicity and fast response. The disadvantage of the open loop controller is the high steady state error. The Feedback controller has the advantage of accurate response, but it is complex and causes time-delays. Multi-loop control is used with an outer voltage loop to control the DVR voltage and inner loop to control the load current. This method has the strengths of feed-forward and feedback control strategies, it can improve the system dynamic response rate, shortening the time of compensation significantly [1]-[3].

The injected voltage that is needed to compensate by DVR is

$$u^*_{inj} = u^*_L - u_g \tag{7}$$

The structure of the multi-loop controller is shown in Figure 6. In this method, the three-phase voltages of the grid are sensed and transformed to two-phase system (*ab*) in the stationary reference frame and in the rotating reference frame (*dq*). Then, the positive sequence and the negative sequence components are extracted. Positive sequence grid voltage vector is compared against the positive sequence load voltage command vector. The difference between them becomes the desired injected positive sequence voltage vector across the filter capacitor. The process of the negative sequence controller is similar.

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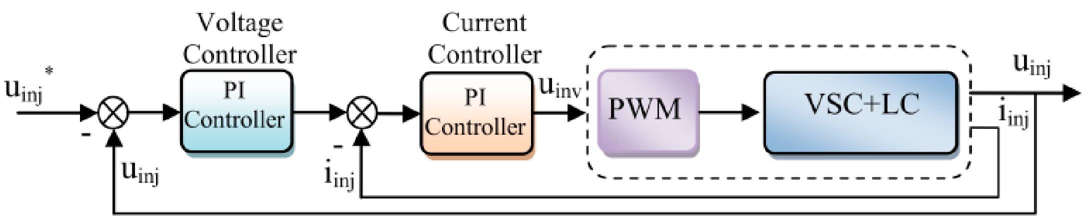

Figure 6. Block diagram of the multi-loop controller.

This controller has two measured process variables, injected current i_{inj} and injected voltage u_{inj} and attempts to minimize the error between the desired u^*_{inj} and u_{inj}. Two separate controllers for each sequence (positive and negative) are used, and the current controller can regulate the injected currents and improve response and proper operation of the voltage controller to restore the load voltage. The controller based on PI control has been presented detail in [8]. The proposed new controller is able to detect the voltage disturbances and control the converter to inject appropriate voltages independently for each phase and compensate to load voltage through three single- phase transformers.

5. Simulation

5.1. Modeling and simulation

The proposed multifunctional DVR is implemented in MATLAB-Simulink for mitigating of balanced, unbalanced voltage sag/swell, fluctuations and distortions voltage. The simulations are based on the real power system as shown in Figure 7 and the details of the system parameters are given below

Source:

115kV, 50Hz, S_{sc}= 250MVA.

Transmission line:

R= 1.309 Ω, L= 9.24 mH.

Transformers:

T1: 25MVA, 110/6.3kV, Y/D1, U_k= 11.5%

T2: 2800kVA, 6.3/0.63kV, D/Yn11, U_k=5.8%.

Load: 16.87MW, 11.24MVAr

Sensitive load:

1975 kW motor, 0.63 kV, rated speed 1000 rpm.

The DVR is designed to protect the sensitive loads at voltage level 6.3 kV and its parameters are below:

Energy storage:

Power rating: 1400kVA, V_{DC}= 700V

Injection transformer: 3 single-phase transformers, 1500kVA, 0.63/6.3kV, U_k=5%.

Filter:

L_f= 7,109 mH, C_f= 6,942 µC.

Switches: IGBT

Switching frequency: 5 kHz.

