DYNAMIC VOLTAGE RESTORER WITH COMPLETE CONTROL OF THE CONNECTION TRANSFORMERS SATURATION

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***Abstract* - This paper proposes a technique to suppress saturation in series transformers applied to dynamic voltage restorer (DVR) systems. The method consists in correcting the voltages which are injected through the transformers into the power system to compensate voltage sags. It restricts the compensating voltages during the sag whenever it predicts that a maximum limit for the flux-linkage is about to be surpassed. The prediction takes place at the beginning of the voltage sag. Moreover, the method always allows a level of sag compensation even if its prediction for exceeding flux limit is confirmed. Simulation and experimental results show the effectiveness of the method.**

***Keywords* – Dynamic Voltage Restorer, Flux-Linkage, Power Quality, Saturation, Transformer, Voltage Inverter.**

I. INTRODUCTION

Voltage sags are the most incident power quality events inflicting the power system. Surveys indicated that 92% of interruptions in industrial facilities may occur due to voltage sags [1]. The economic impact to the industries and utilities is severe due to damage of equipment and loss of production [2]. There are several approaches to mitigate this problem. One can invest in the power system design in order to reduce the number and clearing time of the faults, or to install redundant paths to feed critical loads [3]. These solutions are not simple to implement and are usually costly. Another kind of approach is to apply mitigating equipments at the power system-load interface. One of these equipments, is the dynamic voltage restorer.

A DVR is one of the most effective custom power device for voltage sag and swell compensation and it has been attracting growing attention in recent years [4–6]. A typical test system, incorporating a DVR, is depicted in Figure 1. The DVR injects compensating voltages to the power lines through a three-phase series transformer or three single-phase series transformers. A problem may arise when the DVR system corrects a sag. This demands a compensation voltage which causes the flux-linkage in the core to exceed the transformer nominal limit [7]. This, in turn, leads to overcurrent and overheating, reducing the useful life of the transformer. The exceeding flux may be caused by a dc component whose amplitude depends on the initial phase angle of the compensating voltage. To overcome this problem, one alternative is to oversize the series transformers. This solution brings an increase in physical size, weight, and cost to the transformer [8]. Another approach is to control the flux-linkage by limiting the voltage injected to compensate the sag.

In [9], the flux-linkage in the DVR's transformers is kept under a maximum limit by shutting off the reference voltage once the converter currents reach a specified limit, until the current is reduced or the reference voltage is reversed. In [10], the flux is estimated by means of the integral of the voltage and whenever it reaches a given limit the voltage is set to zero. The method proposed in [11] also makes use of the flux estimation in order to limit the compensating voltages. The injection voltage action is divided into three intervals. Between the sag detection instant and one sixth of the fundamental period T, after the sag detection, the injected compensating voltage is fully applied to compensate the sag. Between $T/6$ and $T/3$, the injected voltage is adjusted to zero. From the instant $T/3$ on, again the full compensating voltage is applied. In [12], two methods for flux-linkage control are presented. In the first one, the compensating voltage is multiplied by half during the first half fundamental cycle after the sag detection instant and, afterwards this period, the full compensating voltage is used. This assures that the dc flux is wiped off. The second method predicts whether the flux surpasses the maximum limit within half a cycle past the zero cross. If the flux is exceeded, then it is introduced a form factor to limit the compensating voltage.

In many compensating sag systems, the transformers are designed to correct minor sags, usually equal or less than the nominal voltage of the protected load [1], [13]. Thus, it is important to the flux control system to account the possibility of greater sags in order to keep the flux within the transformer limit. This paper proposes a flux control technique that copes with this hypothesis while it still allows an efficient sag correction to be performed.

II. PROPOSED METHOD

Consider the compensating voltage, v_c, is described as

$$v_c(t) = V cos(\omega t + \alpha), \tag{1}$$

where ω is the fundamental frequency and α is the initial phase of the compensating voltage. By Faraday's law, the linked flux, λ, in the transformer's core at a given instant t, can be expressed by

$$\lambda = \int_0^t V cos(\omega \tau + \alpha) d\tau. \tag{2}$$

Solving (2), and supposing the transformer is demagnetized, that is, $\lambda = 0$ at the initial instant, we obtain the following

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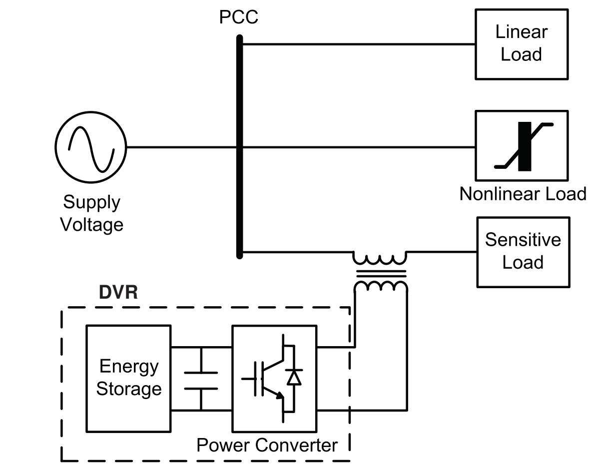


Fig. 1. System configuration with a DVR.

expression for the flux

$$\lambda = (V/\omega)\left[sin(\omega t + \alpha) - sin(\alpha)\right]. \quad (3)$$

The first part of (3) represents the ac component of the flux, while the second one is its dc component. Whenever, the injected voltage starts at a zero cross, that is, $\alpha = \pi/2 \pm n\pi$ the peak of the flux reaches its maximum value. For instance, if $\alpha = 3\pi/2$, the expression for the flux is given by

$$\lambda = (V/\omega)\left[cos(\omega t) + 1\right]. \quad (4)$$

This situation is illustrated in Figure 2(a). In order to eliminate the dc flux, one of the methods described in [12] can be applied. Hence, it is enough to multiply the injected voltage by a factor $K = 0.5$ during half cycle after the compensating voltage is started. Figure 2(b) shows the result of such technique to control the flux depicted in Figure 2(a). Figure 2(c) shows how the injected voltages are modified to compensate the sag while still inducing a flux within the established limits. In this figure, one of the phase voltages is multiplied by the factor K.

