Series Compensator in order to Improve Voltage Quality Problems

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Abstract: *Voltage sags can have severe impact on sensitive loads. To solve this problem, custom-power devices are applied. One of those devices is the dynamic voltage restorer (DVR), which considered as one of the most efficient and effective new custom power devices used in electrical power distribution networks. The DVR is a series compensator which is installed among the source voltage and the sensitive load. It traditionally consists of a voltage source converter with an insertion transformer and it is applied to mitigate voltage sags, other voltage disturbances and to restore load voltage to its rated value. Its attraction includes smaller size and quick dynamic response to disturbances.*

This work describes the performance of DVR in power distribution systems. A control technique based on a PI controller and a selective controller is applied. The controller is designed in a synchronously-rotating reference frame. Actually, three independent controllers (homopolar component, d-axis and q-axis components) have been applied to tackle balanced and unbalanced voltage supplies. Simulation results using the SimPower MATLAB toolbox are presented to illustrate the principle and performance of a DVR operation in load voltage compensation.

Keywords: *Dynamic Voltage Restorer (DVR), voltage disturbances, compensation strategy, synchronous reference frame controller.*

1. Introduction

Now a days, modern industrial devices are mostly based on electronic devices like computers, programmable logic controllers, variable-speed drives, etc. Most of these electronic devices are sensitive to supply-voltage quality problems such as voltage sags and swells, harmonics or unbalances. Voltage sags are considered to be one of the most severe disturbances from the point of view of industrial equipment[1].

Voltage sag is a momentary decrease in the root-mean-square (rms) voltage value in the range of 0.1 to 0.9 per unit. It is frequently caused by balanced or unbalanced faults in the distribution system or by the starting of large induction motors [2-3].Several techniques are available to prevent equipment mal operation due to voltage sags. One of often applied methods is the use of DVR in order to mitigate voltage sags.

DVR is a series custom power device intended to protect sensitive loads from the effects of voltage sags and other voltage disturbances at the point of common coupling (PCC). A DVR consists, basically, of a series connected injection transformer, a voltage source inverter (VSI), an inverter-output filter and an energy storage connected to the dc-link [4], [5].

The basic operation principle of a DVR is to inject a voltage of the desired magnitude, phase angle and frequency in series with a distribution feeder to keep the desirable voltage waveform at the load even when the source voltage is distorted [6].Some references [7],[8] suggest that the DVR insertion transformer can avoided if the distribution transformer is applied appropriately. Although this alternative has been recognized for some time, a side-by-side comparison among the alternatives with and without insertion transformer has been seldom addressed[9].

This research focus on the DVR distribution system study in the context of voltage sag compensation. Although, the inverter applied in the a DVR can have many different topologies, this article will use a traditional 2-level, 3-phase PWM inverter since this topology is still the most popular one and the comparison of various topologies is beyond the scope of the paper.

This paper is structured as follows after introduction. Section (2)illustrates briefly the DVR compensation techniques. The fundamental difference is investigated looking at the transfer function among the inverter voltage and the sensitive-load voltage. Strong and weak voltage supplies are considered. Section (3)describes the control system employed. To start with, two independent PI controllers using a synchronously-rotating frame (one for the d-axis and one for the q-axis) are proposed. Section (4) will present the simulation set-up and will provide extensive simulation results of different scenarios. Balanced and unbalanced faults in the distribution systems will be considered. Section (5) will investigates simulation results of the operation of the DVR when switching extra loads suddenly close to the sensitive load. Balanced and unbalanced extra loads will be investigated. It will be shown that an extra controller for the homo polar component is necessary in the latter case and its structure will be proposed and justified. Finally, Section (6) will summarize the important conclusions of the work presented in this article.

2. DVR Compensation Techniques

Figure 1show a classical DVR with a series insertion transformer connected among the distribution transformer and the sensitive load. The electrical system viewed from the point of common coupling (PCC) has been modeled as a 3-phase voltage source with a short-circuit impedance. The DVR can compensate voltage sags by means of the injection of the inverter voltage through series connected transformer [10].Basically, the DVR consist of a series-connected injection transformer, a voltage source inverter (VSI), a filter capacitor and storage device connected to the inverter DC link.

