International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 02 Issue: 08 | Nov-2015 www.irjet.net p-ISSN: 2395-0072

DESIGN OF A FUZZY LOGIC CONTROLLED DVR TO PREVENT SATURATION FROM SERIES TRANSFORMERS

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Abstract-This paper introduces a technique for preventing saturation in transformer from Fuzzy logic based feedback controller for injecting voltage to the Dynamic voltage restorer. This method reduces the voltage sags by correcting the voltages which are injected through the transformers into the power systems to reduce voltage sags. Whenever a maximum limit of flux linkage is about to increase during the voltage sag the fuzzy system predicts it and restricts the compensating voltage. The prediction is carried out at the beginning of a stabilized voltage sag. Moreover, we can also allow a certain level of voltage sag compensation even when the estimated flux is expected to exceed the saturation limit by using the linguistic rules in the fuzzy logic controller. A set of simulations using SIMULINK/MATLAB software for various scenarios of voltage sags are analyzed to show the effectiveness of the method.

Index terms- Dynamic Voltage Restorer(DVR), flux linkage, Power Quality(PQ), fuzzy logic based feedback controller, saturation, transformer

1.INTRODUCTION

We are in the generation where the usage of power demand is increasing expeditiously. Increase in demand increases the burden to provide the seamless power to the consumer. Most of the occurring disturbances inflicting the power system are caused by voltage sags. In some the recent surveys indicates that 92% of incidents in industrial facilities are caused due to the voltage sags, resulting in damage of the equipment and loss of production which affects the economy of the industries. To mitigate this problem, the industries have to invest in the power system design so as to decrease the fault clearance time. However, these solutions are complex moreover the cost of implementation is very high. This enables local based substitutes where some equipment is corrected in the system load interface. One example of this approach is the usage of dynamic voltage restorer.

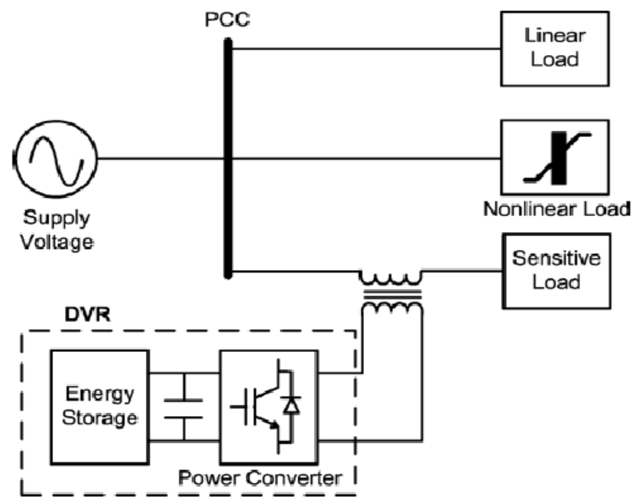

Fig. 1. System configuration with a DVR

A DVR is one of the most effective custom power devices for voltage sag and swell compensation and it has been attracting growing attention in recent years [1], [4]–[8]. A typical test system, incorporating a DVR, is depicted in Fig. 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 severe sag. In this situation, the compensating voltages can cause flux linkage in the core to exceed the transformer nominal limit. The exceeding flux is caused by a dc component whose amplitude depends on the initial phase angle of the compensating voltage. This, in turn, leads to over current and overheating, reducing the life of the transformer. To overcome this problem, one alternative is to enlarge the series transformers. This solution brings an increase in physical size, weight, and cost to the transformer. Another approach is to apply DVR systems without transformers. This increases the number of switches and their associated control circuits needed to apply the compensating voltage. Finally, there is the strategy of controlling the flux linkage by limiting the voltage injected to compensate the sag. This approach has a compromising nature. It deals with the necessity of reducing the sag and the demand of not changing the transformer's flux limit.