The technique proposed in this paper is inspired by the one described in [12]. Considering Figure 3, where the injected voltage starts at angle α, it is possible to predict the flux-linkage at the instant corresponding to the angle $3\pi/2$ through the following integration

$$\lambda' = \int_{\alpha/\omega}^{(\pi/2)/\omega} V\,cos(\omega t)\,dt + \xi \int_{(\pi/2)/\omega}^{(3\pi/2)/\omega} V\,cos(\omega t)\,dt, \quad (5)$$

where ξ is a form factor that is firstly set to unity. Note that between α and $\pi/2$ the injected voltage contributes positively to the flux. Between $\pi/2$ and $3\pi/2$, the voltage contributes negatively to the flux. Therefore, in the situation depicted in Figure 3, at the angle $3\pi/2$, the flux reaches its minimum value. If the prediction provides a value whose module is higher than the transformer's maximum flux-linkage then the parameter ξ must be adjusted to a value such that the module of the flux does not exceed the maximum value allowed. Thus, if $\lambda' < -\lambda_{max}$, make $\lambda' = \lambda_{max}$ in equation (5) and find ξ as

$$\xi = \frac{-\lambda_{max} - V\int_{\alpha/\omega}^{(\pi/2)/\omega} cos(\omega t)\,dt}{V\int_{(\pi/2)/\omega}^{(3\pi/2)/\omega} cos(\omega t)\,dt}. \quad (6)$$

This equation makes sure that flux will not surpass the minimum limit. Nevertheless it does not assure that the maximum limit will not be exceeded within the positive semicycle of the voltage. The form factor ξ is applied to the voltage during the negative semicycle of the sinusoid voltage. When the injected voltage starts within a negative semicycle of the sinusoidal, λ' must be computed as

$$\lambda' = \int_{\alpha/\omega}^{(3\pi/2)/\omega} V\,cos(\omega t)\,dt + \xi \int_{(3\pi/2)/\omega}^{(5\pi/2)/\omega} V\,cos(\omega t)\,dt. \quad (7)$$

If $\lambda' > \lambda_{max}$, the injected voltage requires scaling, and then, the form factor is written as

$$\xi = \frac{\lambda_{max} - V\int_{\alpha/\omega}^{(3\pi/2)/\omega} cos(\omega t)\,dt}{V\int_{(3\pi/2)/\omega}^{(5\pi/2)/\omega} cos(\omega t)\,dt}. \quad (8)$$

The procedure described above does not eliminate the dc flux. It only shifts the flux curve so that within the period comprised by the next sinusoid semicycle, afterwards α, the flux does not surpass the limit. It still can remains a net flux λ_{net}, and this net flux can surpass the limit after this period. In other words, the opposite peak of flux waveform may exceed λ_{max} when displacement procedure is performed. The procedure only assures that for the condition of $0 \leq \alpha < \pi/2$ or $3\pi/2 \leq \alpha < 2\pi$, the flux does not surpass a maximum limit. For the condition $\pi/2 \leq \alpha < 3\pi/2$, the flux does not exceed the minimum limit (whose module is the same as the minimum limit). For the first condition, the net flux, λ_{net}, is given by

$$\lambda_{net} = \int_{\alpha/\omega}^{(\pi/2)/\omega} V\,cos(\omega t)\,dt + \xi \int_{(\pi/2)/\omega}^{(3\pi/2)/\omega} V\,cos(\omega t)\,dt + \int_{(3\pi/2)/\omega}^{(5\pi/2)/\omega} V cos(\omega t) dt. \quad (9)$$

The third part of (9) indicates whether flux will be exceeded after displacement. For the second condition, $\pi/2 < \alpha < 3\pi/2$, the net flux is computed through

$$\lambda_{net} = \int_{\alpha/\omega}^{(3\pi/2)/\omega} V\,cos(\omega t)\,dt + \xi \int_{(3\pi/2)/\omega}^{(5\pi/2)/\omega} V\,cos(\omega t)\,dt + \int_{(5\pi/2)/\omega}^{(7\pi/2)/\omega} V\,cos(\omega t) dt, \quad (10)$$

The method proposed in [12] cannot deal with the situation where the net flux is higher (or lower) than the maximum (or minimum) flux limit of the transformer. To cope with this hypothesis, this paper proposes a method which predicts at the instant corresponding to angle α whether the net flux will surpass the transformer limit. The algorithm below summarizes the proposed method implementation:

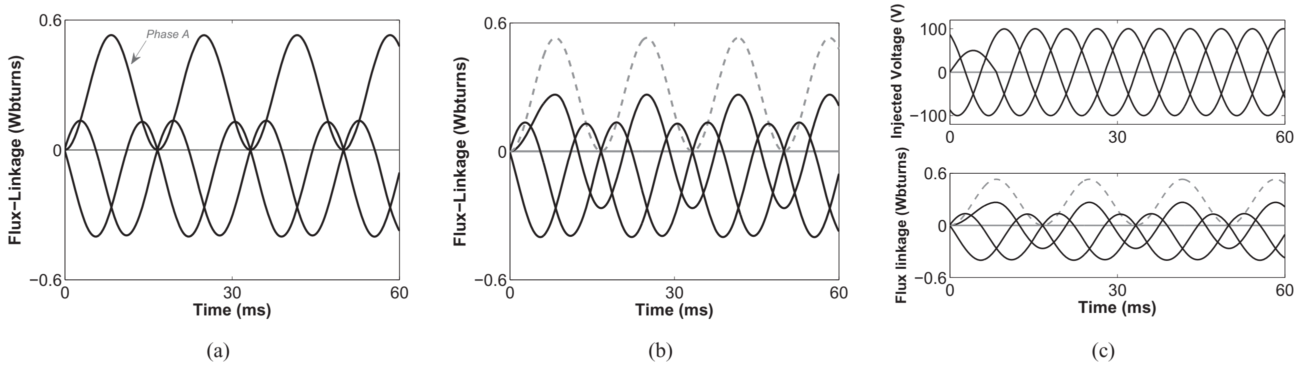


Fig. 2. Flux-linkage in the three injection transformers. (a) Maximum flux-linkage on phase-A. (b) Elimination of dc flux-linkage on phase-A. (c) Reduction of the voltage injection on phase-A (top graphic).

1. Read $v_c(t)$, identify phase-angle α (between 0 and 2π), and calculate the amplitude of $v_c(t)$;
2. Make ($\xi = 1$). If ($0 \leq \alpha < \pi/2$) or ($3\pi/2 \leq \alpha < 2\pi$) then apply equation (5). If ($\pi/2 \leq \alpha < 3\pi/2$) apply equation (7);
3. If ($\lambda' < -\lambda_{max}$) then compute ξ through equation (6). If $\lambda' > \lambda_{max}$, then compute ξ through equation (8). If none of these conditions are verified then $\xi = 1$;
4. If ($0 \leq \alpha < \pi/2$) or ($3\pi/2 \leq \alpha < 2\pi$) then compute λ_{net} through equation (9). If ($\pi/2 \leq \alpha < 3\pi/2$), use equation (10);
5. If ($|\lambda_{net}| < \lambda_{max}$) then,
   if ($0 \leq \alpha < \pi/2$) or ($3\pi/2 \leq \alpha < 2\pi$), the compensating voltage is given by

   $v_c(t) = V cos(\omega t + \alpha),\ for\ (\alpha \leq \omega t < \pi/2)\ and\ (\omega t \geq 3\pi/2)$

   $v_c(t) = \xi V cos(\omega t + \alpha),\ for\ (\pi/2 \leq \omega t < 3\pi/2),$

   if ($\pi/2 \leq \alpha < 3\pi/2$) then,

   $v_c(t) = V cos(\omega t + \alpha),\ for\ (\alpha \leq \omega t < 3\pi/2)\ and\ (\omega t \geq 5\pi/2)$

   $v_c(t) = \xi V cos(\omega t + \alpha),\ for\ (3\pi/2 \leq \omega t < 5\pi/2);$

6. If ($|\lambda_{net}| > \lambda_{max}$) then make $V_{max} = \lambda_{max}\omega$ and the compensating voltage must be determined by

   $v_c(t) = (V_{max}/2)cos(\omega t + \alpha),\ for\ (\alpha \leq \omega t \leq \alpha + \pi/2)$

   $v_c(t) = (V_{max})cos(\omega t + \alpha),\ for\ (\omega t > \alpha + \pi/2).$

It is worth stating that the phasor of the analyzed signals and the start angle α are estimated through a recursive least-squares-algorithm [14]. Furthermore, the DVR voltage correction only takes place whenever the amplitude estimation is stabilized, that is, during the transition time, the angle α and the phasor is not available to carry out the algorithm previously proposed.

III. METHOD ANALYSIS

In Figure 4, we have three scenarios where the flux exceed the limit value of the transformer saturation. Each one of them was simulated with different injection angles. In the graphics, the dashed curves represent the situation where correction is

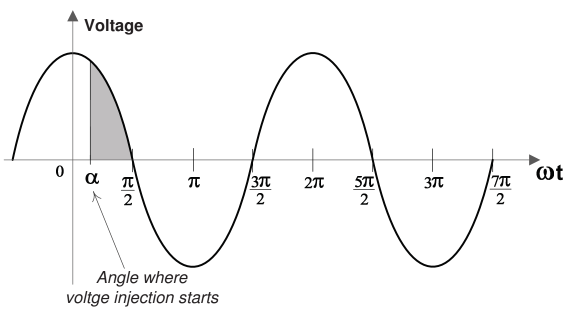


Fig. 3. Compensating voltage for one of the phases.

not worked out. The solid curves make use of the methodology presented. As the limit value is 0.3Wbturn, it is possible to observe that the technique impose the amplitude equal to the maximum value allowed before saturation. For this, the technique just shift the flux waveform by multiplying the respective injected voltage by the ξ factor, but keeping the same amplitude of the waveform. This prevents the maximum flux-linkage excursion from being exceeded and still no entry in saturation mode.