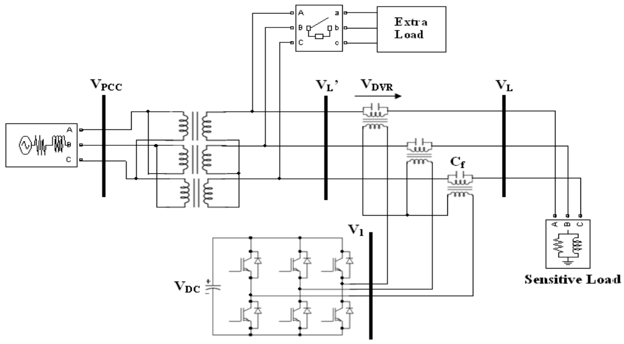


Fig. (1): Schematic diagram of traditional DVR system

Figure(2)illustrates the single-phase equivalent circuit to study the transfer function among the DVR inverter voltage (V_{DVR}) and the sensitive-load voltage (V_L).Fig. (2) depicts the case of a DVR with transformer where L_T' and R_T' represent the leakage inductance of the transformer and its equivalent series resistance, respectively. C_f is added to make a second-order filter together with L_T' in order to filter the inverter output voltage. The voltage supply has been represented by a voltage source V_s with a short-circuit impedance (R_{sh} & L_{sh}) in series with a distribution transformer represented by its leakage inductance (L_T) and an equivalent resistance (R_T). The sensitive load has been modeled by a parallel-connected R-L. The magnetizing branch of the transformers has been ignored. Finally, an additional load (Z_p) has been added after the distribution transformer. The single-phase circuits in Figs. (2) also show that the DVR is nothing but a series voltage compensator. This characteristic has been applied in the literature to present comprehensive compensators including harmonics. [9], [11] and [12].

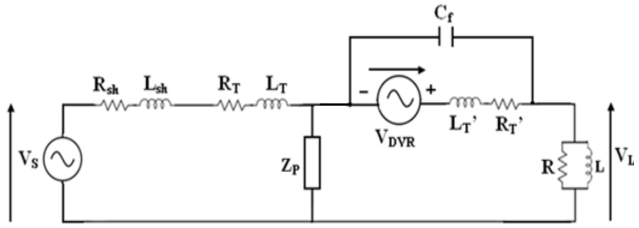


Fig.(2): Single-phase equivalent circuit of DVR

The transfer functions V_L/V_{DVR} for the circuit in Fig. (2) have been investigated using the parameters of the case study to be simulated later on. These parameters can be found in Table (I).Three scenarios are considered bellow.

Figure (3)has been drawn without the additional load Zp. A very strong power supply has been applied (short-circuit power=20pu). Clearly, show exactly the same response and this result also holds when the source short-circuits power changes.

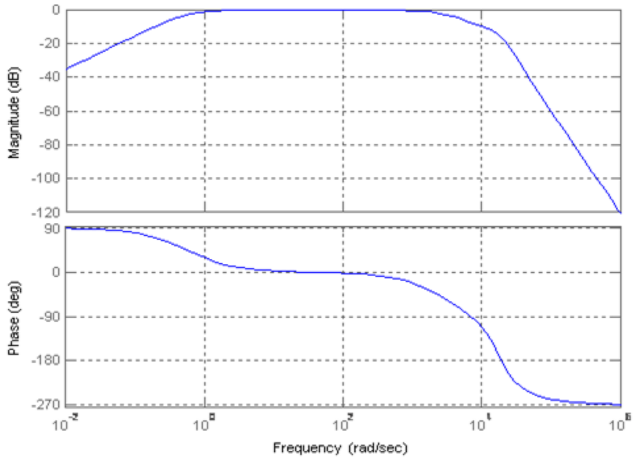
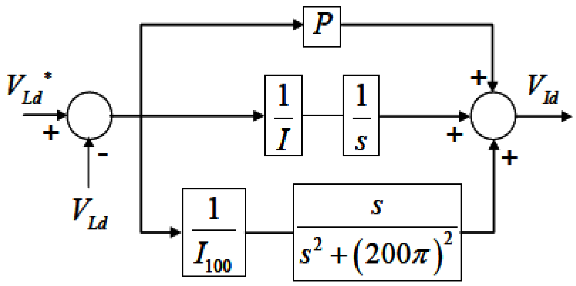


