NEW CONTROL TECHNIQUE FOR THE DYNAMIC VOLTAGE RESTORER FOR SENSITIVE LOW-VOLTAGE LOADS

Piergiovanni La Seta
Technische Universität
Dresden, Germany
laseta@ieeh.et.tu-dresden.de

Mustafa Kizilcay
University of Siegen,
Germany
kizilcay@uni-siegen.de

Liliana Oprea
Fichtner GmbH,
Stuttgart,Germany
opreal@fichtner.de

Viktor Popescu
Fichtner GmbH,
Stuttgart, Germany
popescuv@fichtner.de

Abstract – **The present paper deals with a new control technique for the modelling of a Dynamic Voltage Restorer (DVR). The DVR is a power electronics device that is able to compensate voltage sags and swells on critical loads dynamically.**

By injecting an appropriate voltage, the DVR restores a voltage waveform and ensures constant load voltage. The compensating signals are determined dynamically based on the difference between desired and measured values.

In this work a low-voltage network is considered, where a series connected DVR protects a sensitive load against voltage disturbances. A loop control for the compensating signal evaluation is discussed with the help of numerical simulations.

Keywords – Power quality, power electronic converters, DVR, voltage compensation, PWM (pulse width modulation), ATP-EMTP, numerical simulation

1 INTRODUCTION

Power quality problems in industrial applications concern a wide range of disturbances, such as voltage sags and swells, flicker, interruptions, harmonic distortion. Preventing such phenomena is particularly important because of the increasing heavy automation in almost all the industrial processes. High quality in the power supply is needed, since failures due to such disturbances usually have a high impact on production costs.

The Dynamic Voltage Restorer (DVR) is a device designed to ensure supply of sensitive loads at almost constant voltage. It is capable to provide voltage corrections and compensation, as well as to absorb or inject real and reactive power at its AC terminals. DVR feature considered in this work is to maintain the voltage magnitude as constant as possible at a desired value in the presence of voltage disturbances.

The DVR operating principle can be briefly explained as follows. Amplitude and phase angle of the voltage to be compensated are measured in each phase, to restore it also in case of unbalance conditions. The vector difference between the desired voltage and the actual voltage across the load is then injected. The function of such a device may be interpreted as reactive voltage compensation, resulting in a desired power factor of the load.

Determination of waveforms with desired magnitude, phase and frequency is achieved with modern power electronics technology [1]. A DVR consists of a three-phase DC/AC voltage source inverter (VSI). It is connected on the DC side to a DC source, such as battery, or to the AC network. In the latter case, the connection is realized through a controllable AC/DC rectifier in shunt to the supply system. Tasks of the rectifier are to absorb active power to supply the DVR during voltage sags, and releasing active power through the DVR to the network during voltage swells.

In this work a sensitive load in a low voltage network is considered, which is protected from voltage disturbances by using a loop-controlled DVR at the load buses. The DVR is modelled using ATP-EMTP (ElectroMagnetic Transients Program, version Alternative Transients Program) [8] by means of a three-phase Voltage Source Inverter (VSI) connected in series with the distribution system. An ideal DC voltage source connected on the DC side of the DVR inverter is used. The Pulse Width Modulation (PWM) technique is adopted to modulate the VSI. The output voltages of a PWM VSI are waveforms that have to be filtered before injection in the network.

The filtering stage of a DVR can be placed either on the high-voltage side or the inverter side of the series injection transformers. In the present paper filtering capacitors are placed directly at the secondary of the coupling transformers. This configuration allows to reduce the filter capacitance because of transformer ratio [3], [5].

The DVR modelling and the numerical simulations have been performed as part of an electrical study project for an industrial customer with voltage sensitive manufacturing process.

2 DVR OPERATIONS

A schematic diagram of the system under consideration in the present work is shown in Figure 1. The DVR is installed directly at the load bus. As mentioned, a three-phase PWM VSI constitutes the DVR, supplied by an ideal DC source and connected in series with the network through a coupling step-up transformer. Other possible configurations for high power controllers can be also adopted.