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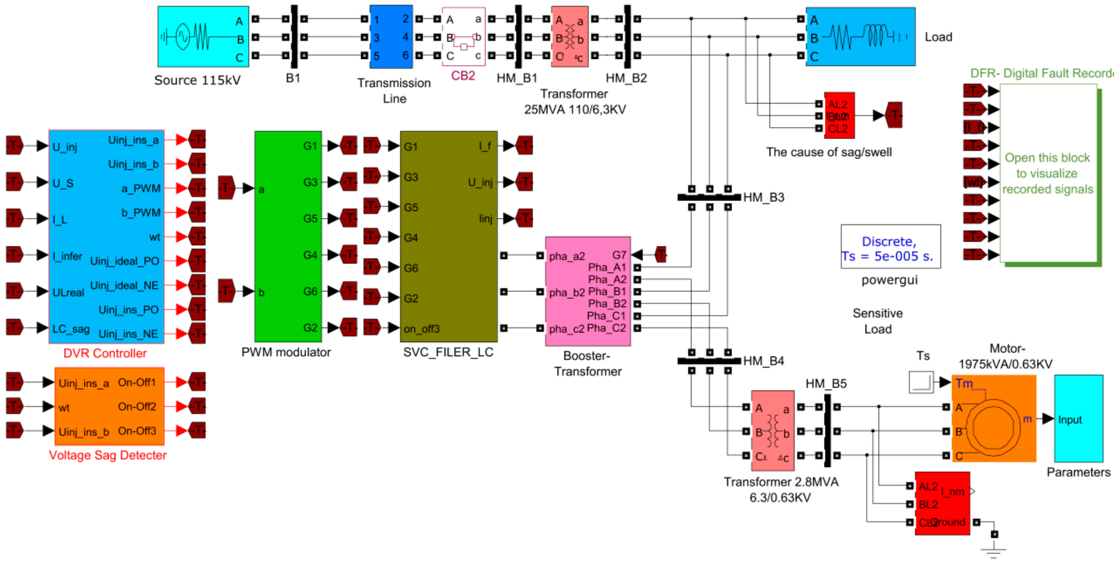

Figure 7. The MATLAB-Simulink model of test system.

5.2. Results and Discussion

5.2.2. Case 1: Three phase balanced voltage sag.

The balanced voltage sag at PCC due to three phase short circuit happens in the power system, the voltage decreased to 50% from 1.00s to 1.10s. Figure 8 shows the simulated waveforms for the grid voltages, the injection voltages of DVR and the load voltages during the sag event. Before the sag, the DVR is in the standby state waiting for the sag detection. It can be observed that the DVR compensates the balanced sag rapidly when the grid-side voltage sag happens. By this simulation, the perfect performance of the grid synchronization algorithm and the control strategy is shown.

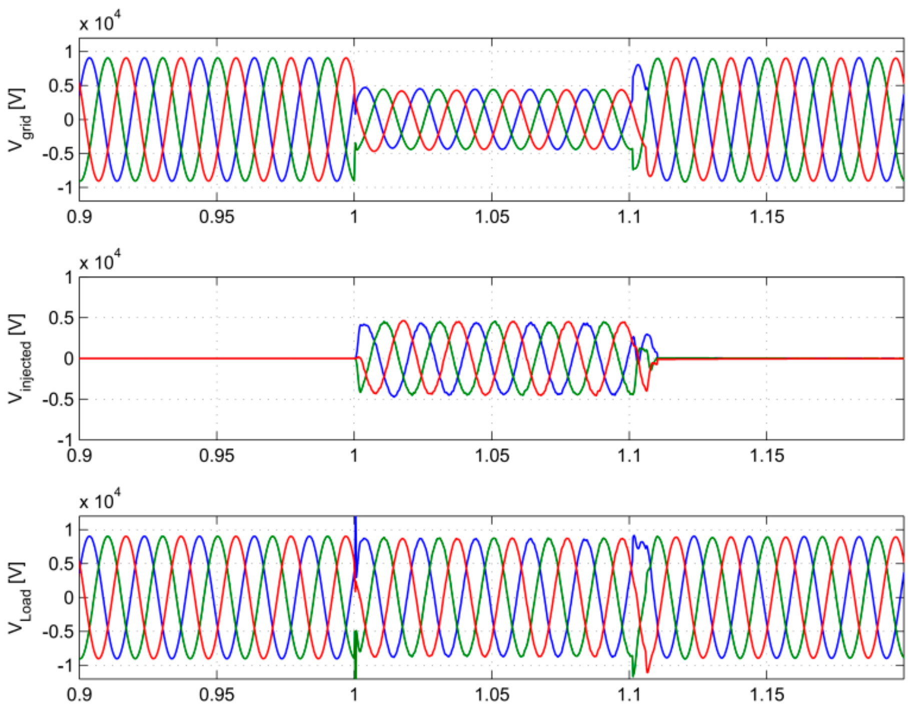

Figure 8. Case 1- Balanced voltage sag: grid voltage, injected voltage of the DVR and load voltage.

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5.2.3. Case 2: The unbalanced voltage sag.