In the flux linkage in the DVR's transformers is kept under a maximum limit by shutting off the reference voltages while the currents are over a specified limit, or the reference voltages are reversed. The drawback is to impose a full sag to load during a certain period. the controller uses the magnitude of the positive-sequence component of the line voltages to identify voltage sags. 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 voltage injection action is divided into three intervals. Between the sag detection instant and one-sixth of the fundamental period, 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, after the detection, again the full compensating voltage is applied. In [16], two methods for flux-linkage control are presented. In the first one, the compensating voltage be multiplied by half during the first half fundamental cycle after the sag detection instant and, after this period, the full compensating voltage is used. This ensures that the dc flux is wiped off. The second method predicts, at the detection instant, whether the flux will surpass 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. This method has the advantage of allowing a level of voltage to be injected through the transformers during all periods of the sag.

The inrush control systems for all of the aforementioned works rely on the estimation of the load voltage phasors to compute the compensating voltages. Some works employ the standard least-squares error to estimate these phasors, not withstanding, in general, that the techniques for estimating them are not exploited or discussed by the authors. This paper expands the ideas developed in by dealing with the possibility of more restrictive limits for the saturation in the transformer's core. In addition, it proposes the use of a fuzzy logic based technique for the estimation of phasors, suitable to be incorporated to the compensation voltage control as well as the inrush control. The voltage phasor amplitudes are employed to verify whether the flux surpasses the transformer's flux limit. The Fuzzy logic based controller necessarily includes a transition time before its estimation achieves a constant level. In the proposed method, it is assumed that the DVR system should not operate before it has a stabilized reference for the sag.

II. METHOD OF CONTROLLING SATURATION

This section devises the method of controlling saturation proposed in this paper. The fundamental idea is to constrain the compensating voltage $\upsilon_c$by multiplying it by a form factor . In order to accomplish such a goal, one must predict, at the moment of the sag detection, the value for the form factor to be applied up to the end of the next half cycle (or the next whole cycle) of the compensating voltage after the sag detection and keep the flux at its limit value. In general, $\upsilon_c$can be described as

$$v_c(t) = V\cos(\omega t+\alpha) \qquad (1)$$

Where ω and α are, respectively, the fundamental frequency and the initial phase of the compensating voltage. By Faraday's law, the linked flux λ in the transformer's core at a given instant can be expressed by

$$\lambda = \int_0^t V\cos(\omega\tau + \alpha)d\tau \qquad (2)$$

Solving (2) and assuming that the transformer is demagnetized, that is, λ=0 at the *t*=0, the following expression for the flux is obtained:

$$\lambda=(V/\omega)[\sin(\omega t+\alpha)-\sin(\alpha)] \qquad (3)$$

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

$$\lambda=(V/\omega)[\cos(\omega t)+1] \qquad (4)$$

The technique proposed in this paper is inspired by the one described in [16]. Consider Fig. 2, where the injected voltage starts at angle . It is possible to predict the maximum excursion for the flux linkage through the following integration:

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

where ξ is a form factor which is first set to unity. Note that between α and π/2, the injected voltage contributes positively to the flux. Between π/2 and 3π/2, the voltage contributes negatively to the flux. Therefore, in the situation depicted in Fig. 2, at the angle 3π/2, the flux reaches its minimum value. If the module of the prediction provides a value higher than the allowed limit for the transformer, then the parameter must be adjusted to a value which restricts the amplitude to be equal to the lower limit. Thus, if $\lambda' < -\lambda_{max}$, make $\lambda' = -\lambda_{max}$ in (5) and find ξ as

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

Applying the factor , computed through (6), to the compensating voltage during its negative semicycle, ensures that the flux will not surpass the minimum limit. When the injected voltage starts within a negative semicycle, λ' at the point 5π/2, is predicted through

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

If $\lambda' > \lambda_{max}$, the injected voltage is required to be scaled by the form factor computed by

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

It must be noted that the procedure described before only shifts the flux curve so that, up to end of the semicycle, subsequently after the start of the voltage injection, its value is not higher than the transformer's flux limit. It still remains a dc component which can cause the flux value to surpass the allowed limit within the subsequent opposite semicycle. Therefore, in the proposed method, the condition

$$|\lambda_{max}| \leq |V/\omega| \qquad (9)$$

must be verified. Note that V is the peak value for the compensating voltage. If the condition (9) is not observed, the compensating voltage must be computed as

$$v_c(t) = \frac{V_{max}}{2}\cos(\omega t+\alpha),\ \text{for}\ \alpha \leq \omega t \leq \alpha+\pi/2 \qquad (10)$$

where $V_{max} = \lambda_{max}\omega$.