Fig. (3): Frequency Response for DVR without additional Load (only sensitive load)

3. DVR control system

The main objective of the control system is to keep a constant voltage magnitude at the point where a sensitive load is connected, under system disturbances. The controller will be applied using a synchronously-rotating frame and, to start with, two independent and identical controllers for d and q axes were placed. The controller for the d-q axis is shown in Fig.(4).



d-q axis controller

Figure (4): Controllers for a DVR using a synchronously-rotating frame

Since the direct sequence of the voltage at the fundamental frequency is transformed into a DC voltage, PI d and q-axis controllers have been applied. Nevertheless, if an inverse-sequence voltage can also be present at the fundamental frequency, this is transformed into a100Hz component that has to be controlled using a selective controller. A simple PI (Proportional-Integral) controller is, supposedly, the most common alternative used in the literature because it has a simple structure and it can offer a relatively-satisfactory performance over a wide range of situations. The main problem of this simple controller is the correct choice of the PI gains and the fact that, by using fixed gains, the controller may not provide the required performance, when there are variations in the system parameters and operating conditions [11].

4. Case Study

In order to confirm the proposed control scheme, the system illustrated in Fig. (1)have been implemented in MATLAB-SIMULINK environment. The test system is comprised of a 3-phase voltage source of 11 kV at 50 Hz which feeds an extra load and a sensitive load: The sensitive load is made up of a resistance connected in parallel with an inductance. The inverters have been controlled using space-vector modulation with a switching frequency of 4.95 kHz. The main parameters of the test system are summarized in Table (I).

Table (I): Case-study parameters

Electrical System Viewed From the PCC			
Short Circuit Power	S_{sh}	20	pu
Equivalent Inductance	L_{sh}	158	µs
Equivalent Resistance	R_{sh}	0.007	pu
Distribution Transformer and DVR Transformer			
Short Circuit Power	S_{shT} and $S_{shT'}$	12	pu
Winding 1 Inductance	L_1 and $L_{1'}$	185	µs
Winding 1 Resistance	R_1 and $R_{1'}$	0.03	pu
Winding 2 Inductance	L_2 and $L_{2'}$	185	µs
Winding 2 Resistance	R_2 and $R_{2'}$	0.03	Pu
Magnetizing Inductance	L_m and $L_{m'}$	64	s
Magnetizing Resistance	R_h and $R_{h'}$	2000	pu
Filter			
Inductance	L_f	369	µs
Capacitor	C_f	55	µs-1
Extra Load			
Inductive Load at nom. voltage	Q_L	0.32	pu
Capacitive Load at nom. voltage	$Q_C = Q_L$	0.32	Pu
Sensitive Load (Resistive – Inductive)			
Apparent Power	S_L	1	pu
Power Factor	PF	0.95	---

A. Control System in the case study.

The control system parameters applied in the case study are composed in Table (II).

Table (II): d- and q-axis controller parameters

P	I	I_{100}
1.5	**6.10^{-4}**	**5.10^{-4}**

The control system was applied to control the DVR with a 9.9 kHz sampling frequency and 4.95 kHz switching frequency. Identical controllers for the d and q axes have been applied.