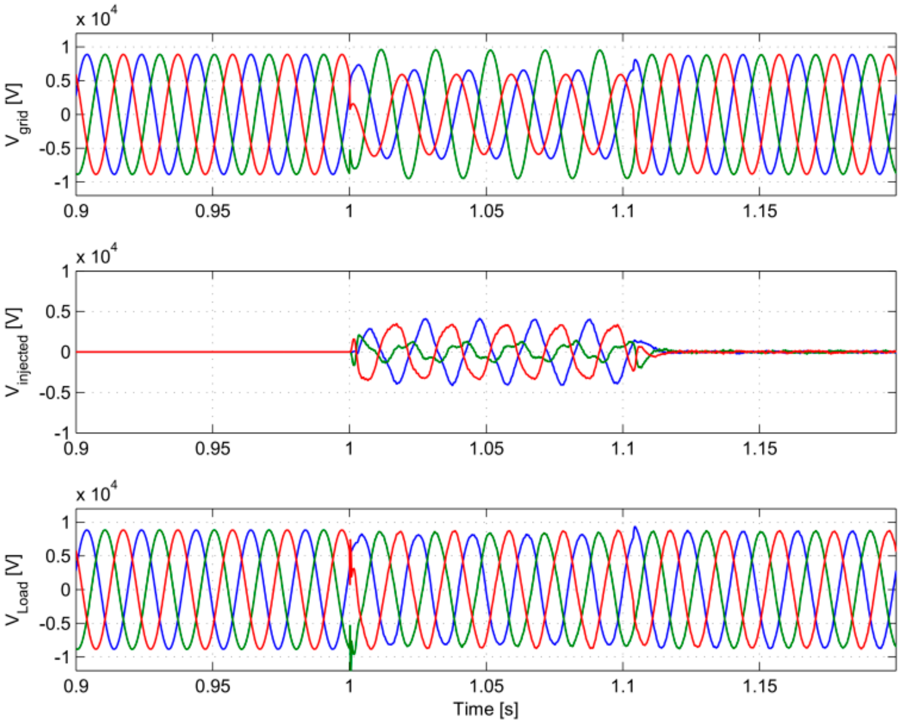

Figure 9. Case 2- Unbalanced voltage sag: grid voltage, injected voltage of the DVR and load voltage.

In this case study, from 1.00s to 1.10s, a phase to phase short circuit (between phase A and C) occurred in power system, the voltage at PCC reduced to 35% in phase A, and to 28% in phase C and increased slightly by 10% in phase B respectively to the reference pre-sag voltage and the phase angle jump of grid voltage. The results of this simulation are shown in Figure 9. Observe that the DVR quickly injects the necessary voltage components, with correct both magnitude and phase angle to maintain balanced load voltages. It is shown that the DVR can detect and mitigate the voltage sag in different phases independently and inject the compensation energy through 3 single-phase transformers to correct the grid voltage.

5.2.4. Case 3: Voltage sags due to starting of a motor.

A typical cause of voltage sags is caused by starting a large three-phase motor. The characteristics of voltage sags depend on various factors, such as motor rating, the method of starting and system's power supply capacity. In this paper, the test system is simulated in the case of starting 1975kW induction motor. The motor is started at 1,50 s by closing motor starting contactor. The three phase voltage sag RMS waveform of grid voltage is shown in Figure 10. Voltage sag caused by starting motor is unbalanced and drops down to 20% of its nominal value.

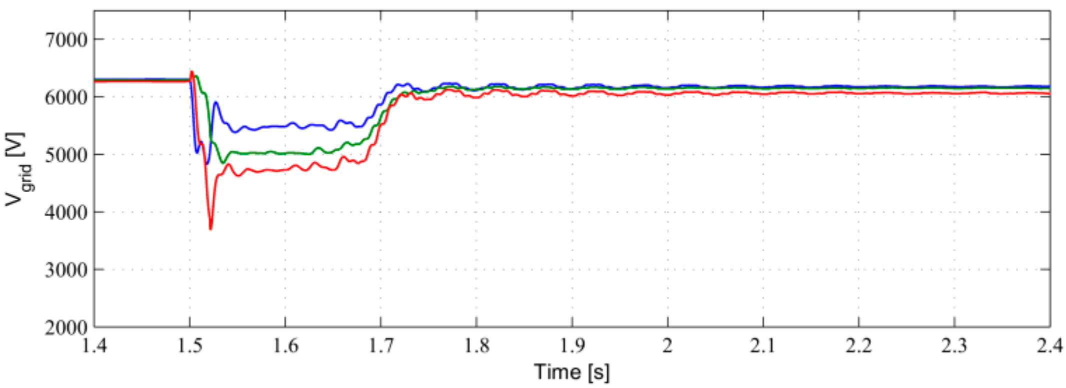

Figure 10. The RMS waveform of grid voltage due to starting motor.