The method implementation is carried out in such a manner that, whenever the initial phase α is detected within the interval from 3π/2 up to 2π , it must be subtracted by 2π .This task is carried out by FLC which, for each instant, updates the amplitude and phase estimation. Furthermore, the DVR voltage correction only takes place in the moment where the estimation for the parameters is stabilized, that is, during the estimation transient when there is no compensating voltage injected into the grid.

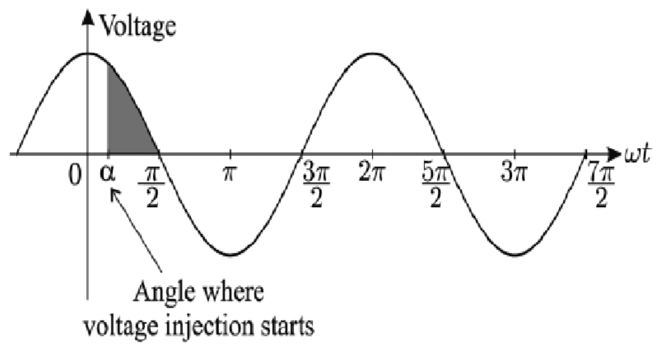

Fig. 2, Compensating voltage for one of the phases.

III. COMPENSATING VOLTAGE CONSTRUCTION

The compensating voltage construction applied in this paper make use of an FLC which uses the linguistic rules and computes the amplitude and phase for each if the grid voltage $v_g(t)$. The FLC is applied to each one of the three grid phasesIn this study, a fuzzy logic based feedback controller is employed for controlling the voltage injection of the proposed Dynamic Voltage Restorer (DVR). Fuzzy logic controller is preferred over the conventional PI and PID controller because of its robustness to system parameter variations during operation and its simplicity of implementation. Since the proposed DVR uses energy storage system consisting of capacitors charged directly from the supply lines through rectifier and the output of the inverter depends upon the energy stored in the dc link capacitors. But as the amount of energy stored varies with the voltage sag/swell events, the conventional PI and PID controllers are susceptible to these parameter variations of the energy storage system; hence the control of voltage injection becomes difficult. The proposed FLC scheme exploits the simplicity of the Mamdani type fuzzy systems that are used in the design of the controller and adaptation mechanism.

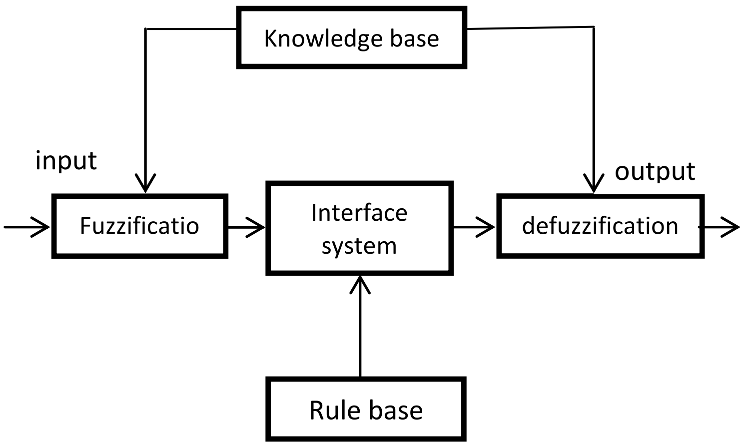

Fig. 3.Schematic representation of Fuzzy Logic Controller.

III. FUZZY LOGIC CONTROLLER

In Recent years, to implement different types of applications of fuzzy logic and the number of fuzzy logic applications are have increased significantly. In FLC, a basic control action through a set of linguistic rules to finding by the system, since the mathematical modeling of system variables is not required in FC and numerical variables are transferred into linguistic variables.