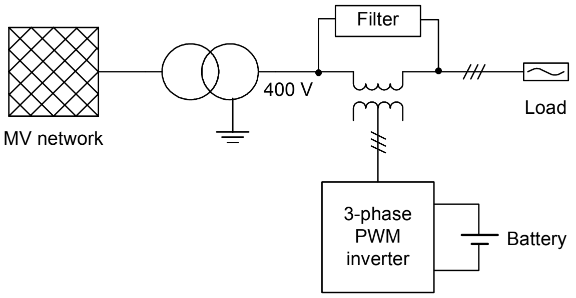

Figure 1: Schematic circuit of a DVR.

A simplified representation of the voltage regulation scheme is depicted in Figure 2 [7]. The supply side network is reduced to an equivalent ideal voltage source – line impedance scheme. The ideal voltage sources on the supply side are called V_{Na}, V_{Nb}, V_{Nc} and constitute a balanced three-phase system. Series line impedances are assumed equal in the three phases. Finally, also the load impedances are assumed balanced.

The DVR is represented by three ideal voltage sources between the supply side and the load side, called V_{DVRa}, V_{DVRb}, V_{DVRc}. The DVR model proposed here is used only for explanation purposes.

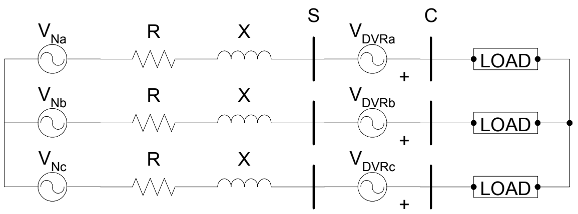

Figure 2: Simplified diagram of a DVR-connected balanced power system.

When the DVR is designed, it is generally not possible to know exactly the nature of voltage perturbations on the supply side. This has two main consequences. The first one is that the corrective action to be realized by the DVR has to be based on the voltages at the bus to which the DVR is connected. The second consequence is that a design of the DVR is needed in order to compensate a relatively wide range of disturbances. Common DVR applications concern for example unbalanced voltage sag/swell, optionally with harmonics cancellation.

The assumption of balanced perturbation in the supply voltages is in fact generally not realistic. It can be useful on the other hand to perform a basic analysis of the balanced conditions in which the DVR has to operate.

The type of compensation expected from the device is also important for the control strategy of DVR. It can be for example designed to operate only in case of voltage perturbation, or to operate continuously. The first alternative allows the presence of “blank” periods during which no compensation is provided. This approach is followed in the paper [7], where a DVR compensating unbalanced voltage disturbances with zero real power absorption or injection during steady-state operations is proposed. The DVR can be furthermore designed to provide or not power factor correction. A double converter stage for the compensation of the voltage unbalances with power factor correction during normal operations is proposed in the paper [2].

Finally, main task of the DVR can be the full voltage compensation. In this case the real power exchange is to be considered secondarily. For sensitive loads, where the required tolerance on the unbalance is very narrow, the operative capacity of control strategy should be as broad as possible and the speed of DVR response as high as possible.

3 DVR CONTROL STRATEGIES

To control the voltage during disturbances such as sags or swells, even unbalanced, a DVR has to compensate continuously on each phase. This task can be achieved using real-time measurement of amplitude and phase of the voltage to be controlled [2], [3], [4], [7]Being the DVR series connected between supply and load, its output voltage is added to the supply voltage after a proper filtering stage. With reference to Figure 3, the supply voltage is indicated as V_S. The sum of V_S and the DVR injected voltage is indicated as V_C, i.e. the controlled voltage at the load bus. This has to be maintained in each moment at the desired amplitude and phase.

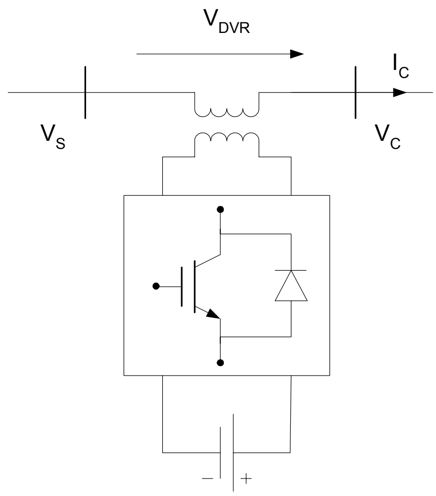

Figure 3: Principle of a DVR connected to the supply circuit.