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Figure 11 shows the simulated wave form of the grid voltage, injected voltage of the DVR and load voltage when starting motor. The DVR generated unbalanced three phase voltages for each phase to compensate grid voltage unbalance. As a result, the voltage sag is fully compensated, the load voltage is maintained balanced and constant.

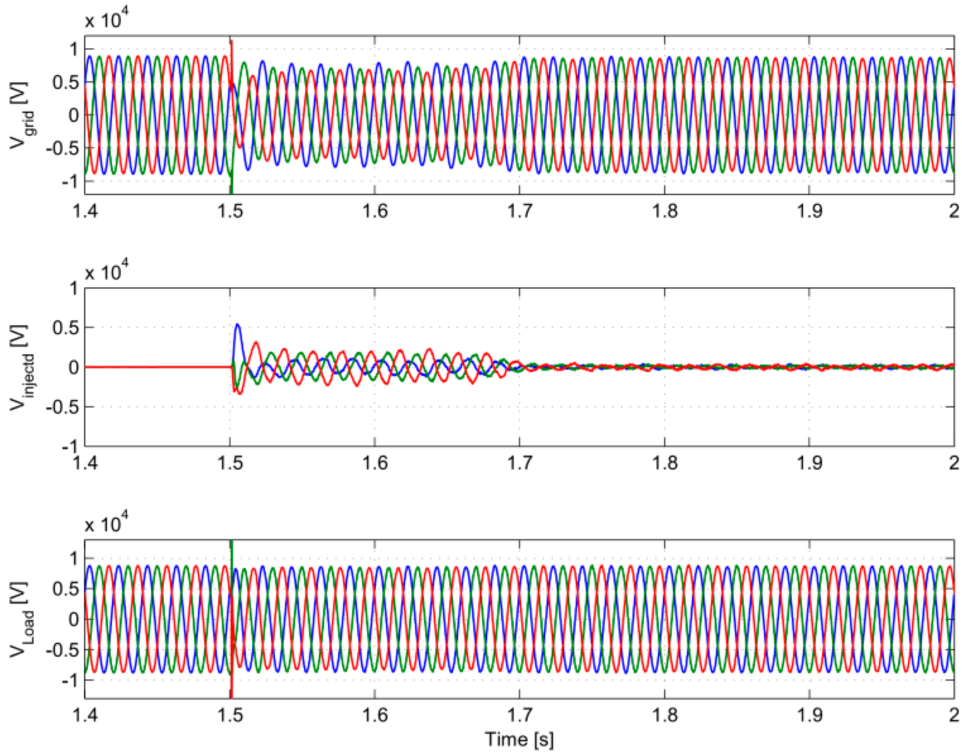

Figure 11. Case 3- Voltage sag due to starting motor: grid voltage, injected voltage of the DVR and load voltage.

5.4.5. Case 4 and Case 5: Balanced and unbalanced voltage swells.

From the technical point of view, the DVR should mitigate voltage swells in the same way it mitigates voltage sags. The detection technique is based on the difference between the magnitude and phase angle of grid voltage and load voltage. The VSC generates the missing voltage through the transformer for compensation. However, it is completely different from the viewpoint of the energy handling capability. In the case of voltage sags, the DVR supplies an active power to the load but in the case of voltage swells, the DVR must absorb the power from the grid.