However, in some cases the flux waveform displacement may cause exceed on the opposite peak of the sinusoid which was limited by the maximum flux. This is can be observed in the Figure 4(c), now assuming 0.2Wbturn as the saturation value. In this case it is necessary to limit the negative and positive peaks of the flux, following step 6 of the algorithm. These values are determined by the maximum flux of the transformer. The proposed algorithm provides the solution to this problem packaging the sinusoid between $-\lambda_{max}$ and λ_{max}, as can be observed in the figure. This is a precaution so that the transformer does not entry into the non-linear mode, despite the amplitude of the injected voltage be less than the necessary to restore the correct voltage. Running in this mode of operation is more adequate than makes use of the transformer on saturation mode, since it generates non-linear waveforms and can cause overheating in the device.

IV. SIMULATED RESULTS

A model of the proposed DVR has been implemented in the packages *SimPowerSystems* and *Simulink* of the Matlab.

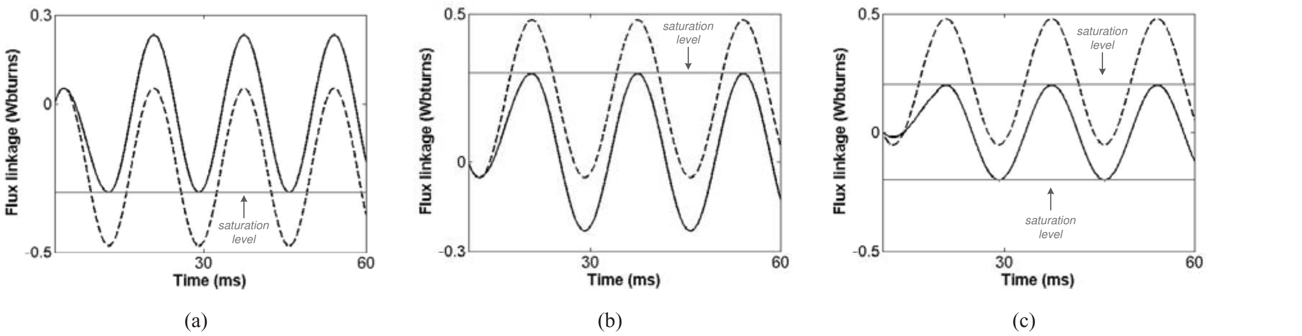


Fig. 4. Flux-linkage in the transformer. (a) Flux exceeding down limit (dashed) and correction (solid). (b) Flux exceeding upper limit (dashed) and correction (red). (c) Flux-linkage where upper and lower limits are necessary.

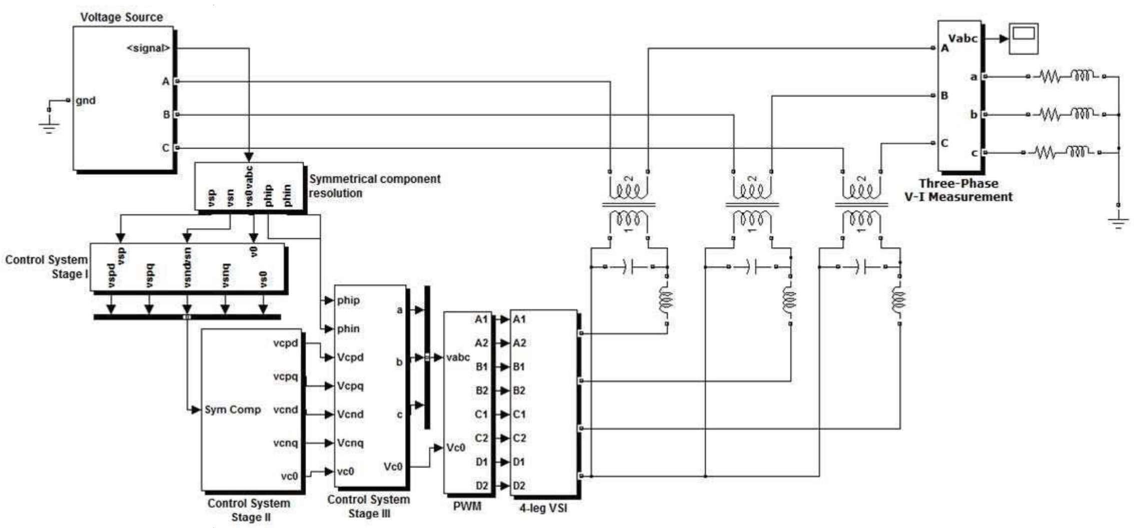


Fig. 5. Simulation platform of the dynamic voltage restorer system.

The methodology to avoid transformer saturation described in previous sections is implemented together with the control system. Figure 5 shows the simulated system. Table I shows the parameters used in the simulation.

TABLE I
Simulated system parameters

Parameter	Value
transformer saturation	0.38Wbturn
L (filter)	2mH
C (filter)	16μF
R (load)	15Ω
L (load)	1mH
transformer ratio	1:1

A four-leg inverter is adequate for synthesizing asymmetric voltages. Figure 6 shows the inverter in details, which was used in the block "4-leg VSI" of the Figure 5. The inclusion of the fourth leg allows zero-sequence to be generated. The PWM strategy applied to control the inverter is described in [6]. Details from the DVR control system can be found in [15].