B. Simulation Results for voltage sags

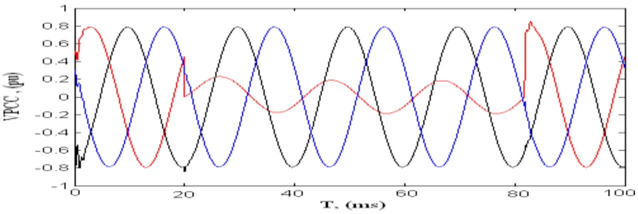
In this part representative simulation results are included to illustrate and compare the performance of the topology described in this research. The simulation studies have been done using MATLAB software. Fig. (5)depicts the voltage restoration performance of the DVR with transformer. The configuration of the studied system is as shown in Fig. (1). A strong voltage supply has been applied (short-circuit power=20pu). Since the fault detection mechanism is out of the scope of this study, the DVR has been connected all the time in the simulation experiments reported in this work. Fig.(5)present the results of simulation when a phase to ground resistive fault occurs, with a fault resistance equal to 0.012 ohm. The fault is created at the high-voltage (HV) side of the distribution transformer. It starts at 20 ms and last for three periods of the fundamental frequency. Notice that, the DVR quickly injects the necessary voltage components to keep the load voltage. The DVR injected voltage and the load voltage are shown in Fig. (5) (b) and (c), respectively. Per-unit variables have been applied and nominal powers and nominal phase-phase voltages have been chosen as base magnitudes. It can be observed that through the fault the A-phase voltage at the PCC drops down to 20% of its nominal value, while phase to ground load voltages remain almost constant during the whole event, due to the compensating actions of the (DVR). In spite of being an unbalanced fault, the voltage at the low-voltage (LV) side of the distribution transformer shows positive and negative-sequence components only. The same experiment has been carried out using a weak voltage supply of short-circuit power equal to 2 pu. Results are shown in Fig. (6) for a DVR with transformer. As can be seen from the results, the DVR was able to generate the required voltage component swiftly and helped to maintain a balanced and constant load voltage at 1 pu.

5. Simulation Results switching additional loads

Figure(7)presents the results of simulation for the system when switching a 3-phase capacitive load, suddenly at 20ms and close to the sensitive load. The additional load is disconnected at 80ms. No fault is present. The performance of DVR for a voltage swell condition was examined. As can be seen from the results, the load voltage was kept at the nominal value 1 pu with the help of the DVR.

The performance of the DVR when a zero-component of the supply voltage has to be tackled has been addressed in this study using simulation. A single phase capacitor load was switched among phase A and ground at the LV-side of the distribution transformer. The results are plotted in Figures (8) and (9)using a symmetrical-component meter supply by MATLAB-SIMULINK in its Sim Power toolbox. Fig. (8) shows the DVR performance when no zero-component controller is executed and a single-phase capacitor load is connected as described before. Although the HV-side voltage has no zero components, this appears at the LV-side and it is transferred to the load. Positive and negative sequences are controlled properly by the DVR.

A DVR with a transformer has been applied to illustrate the problem. Fig. (9)depicts the performance when a zero-component controller is placed. Now the sensitive-load voltage is freed of the zero voltage components. This simulation case uses a DVR with an insertion transformer.



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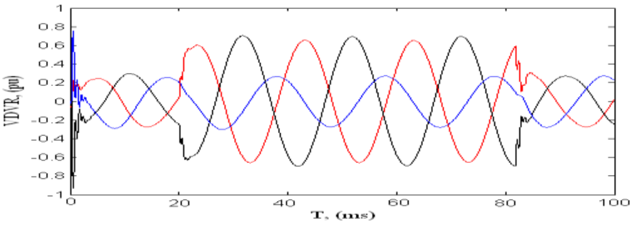

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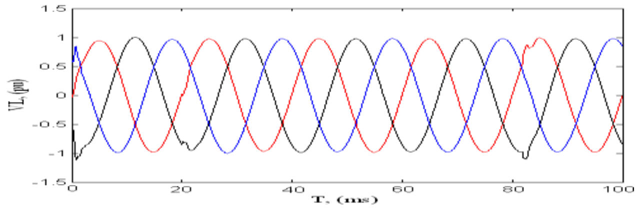