3.1 Direct Compensation

Several methods based on this compensation technique have been proposed in the literature [2], [3], [4], and it is here mentioned for the sake of completeness. With the direct compensation approach, the voltage to be injected by the DVR is obtained as phasor difference between the desired voltage V_C and the measured voltage V_S.

This compensation can be realized in the three-phase domain, establishing a 120° displacement in each of the other two phase voltages to set at the load. Alternatively, equivalent reference systems can be considered, for example the $\alpha\beta 0$ or the $dq0$ domain.

The use of the mentioned equivalent representations has however as basic assumption, that the analyzed system and the signals, voltages and currents, are balanced. It can be proved that this assumption introduces errors especially in case of disturbances with unbalance in the phase angle, which can be tolerated in some cases, but not in general.

The compensation signals are at each moment calculated on the base of the measured voltage, and taking into account the load data and the desired power factor. If the voltage V_S on the supply side is taken as phase reference, a phasor diagram can be given as depicted in Figure 4 [2].

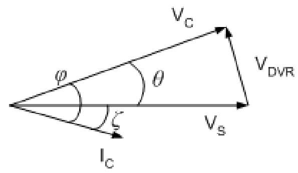

Figure 4: Operational principle of the DVR with the direct compensation approach.

In Figure 4 the following notation is used: φ is the load angle, $\zeta = arccos(P.F.)$ is the desired power angle, whereas $P.F.$ is the desired power factor, and θ is the compensation angle, expressed as $\theta = \varphi - \zeta$.

Since the load has been assumed balanced, the angle θ is calculated once. The components of the DVR voltage are then written:

$$\begin{aligned} V_{DVR}^{R} &= -V_S + V_C \cos\theta \\ V_{DVR}^{I} &= V_C \sin\theta \end{aligned} \qquad (1)$$

R and I represent two reference axes with respect to which the DVR compensation voltage is determined. Those axes can be identified with the real and imaginary axes in the complex plane, if the compensation is realized in three-phase domain. Alternatively they can be identified with the d and q-axes, if a system equivalent representation in the d-q domain is adopted.

3.2 Loop Control Compensation

The loop control technique has its origin in the classical control theory, where the output of a system is regulated to a desired value by means of adjustment of its input signals.

Main contribution of this paper is the proposal of a loop control compensation approach for the DVR. The determination of the voltages injected by the DVR is done in the $\alpha\beta 0$ equivalent reference system and it is not based on the phasor difference between the desired and the measured voltage at load bus.

The currents measured on the supply side that flow at the same time into the VSI, are expressed in the $\alpha\beta 0$-reference system and adjusted to the desired load current I_C by means of PI-controllers applied to each component. The three-phase current I_C is determined on the base of the desired load voltages V_C and power factor $\cos\varphi_C$, and of the load data. The output signals of the controllers are the $\alpha\beta 0$-components of the voltage that the DVR must inject. This way a Voltage Source Inverter is driven as a Current Source Inverter. After back transformation to phase-domain and normalization, these signals are passed to the modulator to obtain the pulses for the inverter.

The use of an equivalent representation of three-phase signals is done in order to reduce the complexity of the control implementation.

When voltage disturbances take place in a three-phase power system, they cause unbalance by generating negative- and zero-sequence voltages. In the $\alpha\beta 0$ reference system the negative-sequence voltage is emphasized in the α- and β-components, while the zero-sequence voltage is shown in the 0-component. Thus separate control actions are possible.

A transformation from an $\alpha\beta 0$ into a $dq0$ reference system under distorted conditions has the disadvantage to introduce higher order harmonics. Since a strong unbalance could take place, a further transformation into a $dq0$ system is avoided.

4 PROPOSED CONTROL IMPLEMENTATION

Figure 5 illustrates the DVR control scheme proposed in this paper. The load current I_M, that is also the current flowing into the VSI, is measured and transformed in the $\alpha\beta 0$-reference system (lower-left part of Figure 5). At the same time in the unit D.V.E (Desired Voltage Evaluation) the desired load current I_C is determined from the desired voltage V_C and assuming that the load is accurately described (upper-left part of Figure 5). Being load voltages and currents required always to be balanced, the 0-component of I_C is always equal to zero.

By means of PI-controllers applied to the difference between desired and measured values of the α- and β-components of the current, the voltages that have to be injected by the DVR can be calculated.