The fuzzy logic based control scheme (Fig. 3) can be divided into four main functional blocks namely Knowledge base, Fuzzification, Inference mechanism and De-fuzzification. The knowledge base is composed of data base and rule base. Data base consists of input and output membership functions and provides information for appropriate fuzzification and de-fuzzification operations. The rule-base consists of a set of linguistic rules relating the fuzzified input variables to the desired control actions. Fuzzification converts a crisp input signals, error (e), and change in error (c_e) into fuzzified signals that can be identified by level of memberships in the fuzzy sets.

The inference mechanism uses the collection of linguistic rules to convert the input conditions to fuzzified output. Finally, the defuzzification converts the fuzzified outputs to crisp control signals using the output membership function, which in the system acts as the changes in the control input (u).The typical input membership functions for error and change in error are shown in Fig 8a and Fig 8b respectively, whereas the output membership function for change in control input is shown in Fig 8c. The output generated by fuzzy logic controller must be crisp which is used to control the PWM generation unit and thus accomplished by the defuzzification block. Many defuzzification strategies are available, such as, the weighted average criterion, the mean-max membership, and center-of-area (centroid) method. The defuzzification technique used here is based upon centroid method.

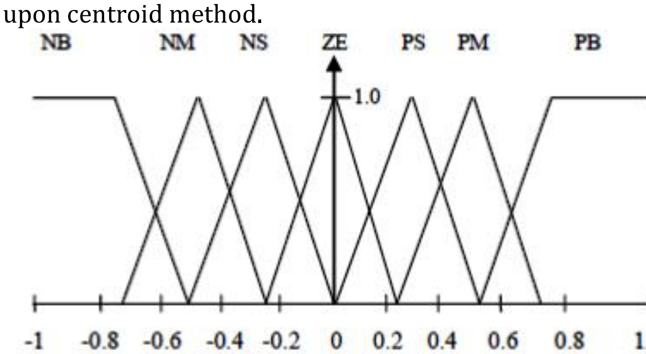

Fig. 4.Membership Function for Input Variable Error, ‘e’.

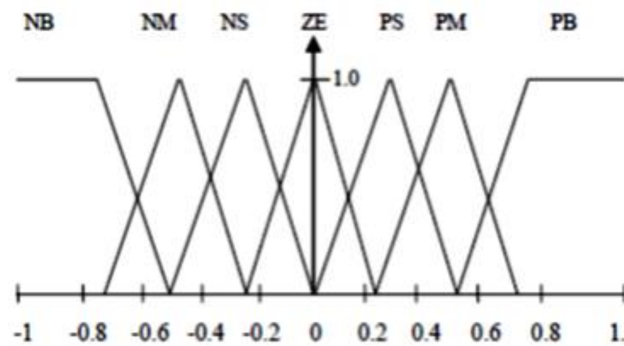

Fig.5 .Membership Function for Input Variable Change in Error, ‘ce’.

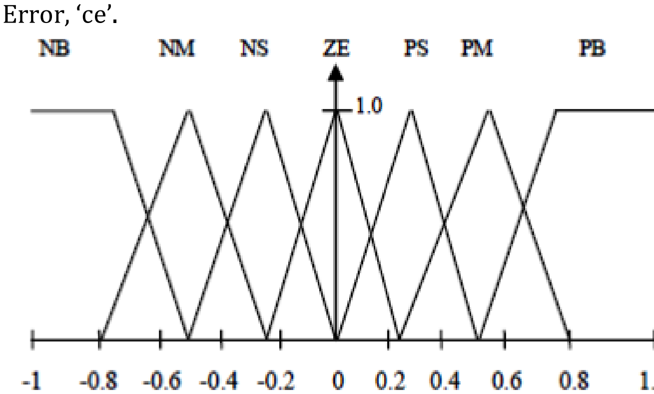

Fig.6 .Membership Function for Output Variable Change in Control Signal, ‘u’.

The set of fuzzy control linguistic rules is given in Table 1. The inference mechanism of fuzzy logic controller utilizes these rules to generate the required output.