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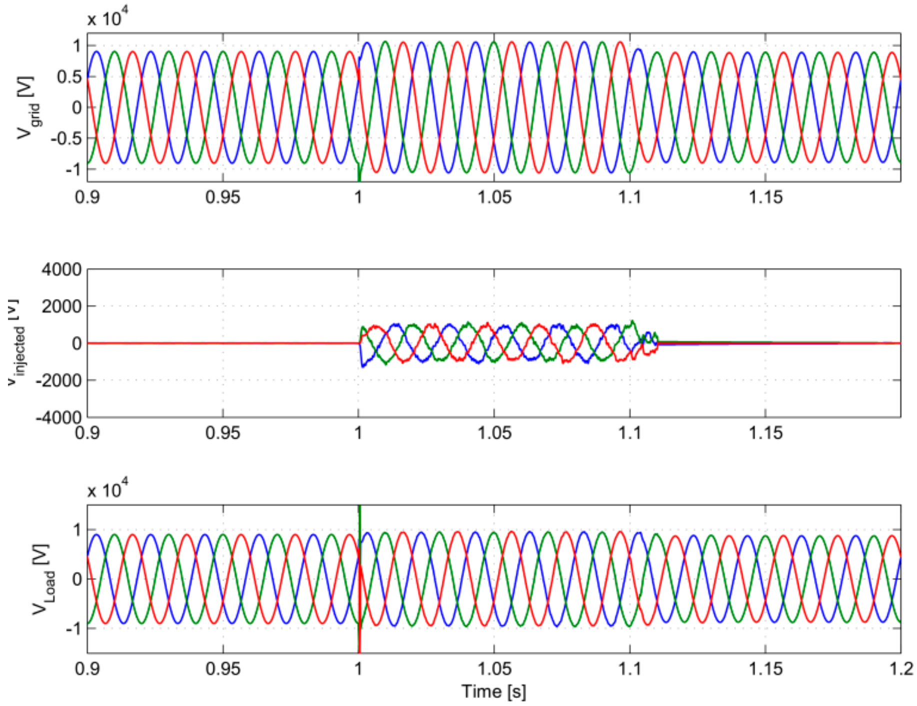

Figure 12. Case 4: Balanced voltage swell: grid voltage, injected voltage of the DVR and load voltage.

Table 1. RMS Voltage of Case 4- Balanced Voltage Swell.

Voltage at PCC before swell (V)	Balanced voltage swell at PCC (V)	Load voltage during swell (V)
6320	7450	6580

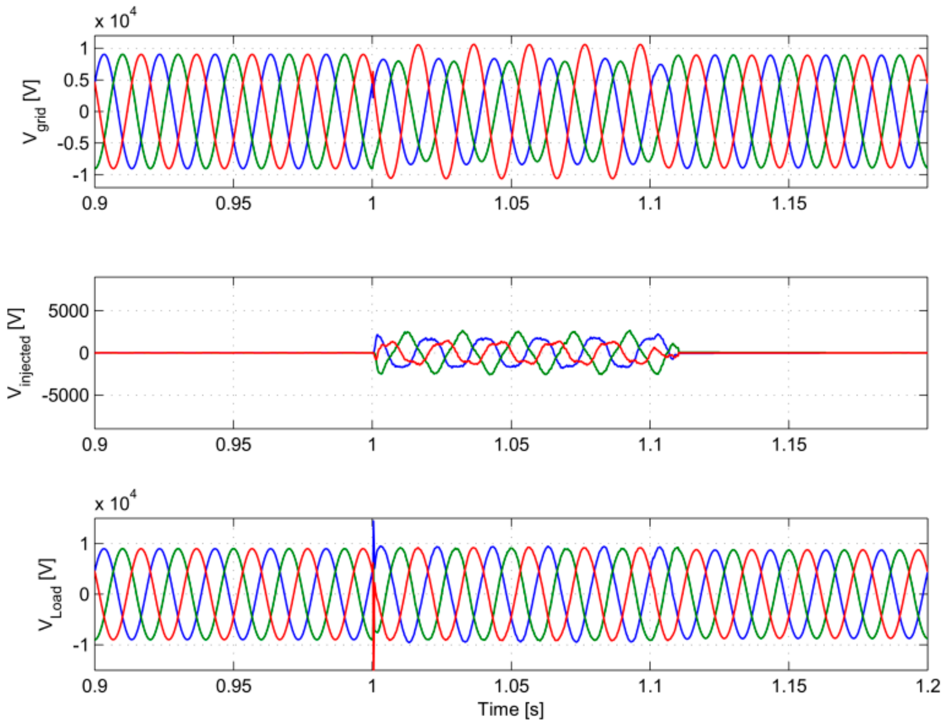

Figure 13. Case 5- Unbalanced voltage swell: grid voltage, injected voltage of the DVR and load voltage.