A back transformation from the α-, β- and 0-components of the DVR injected voltage into the three-phase reference system is finally performed. These are then normalized and passed to the modulator for the inverter driving pulses determination (unit PWM). The normalization with the battery voltage is done in order to obtain a maximum possible value of the modulating signals equal to one. A good controllability of the DVR is in fact reached when the inverter works in linear zone, i.e. avoiding over-modulation in normal conditions.

4.1 $\alpha\beta 0$ reference system

The transformation of three-phase signals, such as currents and voltages, from a three-phase reference to an equivalent $\alpha\beta 0$-reference system is well known as Clark transformation in the literature. However its mathematical expression is given for completeness:

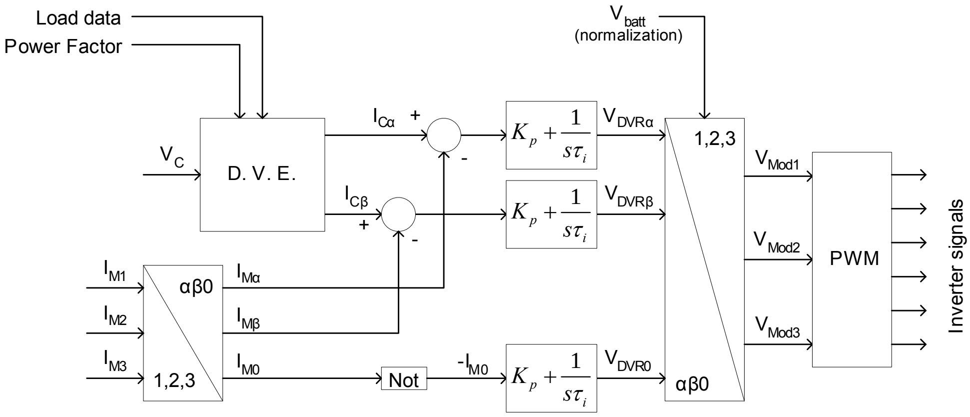

Figure 5: Proposed loop control compensation structure for the DVR.

$$\begin{aligned}\mathbf{x}_{\alpha\beta 0} &= \mathbf{T}\,\mathbf{x}_{123} \\ \mathbf{x}_{123} &= \mathbf{T}^{-1}\,\mathbf{x}_{\alpha\beta 0}\end{aligned} \qquad (2)$$

where the transformation matrix **T** follows:

$$\mathbf{T} = \frac{1}{\sqrt{3}}\begin{bmatrix} \sqrt{2} & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \\ 1 & 1 & 1 \end{bmatrix} \qquad (3a)$$

The transformation matrix **T** is normalized, and it is also orthogonal:

$$\mathbf{T}^{-1} = \mathbf{T}^{T} \qquad (3b)$$

Applying the *αβ0*-transformation to a three-phase balanced signal, the *0* component results to be always zero, so that in this case such component can be neglected. This is emphasized with the third equation of (2). Furthermore, it can be proved that for a three-phase balanced signal the α and β components present the same amplitude, are 90° phase displaced, and have the same frequency as the three-phase system.

The system matrices of a balanced three-phase circuit, that are generally coupled, are able this way to be expressed as uncoupled equivalent matrices. As a consequence, a coupled balanced three-phase system can be represented as an equivalent uncoupled two-phase system.

4.2 Unit D.V.E.

The unit D.V.E. determines the α- and β-components of the desired load current I_C. Under the assumption that the load is accurately described, let us denote with Z_L the magnitude of the load impedance and with φ the load angle, and with $\zeta = arccos(P.F.)$ the desired power angle, where *P.F.* is the desired power factor. The amplitude of the desired load voltage will be indicated with V_C. As assumption the phasor of the voltage V_C is taken as reference. The current I_C is then determined in amplitude and angle as follows:

$$\left|I_C\right| = \frac{V_C}{Z_C} \quad , \quad \arg\left(I_C\right) = -\arg\left(Z_C\right) + \varphi - \zeta = -\zeta \qquad (4)$$

The DVR injected voltage has to be synchronized with the exact phase angle of the supply side voltage. A phase detection on the first phase *a* has to be carried out. Phase angles of the other phases *b* and *c* are in steady-state conditions opportunely shifted. Denoting with γ the phase angle of the supply voltage, the α- and β-components of the desired load current are calculated as follows:

$$\begin{aligned} I_{\alpha d} &= \left|I_C\right|\cos\left(\omega t + \gamma + \arg\left(I_C\right)\right) \\ I_{\beta d} &= \left|I_C\right|\sin\left(\omega t + \gamma + \arg\left(I_C\right)\right) \end{aligned} \qquad (5)$$

where ω is the supply pulsation.