Fuzzy Rules

Change in error	Error						
	NL	NM	NS	Z	PS	PM	PL
NL	PL	PL	PL	PM	PM	PS	Z
NM	PL	PL	PM	PM	PS	Z	NS
NS	PL	PM	PS	PS	Z	NS	NM
Z	PL	PM	PS	Z	NS	NM	NL
PS	PM	PS	Z	NS	NM	NL	NL
PM	PS	Z	NS	NM	NL	NL	NL
PL	Z	NS	NM	NM	NL	NL	NL

Table 1. Rule Base for Fuzzy Logic Controller

In practice , the fuzzy rule sets usually have several antecedents that are combined using Fuzzy operators, such as AND, OR and NOT, though again the definitions tend to vary. AND, in one popular definition, simply uses the maximum weight of all the antecedents, while OR uses the maximum value. There is also a NOT operator that subtracts a membership function from 1 to give the “complementary” function. DVR is generally connected in feeders having sensitive loads whose terminal voltage has to be regulated. The SIMULINK model of proposed fuzzy logic controller.

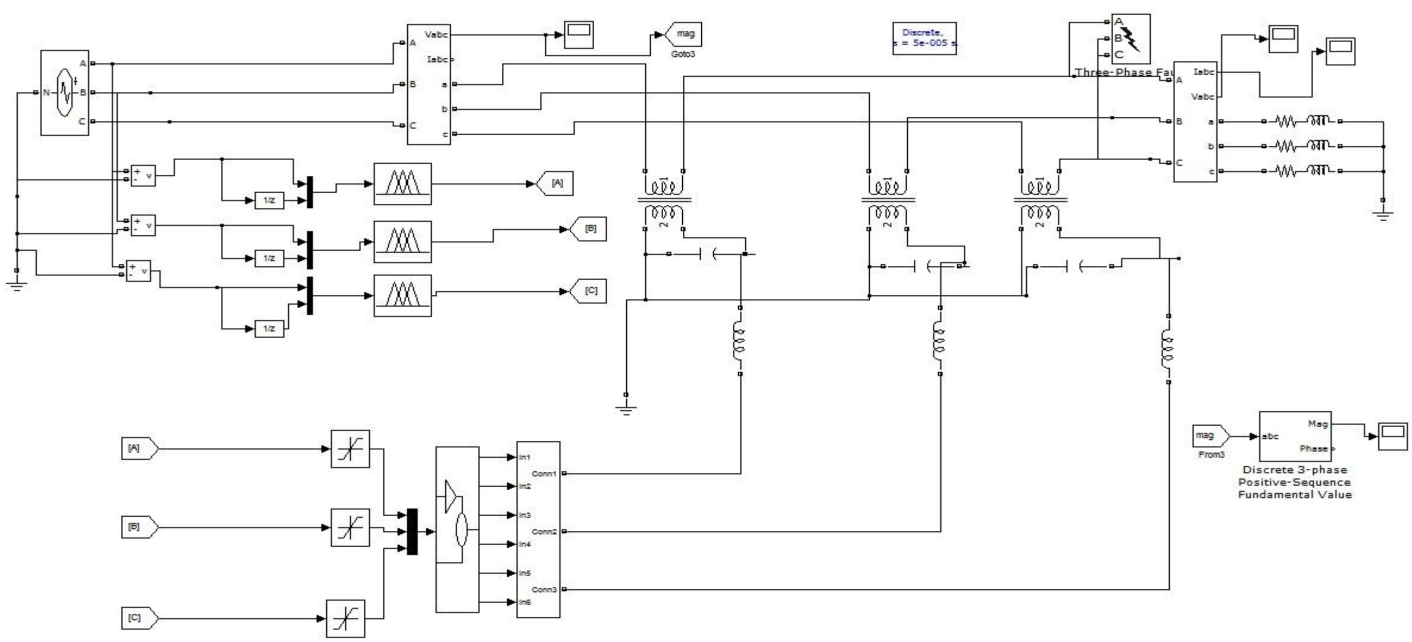

Fig. 7. Simulation platform of the DVR system

IV. SIMULATED RESULTS

In order to test the performance of the proposed method a DVR system has been simulated by using the packages *sim-powersystems* and *Simulink* from Matlab. In the figure, it can be observed that the compensating voltage is injected by means of a four-leg voltage-source inverter(VSI) controlled by a pulsewidth-modulation (PWM) strategy. The four-leg VSI allows the compensating voltages to be unbalanced . The VSI voltage output is passed through an LC filter. The FLC block incorporates the procedure for detecting whether the FLC estimation for the amplitude and phase is stabilized.