Consider that a three-phase grid is under a phase-to-phase sag during 50ms, as it is illustrated in Figure 7(a). Figure 7(b) shows the least-squares amplitude estimation for phase A. Besides the amplitude, a least-squares algorithm also estimates the angle α. Moreover, the estimation allows to detect where the changing in the estimation starts and where it is finished. In Figure 7(b) these instants are indicated by the dotted lines. We can highlight four instants. The first two are related to the beginning of the sag and the last two are associated to the end of the sag. It must be pointed out that there is a transition time where the amplitude is changing and the voltage correction is not triggered. Figure 7(c) shows the injected voltage by the DVR for the two sagged phases. It is worthy noticing that the injected voltage for phase A is

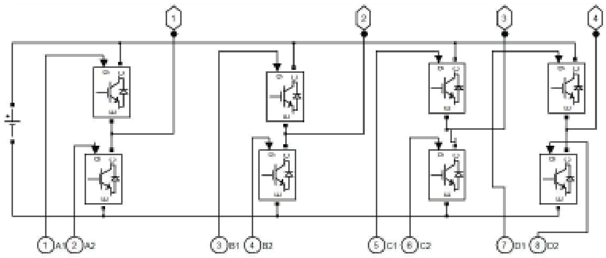


Fig. 6. Detail of the 4-leg voltage source inverter used in the DVR system.

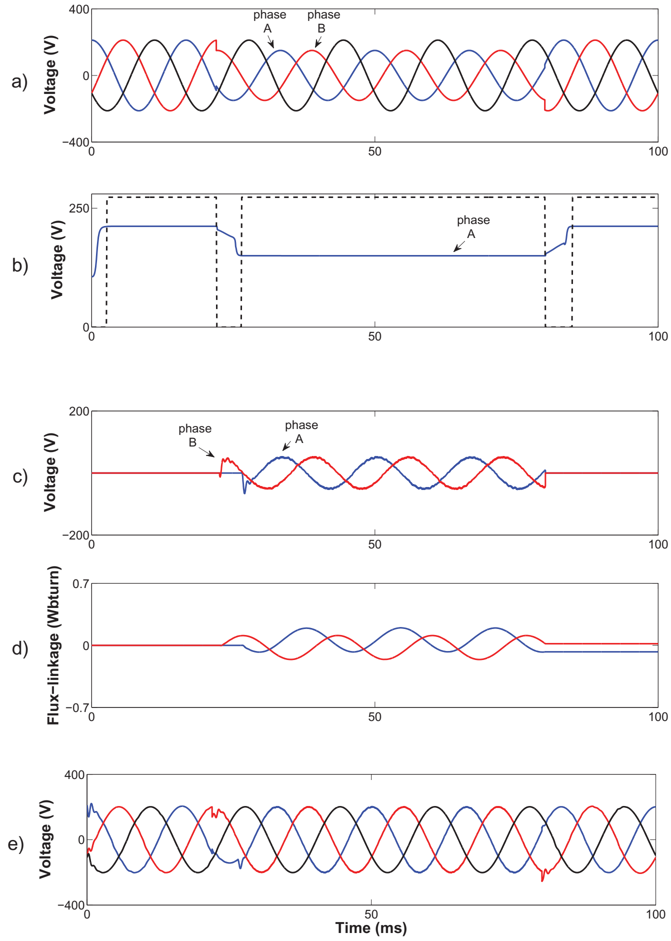


Fig. 7. Simulation results for the DVR system: Case I. (a) Voltage sags on phases A and B. (b) Estimated amplitude for phase A. (c) Voltages injected by the DVR. (d) Flux-linkage in the transformers. (e) Corrected voltages on the load.

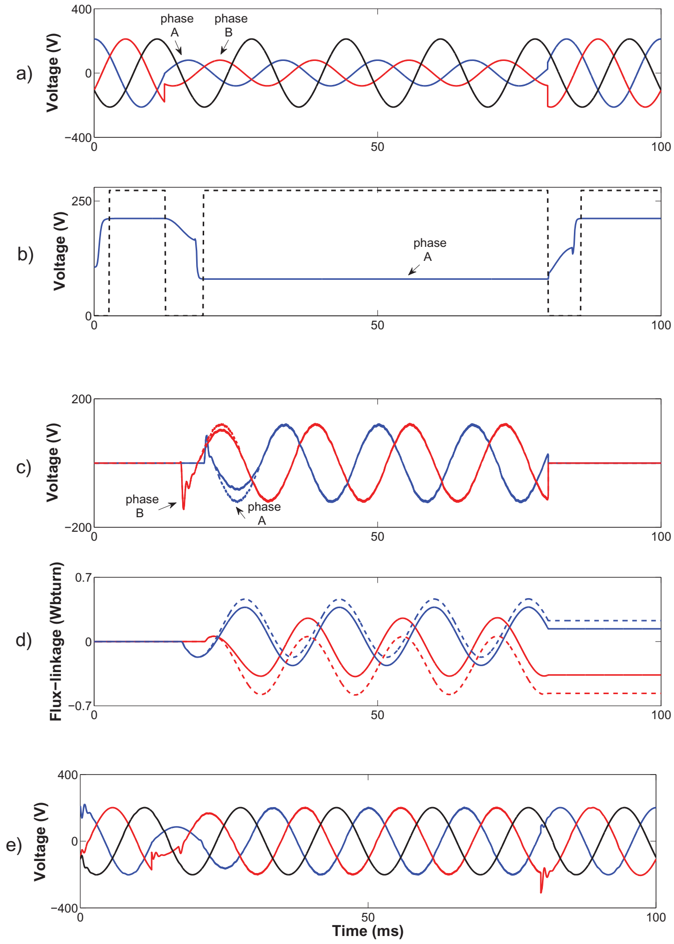


Fig. 8. Simulation results for the DVR system: Case II. (a) Voltage sags on phases A and B. (b) Estimated amplitude for phase A. (c) Voltages injected by the DVR. (d) Flux-linkage in the transformers. (e) Corrected voltages on the load.

ignited at the instant time where the estimation for the phase A amplitude is stabilized. Although not shown in this figure, the same is true for the other phase. Figure 7(d) shows the flux-linkage associated to each phase. The fluxes for the two phases do not exceed the limit of 0.38 Wbturn. Figure 7(e) shows the corrected voltages applied to the load.