4.3 Inverter driving signals

In this paper a series connection of the DVR inverter using a yY configuration has been assumed. Another possible connection would be a delta/open connection, but in this last case a phase shift and an amplitude correction factor $\sqrt{3}$ are needed. With reference to Figure 5, the modulating waves are determined through normalization of the PI-controllers output signals on each phase *i* (*i = a,b,c*):

$$V_{Modi} = \frac{V_{DVRi}}{V_{batt}} \qquad (6)$$

The driving pulses for the VSI are determined using a conventional PWM method, as illustrated in Figure 6.

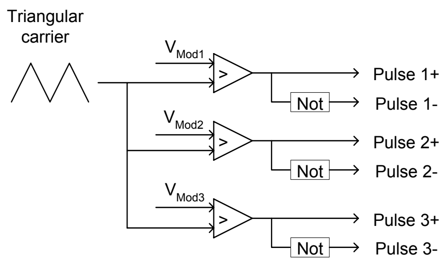

Figure 6: PWM signals generation technique.

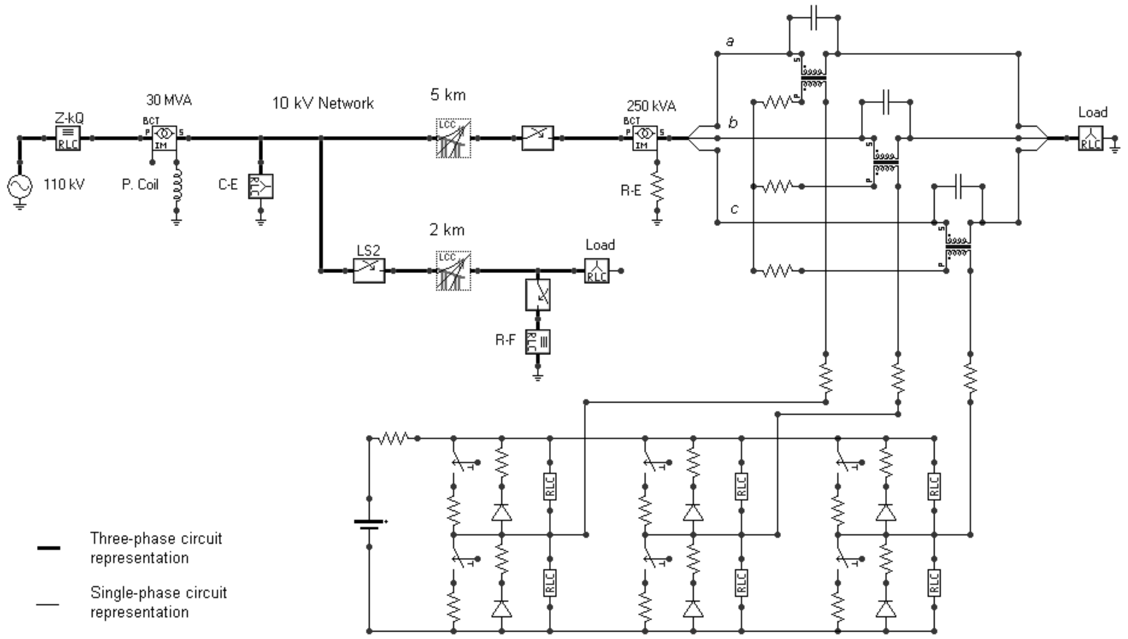

Figure 7: ATPDraw representation of the simulated network with DVR insertion.

5 NUMERICAL SIMULATION AND RESULTS

In this section a simulation example of the implemented loop compensation technique proposed in this work is shown. The analyzed system is shown in Figure 7. The simulation is performed under ATP-EMTP and the network is represented with the help of the graphical preprocessor ATPDraw.

The 10-kV distribution network is fed by a 110 kV network source. The DVR compensation is provided on the low voltage side of the 250-kVA, 10-kV/0.4-kV, delta-wye-transformer for a three-phase symmetrical load with P = 100 kW and Q = 75 kvar.