Table 2: SIMULATED SYSTEM PARAMETERS

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

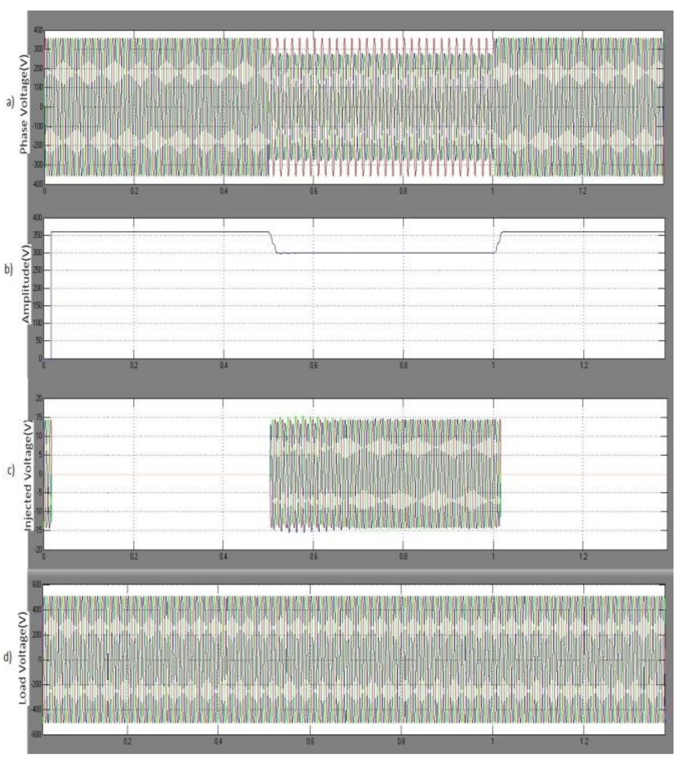

Fig. 8. Simulated results for the DVR system: Case I. (a) Voltage sags on phases A and B. (b) Amplitude estimation of phase-A. (c) Compensating voltages injected by the DVR. (d) Corrected voltages applied to the load.

Three different scenarios of voltage sags have been simulated. For the first case, consider that a three-phase grid is under a phase-to-phase sag during 4ms as illustrated in fig. 8(a).a phase-to-phase sag during 4*ms*, as illustrated in Fig. 8(a).Fig. 8(b) shows the least-squares amplitude estimation for phase-A. Besides the amplitude, the Fuzzy logic controller also estimates the angle α.

Moreover, the estimation enables detection where the changing in the estimation starts and where it is finished by means of a flag signal. In Fig. 8(b), theseinstants are indicated by the dashed line. We can highlight four instants. The first two are related to the beginning of the sag and the last two are associated with the end of the sag. Recall that the compensating voltage is not triggered while the amplitude and phase are varying. Fig. 8(c) shows the injected voltage by the DVR for the two sagged phases. It is worth noting that the injected voltage for phase-A is ignited at the instant where the estimation for the phase-A amplitude is stabilized. Although not shown in this figure, the same is true for the other phase. Fig. 8(d) shows the corrected voltages applied to the load.In the second case, the voltage sag is depicted by Fig. 9(a) where it is shown that a phase-to-phase fault for an angle α is different from the previous one.