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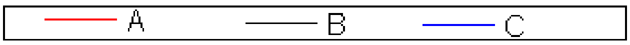
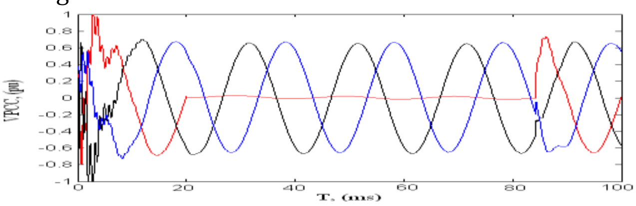


Fig. (5):Load voltage Compensation of DVR (single-phase fault and short circuit power = 20 pu);

(a) Source Voltage; (b) Injected Voltage; (c) Load Voltage.



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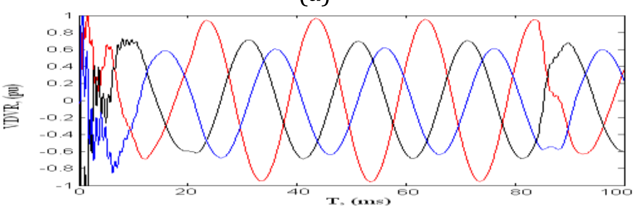

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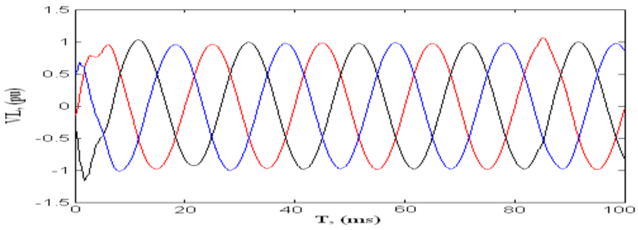
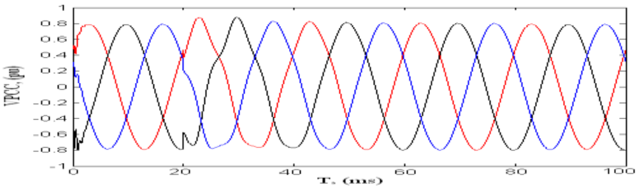


(c)

Fig. (6):Load voltage Compensation of DVR (single-phase fault and short circuit power = 2 pu);
(a) Source Voltage; (b) Injected Voltage; (c) Load Voltage.



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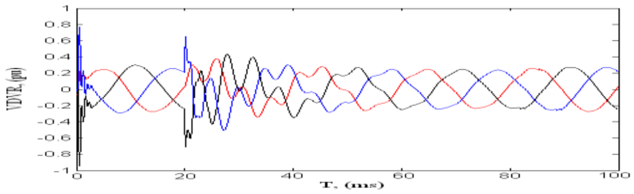

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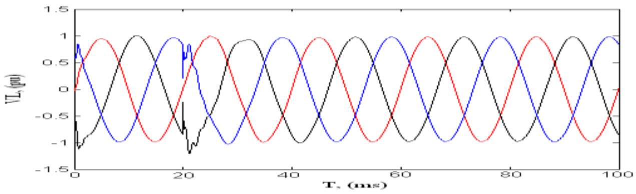

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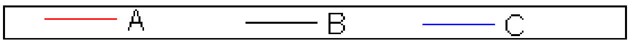
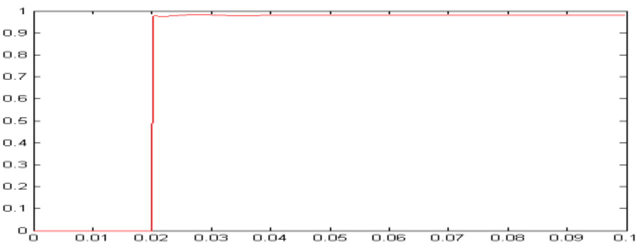


Fig. (7):Load voltage Compensation of DVR (Capacitive loadQ_c in Table (I) and short circuit power = 20 pu); (a) Source Voltage; (b) Injected Voltage; (c) Load Voltage.