In the 10-kV network with Peterson coil connected to neutral point of the 110-kV/10-kV transformer, a fault is simulated at the end of a parallel cable feeder of length 2 km. The DVR compensated load is fed through a 10-kV, 5 km long overhead line.

The DVR inverter is constituted by six IGBTs each with its snubber circuit. Ideal coupling step-up transformers for the connection with the low voltage network are considered. These have a ratio from DVR to network of 1:2.

Fault is initiated at t = 140 ms and cleared at t = 220 ms. For the network configuration, the fault is chosen as two-phase to ground (a-b-g) with fault resistance of 1 Ω from each phase to ground. This way the highest unbalance in the low voltage side is introduced. The total simulation time is 250 ms.

The proposed control scheme is tested without and with power factor correction. Results of two cases are reported in the next subsections.

5.1 Compensation without power factor correction

The voltages measured at the low-voltage side of 250-kVA transformer before the insertion of the DVR are given in Figure 8. By using DVR with loop control compensation, the voltages on the load side are shown in Figure 9. The injected voltages on the network side are depicted in Figure 10.

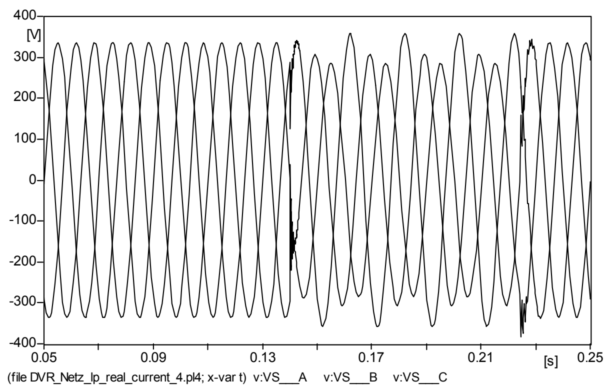

Figure 8: Voltage waveforms on the network side before the DVR insertion, no power factor correction.

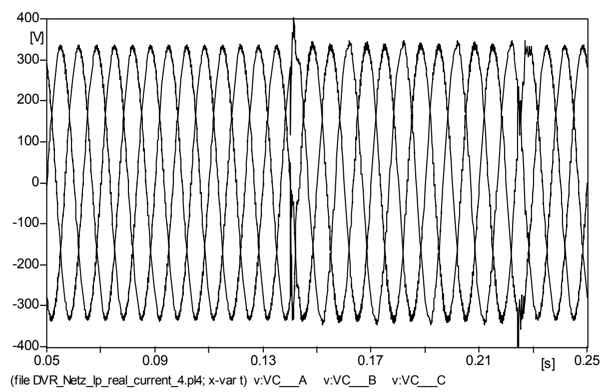

Figure 9: Voltage waveforms at the load bus with DVR loop control compensation, no power factor correction.

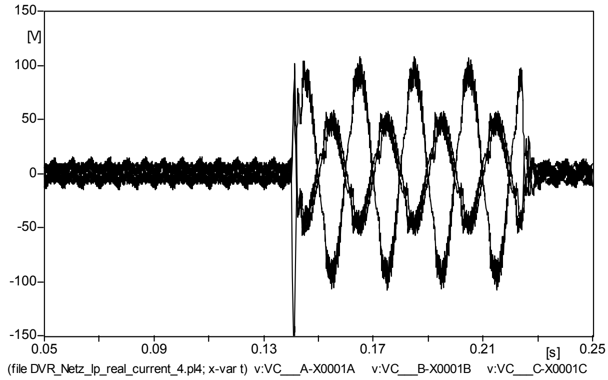

Figure 10: Injected DVR voltage waveforms on the network side of the coupling transformers, no power factor correction.

5.2 Compensation with power factor correction

The voltages measured at the low-voltage side of 250-kVA transformer before the insertion of the DVR are the same of Figure 8. By using DVR with loop control compensation and specifying a power factor correction to $cos\ \varphi_C = 0.9$, the voltages on the load side results to be as depicted in Figure 11. The injected voltages on the network side are reported in Figure 12.

It should be emphasized that the power factor correction as shown in Figure 12 functions in the steady-state normal operation as well as under fault conditions.