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In the case of balanced and unbalanced voltage swell, swell has occurred at 1,00 s of the duration 0,1s. Figures 12 and 13 present the simulation results of the grid voltage, injected voltage of the DVR and load voltage. The information on the voltage at PCC and load voltage is presented in Tables 1 and 2. When voltage swell occurs, the grid voltage increased by 18%, the DVR compensates so the load voltage increased below 4%. In such way the swell doesn't influence the operation of the load. We can see, that the DVR has successfully maintained the load voltage is spite of balanced or unbalanced swells.

Table 2. RMS Voltage of Case 5- Unbalanced Voltage Swell.

Voltage at PCC before swell (V)	Balanced voltage swell at PCC (V)	Load voltage during swell (V)
6320	7450 5950 5550	6500

5.4.6. Case 6: Fluctuations and distortions of voltages

In this simulation, the fluctuations and distortions of voltages caused by switching on and off the capacitor at HV side of the distribution transformer, were created for the duration of 1,0 s to 1,5 s.

The voltage waveform of grid voltage, injected voltage of the DVR and load voltage are shown in Figure 14. The THD (Total Harmonic Distortion) of the voltage at PCC is 2.86% (measured for 10 cycles' interval after switching on the capacitor) and decreased to 0.94% at load side. It can be observed that the load side voltages are maintained and sinusoidal waveforms are kept almost intact.

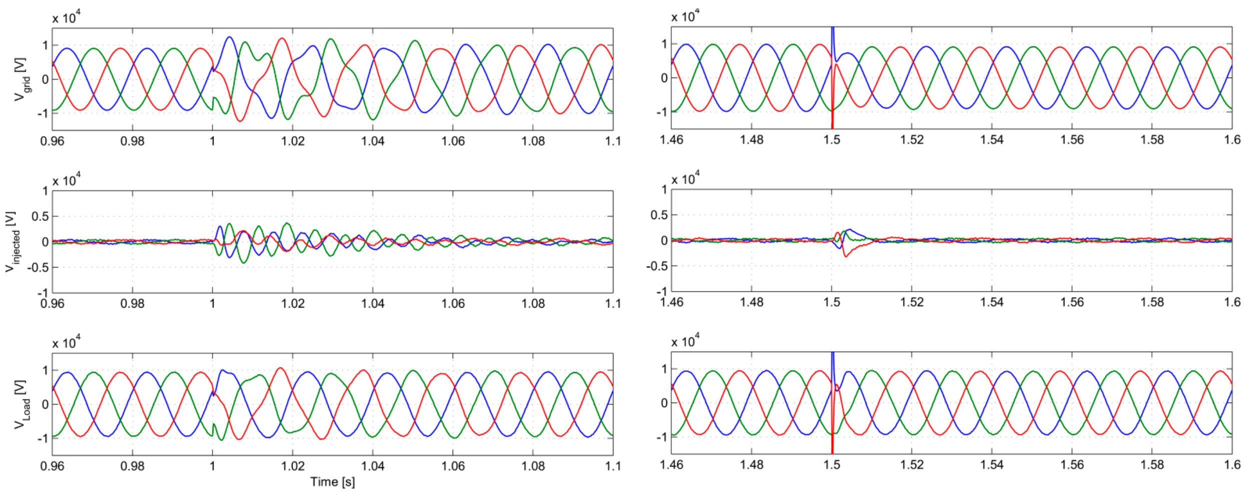

Figure14. Case 6- Fluctuations and distortions voltages: grid voltage, injected voltage of the DVR and load voltage.

5. Conclusions

In this paper it was presented a DVR which can compensate balanced and unbalanced voltage sags and swells and other utility voltage disturbances. The DVR is described in detail, configuration, and its sag/swell detection voltage technique, grid synchronization techniques and control technique. The simulation results under several conditions, balanced and unbalanced voltage sags and swells, fluctuations and distortions are presented. The results demonstrate that the proposed DVR is capable of compensating efficiently most of power quality problems, as well as harmonics in the grid voltage. It provides fast dynamic response and has the advantage of simple structure and high .