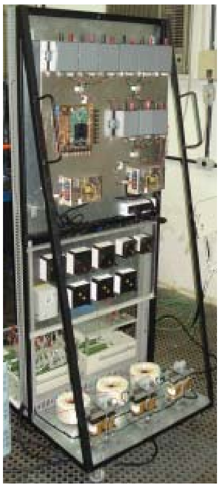
Figure 8(a) shows a phase-to-phase fault for a different start angle α. Figure 8(b) shows the amplitude estimation carried out by the least-squares algorithm for phase A. Again, the instants where the sag is initiated and finished are highlighted by the dotted lines. Figure 8(c) shows a set of four curves of voltages injected by the DVR on the grid. The dotted curves are the injected voltages that would be injected without the flux control proposed in this paper. On the other hand, the solid lines are the voltages controlled taking into account the flux controlled method proposed in this paper. In this particular case, the flux is controlled taking the first five steps of the algorithm proposed in second section. Figure 8(d) shows four curves for fluxes-linkages within the transformers. The dotted curves are the ones obtained without the use of the flux control scheme. The solid ones use the proposed algorithm. We verify in this case that the solid lines do not surpass the exceeding limits opposed to the situation depicted with the dotted lines. Figure 8(e) show the corrected voltages imposed on the load.

V. EXPERIMENTAL RESULTS

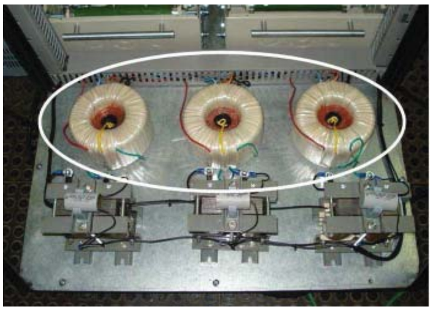
The DVR has been set up in the laboratory as shown in Figure 9. The experimental apparatus is composed by an stage of power and other stage of data and acquisition of the signals (Figs.9(a) and 9(b)). With regards to the stage of power, the main component is the voltage source inverter (VSI), composed by four-legs. The dc-link is made out of four capacitors of 2200μF/450V equivalent to 2200μF/900V. The modulated voltages are filtered by an LC filter for each phase. The values for the components are the same presented in Table I. The load are made of power resistors. The data acquisition system is formed by Hall sensors for voltages and currents. The signal processing is carried out by a Texas Instruments digital signal controller (DSC) TMS320F28335.

The transformers used by the DVR system are shown in Figure 9(c). The core of the transformers is made

(a)



(b)



(c)

Fig. 9. Laboratory-scale dynamic voltage restorer. (a) Power stage. (b) Control and acquisition system. (c) Detail of the transformers used in the DVR.

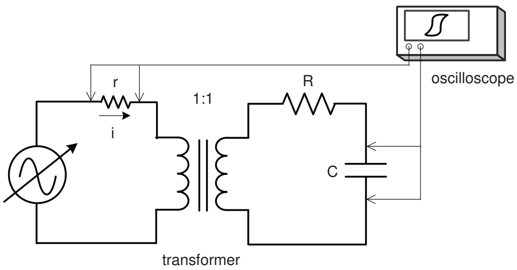


Fig. 10. Circuit used for measuring saturation level of the transformer.

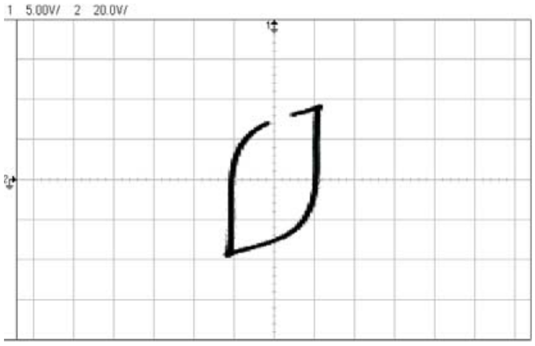
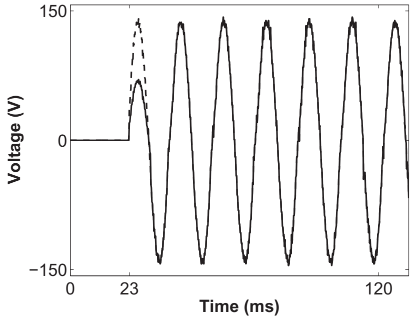
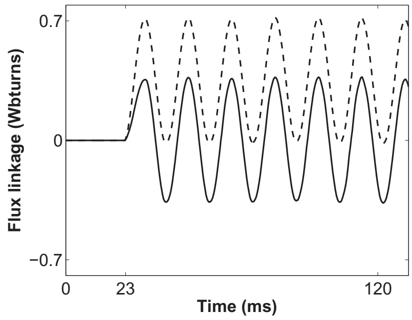


Fig. 11. Experimental hysteresis curve of the transformer (vertical scale= $5V/$div; horizontal scale= $20V/$div).