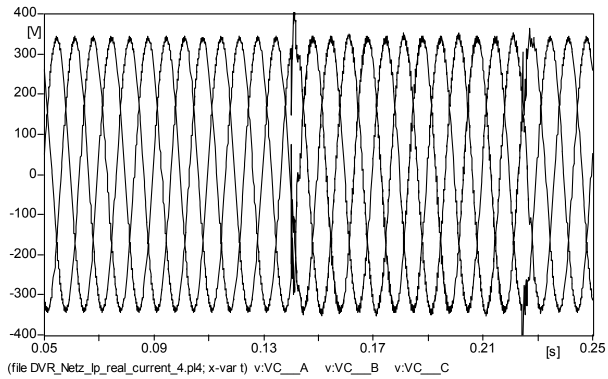

Figure 11: Voltage waveforms at the load bus with DVR loop control compensation with power factor correction.

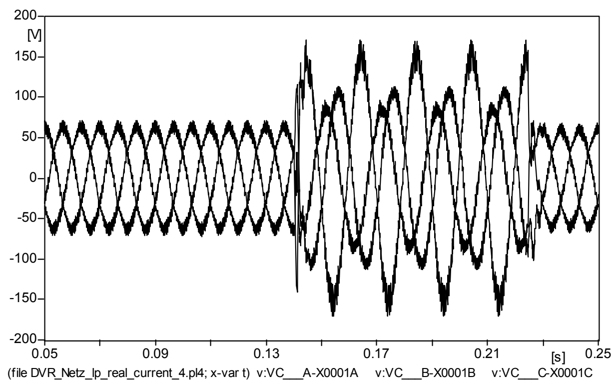

Figure 12: Injected DVR voltage waveforms on the network side of the coupling transformers with power factor correction.

6 CONCLUSIONS

A loop compensation control strategy for Dynamic Voltage Restorer (DVR) has been proposed in this paper. The DVR is capable to regulate the voltage at a critical load against any disturbance of the voltage on the supply side. Other control techniques such as direct compensation control have been illustrated as well.

The proposed control technique has been tested using numerical simulations for a DVR connected in series with a low-voltage customer load. Voltage compensation is provided in case of unsymmetrical faults on a parallel branch in the medium-voltage network that feeds the low voltage load.

Numerical simulations using ATP-EMTP show the effectiveness of the presented loop control technique and are important means to test the feasibility of DVR application for a customer plant.

REFERENCES

[1] N. G. Hingorani, L. Gyugyi, “Understanding FACTS, Concepts and Technology of Flexible AC Transmission Systems”, IEEE Press, 2000 (ISBN 0-7803-3455-8)

[2] B.-M. Han, P. Mattavelli, “Performance Analysis of Dynamic Voltage Compensator using EMTP Simulation”, Proceedings ICEE 2000, paper n° A-2-01, pp. 227-230

[3] C. Zhan, V. K. Ramachandaramurthy, A. Arulampalam, C. Fitzer, S. Kromlidis, M. Barnes, N. Jenkins, “Dynamic Voltage Restored Based on Voltage-Space-Vector PWM Control”, IEEE Trans. On Industry Applications, Vol. 37, N° 6, Nov./Dec. 2001, pp. 1855-1863

[4] O. Anaya-Lara, E. Acha, “Modelling and Analysis of Custom Power Systems by PSCAD/ETMDC”, IEEE Trans. On Power Delivery, Vol. 17, N° 1, Jan. 2002, pp. 266-272

[5] S. S. Choi, B. H. Li, D. M. Vilathgamuwa, “Design and Analysis of the Inverter-Side Filter Used in the Dynamic Voltage Restorer”, IEEE Trans. On Power Delivery, Vol. 17, N° 3, July 2002, pp. 857-864

[6] A. Ghosh, A. Joshi, “A New Algorithm for the Generation of Reference Voltages of a DVR Using the Method of Instantaneous Symmetrical Components”, IEEE Power Engineering Review, Jan. 2002, pp. 63-65

[7] A. Ghosh, G. Ledwich, “Compensation of Distribution System Voltage using DVR”, IEEE Trans. On Power Delivery, Vol. 17, N° 4, Oct. 2002

[8] W. S. Meyer, “ATP Rule Book”, Can/Am EMTP User Group, Portland, USA