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Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Shazly A., Mohammed Aurelio G., Cerrada Abdel-Moamen M. A and Hasanin B.. Dynamic Voltage Restorer (DVR) System for Compensation of Voltage Sags State-of-the-Art Review. *International Journal of Computational Engineering Research* (ijceronline.com) Vol. 3 Issue. 1.
2. Rakeshwri Pal, Dr. Sushma Gupta: State Of The Art: Dynamic Voltage Restorer for Power Quality Improvement". *Electrical & Computer Engineering : An International Journal (ECIJ)* Volume 4, Number 2, June 2015.
3. Mahmoud A., El-Gammal Amr, Y. Abou-Ghazala and Tarek I. El-Shennawy. Dynamic Voltage Restorer (DVR) for Voltage Sag Mitigation. *International Journal on Electrical Engineering and Informatics* vol. 3 no. 1 2011.
4. Shazly A., Mohammed Aurelio G., Cerrada Abdel Moamen M. A., and Hasanin B.. Conventional dynamic voltage restorer for mitigation of voltage sag in power distribution systems. *International Journal of Advances in Engineering & Technology (IJAET)* Vol. 6 Issue 1 pp. 415-425 Mar. 2013.
5. Saeed S. A. M. Abdel Aleem H.E. Ibrahim A. M. Balci Essam M. E. El-Zahab E.A.. Power conditioning using dynamic voltage restorers under different voltage sag types. *Journal of Advanced Research*. 2015, vol. 7, iss. 1, pp. 95-103.
6. Resmi R. Reshmi V. and Jacob J. Mitigation of Voltage Sag Swell and Harmonics by Dynamic Voltage Restorer using Matrix Converter. *International Journal of Advanced Research in Electrical Electronics and Instrumentation Engineering*. Vol. 2 Issue-2 pp. 297-304 Dec. 2013.
7. Devaraju T. , Reddy V. C., Kumar M. Vijaya. Performance of DVR Under Different Voltage Sag And Swell Conditions" *ARPN Journal of Engineering and Applied Sciences* Vol. 5 No. 10 October 2010.
8. Dung Vo Tien, Gono R., Leonowicz Z., Trinh Tran Duy, Martirano L. . Advanced Control of the Dynamic Voltage Restorer for Mitigating Voltage Sags in Power Systems. *Advances in Electrical and Electronic Engineering.* (article in press).
9. Bach Q. K., Lian J., Ramachandran B., Srivastava S., Cartes D.. Mitigating voltage sags due to DOL starting of three phase asynchronous motors using dynamic voltage restorer (DVR). Proceedings of IEEE PES Transmission and Distribution Conference and Exposition 2012. 7-10 May 2012. DOI: 10.1109/TDC.2012.6281673
10. Nguyen P. T., Tapan. K. Saha. Dynamic Voltage Restorer against Balanced and Unbalanced Voltage Sags: Modelling and Simulation". Proceedings of IEEE Power Engineering Society General Meeting, vol. 1, pp. 639-644, June 2004
11. Bingsen Wang, Giri Venkataramanan and Mahesh Illindala. Operation and control of a dynamic voltage restorer using transformer coupled H-bridge converters. *IEEE Transactions on Power Electronics*, vol. 21 pp. 1053-1061 July 2006.
12. Fitzer M., Barnes P. Green. Voltage sag detection technique for a dynamic voltage restorer. Proceedings of IEEE Industry Applications Conference. vol. 40 no. 1 pp. 203-212 Jan./Feb. 2004.
13. Trinh Tran Duy, Dung Vo Tien, Gono R. and Leonowicz Z. Mitigating Voltage Sags due to short circuits using Dynamic Voltage Restorer. Proceedings of IEEE International Conference on Environment and Electrical Engineering. Italy: EEEIC, 2016. pp. 2671-2676.
14. Dugan R.C., Granaghan M.F., Santoso S., Beaty H.W. *Electrical Power Systems Quality*. 2nd Edition, McGraw Hill, 2004.
15. Bollen M. H. J. *Understanding Power Quality Problems—Voltage Sags and Interruptions*. Piscataway, New York: IEEE Press, 2000
16. Teodorescu R., Liserre M. and Rodríguez P.. *Grid Converters for Photovoltaic and Wind Power Systems.* John Wiley & Sons, Ltd, United Kingdom, 2011. ISBN: 978-0-470-05751-3

Peer-reviewed version available at *Energies* **2018**, *11*, 1351; doi:10.3390/en11061351

17. Nielsen, J. G. *Design and Control of a Dynamic Voltage Restorer*. Aalborg University, Denmark Publishers, 2002. ISBN 90-77017-83-6.
18. Tarjei Midtsund. Control of Power Electronic Converters in Distributed Power Generation Systems, Norwegian University of Science and Technology, July 2010.