(a)



(b)

Fig. 12. DVR correction for a phase A voltage sag. (a) Voltage compensation without the application of the proposed method (dash) and with the correction (solid). (b) Flux exceeding the saturation limit (dash) and without the dc component (solid).

of ferromagnetic grain-oriented material in toroidal shape. These characteristics minimize the leakage inductance. The transformer is rated 1kVA and the ratio of turns of the secondary to the primary circuit is 1:1.

The first experimental result shown in this section is related to the determination of the saturation value of the DVR's transformers. For this purpose, it has been set a circuit composed by resistors and capacitor for measurement. The circuit is shown in Figure 10.

The parameters R and C are selected so that $1 + sRC$ can be approximated by sRC and $\omega_0 = 377\ rad/s >> 1/(RC)$. Thus, $R = 12k\Omega$ and $C = 1\mu F$. Also $r = 100\Omega$. Figure 11 shows the experimental result for the hysteresis curve of the transformer. The extremes of this curve represent the beginning of saturation. To the right of this curve, the extreme point is (5.94;37.90)V. The second coordinate of this point is the capacitor voltage. This voltage when multiplied by RC provides the maximum value for the flux, λ_{max}, which is $\cong 0.38$Wbturn.

The next experimental result refers to the dc flux elimination. Figure 12 shows the graphics of the voltage and the flux-linkage with and without the dc flux elimination. Figure 12(a) shows the inject voltage during a sag in phase A. Figure 12(b) shows the computed flux in the transformer's core. The dashed curve represents the flux when there is no voltage modification. In this situation, the maximum limit for the flux (0.38Wbturn) is surpassed leading the transformer to work in the saturation level. As already explained, this occurs due to the instant of the voltage injection. Nevertheless,

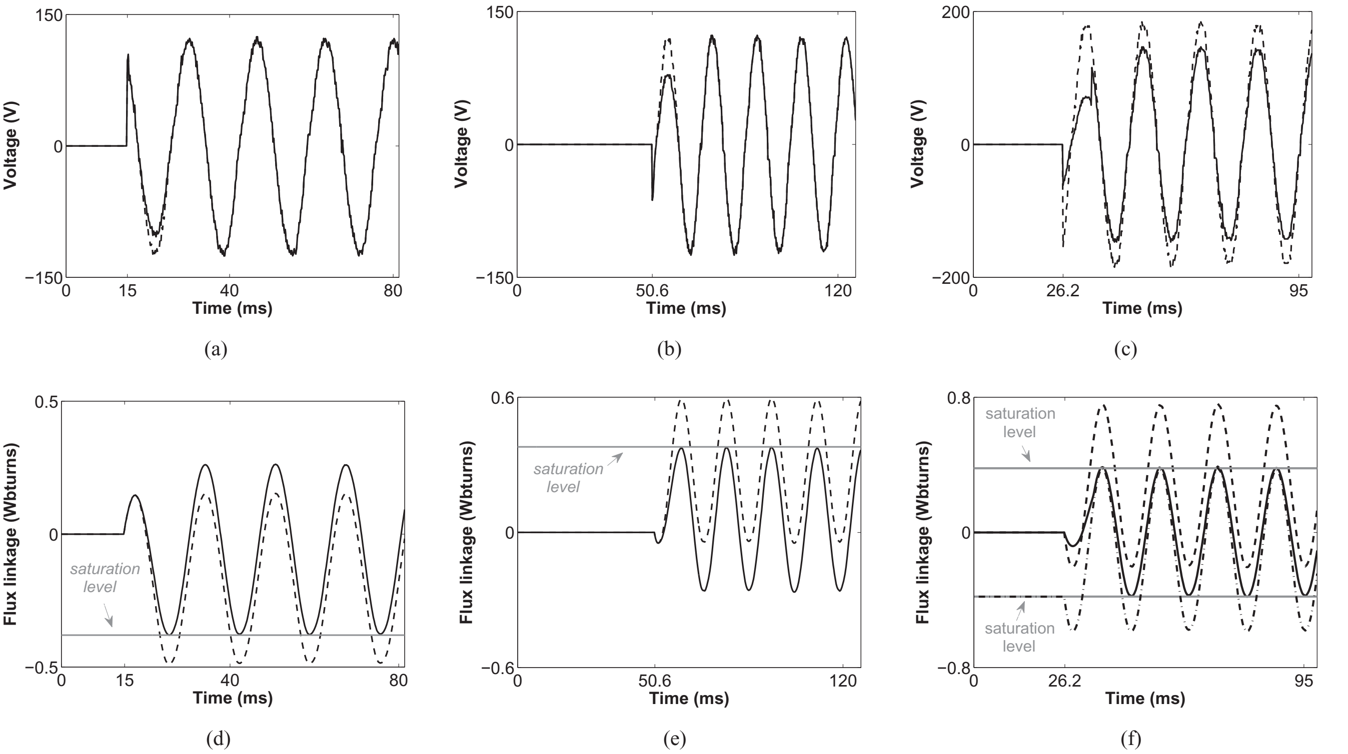


Fig. 13. Voltage corrections and related flux for critical loads. (a),(b), and (c) Injected voltages with and without the use of the form factor. (d),(e), and (f) Flux-linkage curves controlled and not controlled.

applying the method for eliminating the dc flux, the solid curves are obtained, and the flux variation ranges within the transformer's limit.