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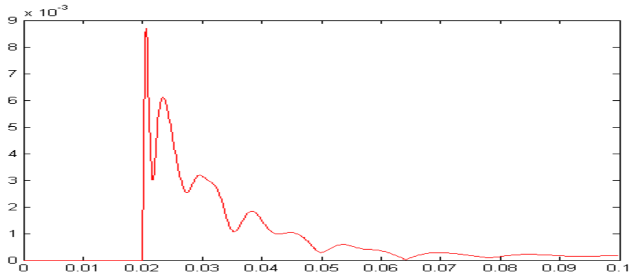

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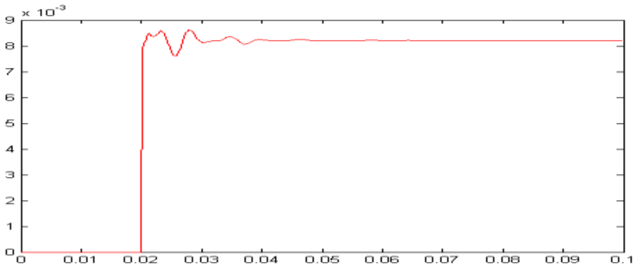
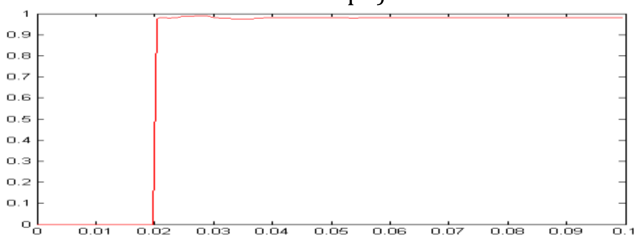


(c)

Fig. (8): Single-phase capacitive load (Qc) for DVR and No zero-component controller. Symmetrical components for Load Voltage(V_L); (a) Positive sequence component; (b) Negative sequence component; (c) Zero sequence component. (Note that, X- axis in second and Y-axis in pu).



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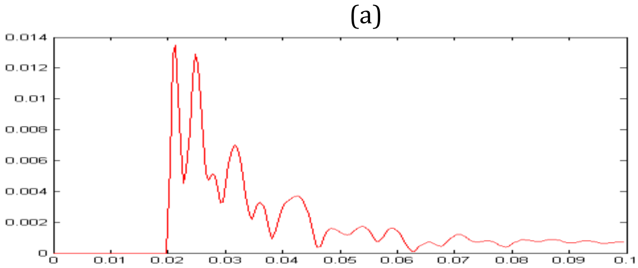

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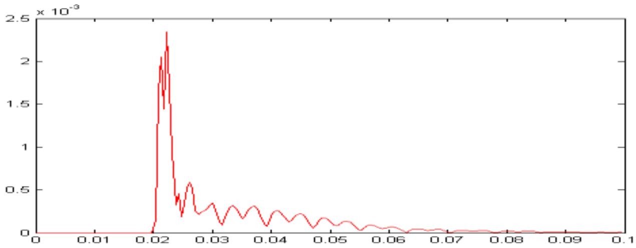

(c)

Fig. (9): Single-phase capacitive load (Q_c) for DVR and zero-component controller is on. Symmetrical components for Load Voltage(V_L); (a) Positive sequence component; (b) Negative sequence component; (c) Zero sequence component. (Note that, X- axis in second and Y-axis in pu).

6. Conclusions

This study investigates the performance of a DVR with insertion transformer. First of all, single-phase equivalent circuits have been studied. Based on the simulation completed, it is clear that a DVR can tackle voltage sags and swells when protecting sensitive loads. If a voltage supply without zero-component is expected two identical controllers can be applied with Park's transformation (one for the d-axis and another one for the q-axis). However, a third controller (zero-component) is required if situations with zero voltage component in the supply is expected. This third controller differs from the other two. The study presented in this work has been done by simulation and losses, size and economical aspects of the device have not been taken into account.

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