The next experiment illustrates the situation where the flux is just shifted according to the application of form factor, and also, the situation where it is limited according to the method proposed in this paper. Figure 13 shows these situations. The compensating voltage starts at 15ms as shown in Figure 13(a). This effect on the flux curves is shown in Figure 13(d) (dashed lines). It can be noticed that the flux curve exceeds the minimum limit. By means of equation (5), it is possible to predict whether the flux will exceed the imposed limit. Thus, through equation (6), a form factor ξ to restrain the compensating voltage is determined. This can be still observed in Figure 13(a) (solid line). Hence the flux is adequately displaced so that it does not surpass the minimum limit, as shown by the solid line.

Similarly to the last case, Figure 13(b) depicts a situation where the injected voltage leads to an exceeding flux. Again, an adequate form factor ξ is computed and applied to the voltage during half of a fundamental cycle which displace the flux to its allowed limit, as shown in Figure 13(e) (solid line).

Figure 13(c) shows a situation where the injected voltage would not be restrained by any factor (dashed line). This implies in a flux depicted in Figure 13(f) (dashed line). Again, we verify that the flux surpasses the maximum limit. Applying the method described in [12], a form factor ξ is computed and applied to the voltage so the flux is displaced to not exceed the maximum limit, as indicated in the dash-dotted flux curve. However, the opposite flux amplitude surpasses the minimum limit. To overcome this problem, we proceed according to the algorithm described in section II, that is, the dc flux is eliminated and its ac amplitude is restrained to the limit value of the flux, as shown by the solid line. The drawback of this method is that the compensating voltage is not sufficient to entirely eliminate the sag. Even so, this is preferable to the transformer saturation which is related to distorted currents.

VI. CONCLUSIONS

This work proposed a method for controlling saturation of the three injected transformers of a DVR. It assures a entire elimination of the dc flux or allows a level of flux that does not exceed the transformer's limit. The simulated results contemplate all possible sag scenarios for generating exceeding flux. An experimental dynamic voltage restorer prototype was set up and used to generate the experimental results which corroborate the efficacy of the method.

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REFERENCES

[1] Y.-H. Chen, C.-Y. Lin, J.-M. Chen, and P.-T. Cheng. An inrush mitigation technique of load transformers for the series voltage sag compensator. *IEEE Trans. Power Electron.*, 25(8):2211–2221, Aug. 2012.

[2] R. H. G. Tan and V. K. Ramachandaramurthy. Voltage sag acceptability assessment using multiple magnitude-duration function. *IEEE Trans. Power Del.*, 27(4):1984–1990, Oct. 2012.

[3] M. A.-Mora and J. V. Milanovic. Monitor placement for reliable estimation of voltage sags in power networks. *IEEE Trans. Power Del.*, 27(2):936–944, Apr. 2012.

[4] A. Y. Goharrizi, S. H. Hosseini, M. Sabahi, and G. B. Gharehpetian. Three-phase HFL-DVR with independently controlled phases. *IEEE Trans. Power Electron.*, 27(4):1706–1718, Apr. 2012.

[5] P. Kanjiya, B. Singh, A. Chandra, and K. A-. Haddad. SRF theory revisited to control self supported dynamic voltage restorer (DVR) for unbalanced and non-linear loads. In *IEEE Industry Application Society Annual Meeting. Proc. of IAS'11*, volume 1, pages 1 – 8, 2011.

[6] D. A. Fernandes and S. R. Naidu. Estratégia de modulação para um inversor de tensão de quatro braços utilizado em um restaurador dinâmico de tensão. *Eletrônica de Potência* - SOBRAEP, 58(13):2580–2587, Dec. 2008.

[7] D. I. Taylor, Joseph D. Law, Brian K. Johnson, and Normann Fischer. Single-phase transformer inrush current reduction using preuxing. *IEEE Trans. Power Electron.*, 27(1):245–252, Jan. 2012.

[8] S. W. Middlekauff and E. R. Collins. System and customer impact: Considerations for series custom power devices. *IEEE Trans. Power Del.*, 13(1):278–282, Feb. 1998.

[9] J. G. Nielsen, M. Newman, H. Nielsen, and F. Blaabjerg. Control and testing of a dynamic voltage restorer (DVR) at medium voltage level. *IEEE Trans. Power Electron.*, 19(3):806–813, May 2004.

[10] P. Cheng, W. Chen, Y. Chen, C. Ni, and J. Lin. A transformer inrush mitigation method for series voltage sag compensators. *IEEE Trans. Power Electron.*, 22(5):890–899, Sept. 2007.

[11] T. Jimichi, H. Fujita, and H. Akagi. An approach to eliminating dc magnetic flux from the series transformer of a dynamic voltage restorer. *IEEE Trans. Ind. Appl.*, 44(3):809–816, May/Jun. 2008.

[12] C. Fitzer, A. Arulampalam, M. Barnes, and R. Zurowski. Mitigation of saturation in dynamic voltage restorer connection transformers. *IEEE Trans. Power Electron.*, 17(6):1058–1066, Nov. 2002.

[13] T. Jimichi, H. Fujita, and H. Akagi. A dynamic voltage restorer equipped with a high-frequency isolated dc-dc converter. *IEEE Trans. Ind. Appl.*, 47(1):169–175, Jan. 2011.

[14] M.Z.A. Bhotto and A. Antoniou. Robust recursive least-squares adaptive-filtering algorithm for impulsive-noise environments. *IEEE Trans. Signal Processing Lett.*, 18(3):185–188, March. 2011.

[15] D. A. Fernandes, S. R. Naidu, and C. A. E. Coura Jr. Instantaneous sequence-components resolution of 3-phase variables and its application to dynamic voltage restoration. *IEEE Trans. Instrum. Meas.*, 58(8):2580–2587, Aug. 2009.

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