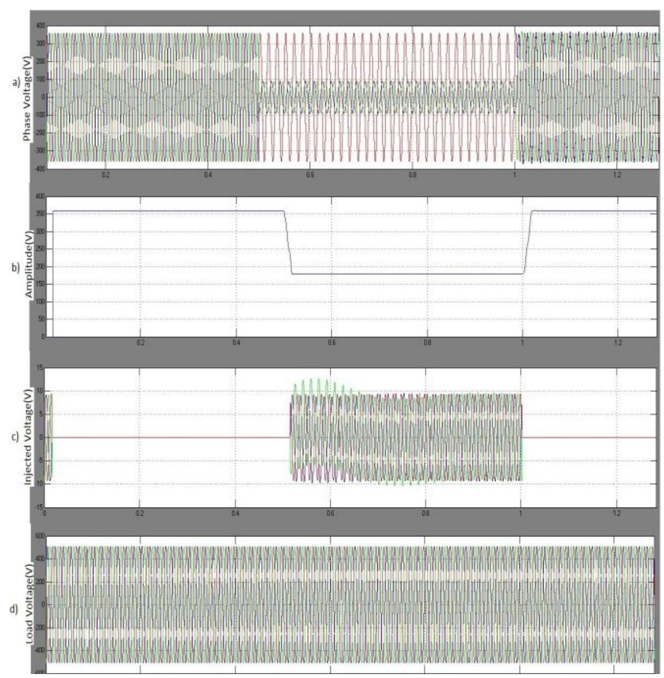

Fig. 9. Simulated results for the DVR system: Case II. (a) Voltage sags on phases A and B. (b) Amplitude estimation

of phase-A. (c) Compensating voltages injected by the DVR. (d) Corrected voltages applied to the load.

Fig. 9(b) Shows the amplitude estimation carried out by the fuzzy logic controller for phase-A. Again, the instants where the sag is initiated and finished are highlighted by the dashed line. Fig. 9(c) shows a set of four curves of voltages injected by the DVR into the grid. The dashed curves are the compensating voltages that would be injected without any control for the saturation. The solid lines represent the compensating voltages restrained by the control of saturation proposed in this paper. Fig. 9(d) show the voltages applied to the load.

The third case simulates a sag for single phase, as depicted in Fig. 10(a). Similar to the other cases, Fig. 10(b) shows the FLC amplitude estimation for the sagged phase voltage. Fig. 10(c) shows the dashed curve for the voltage without any constraint with the control of saturation, and the solid line represents the compensating voltage constrained by the proposed control of saturation. We verify that the difference between the curves is confined to the first quarter of the cycle. This happens because unlike the second case, the condition described in (9) is not verified and the compensating voltage must be given according to (10). This ensures that the dc component is completely removed. The voltages applied to the load are sketched in Fig. 10(d).

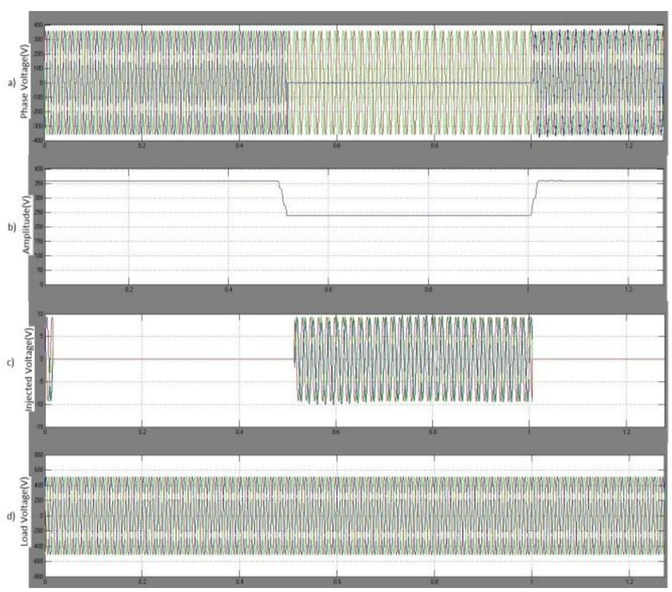

Fig. 10. Simulated results for the DVR system: Case III. (a) Voltage sag on phase-A. (b) Amplitude estimation of phase-A. (c) Compensating voltage injected by the DVR. (d) Corrected voltages applied to the load.

VI. CONCLUSION

This paper has proposed a method for controlling voltage sag and flux saturation in transformers used by a DVR system. The DVR system makes use of an fuzzy logic controller to compute the compensating voltage. The method relies on the correct computation of the compensating voltage phasor which is constrained whenever it can provoke saturation. The compensation is never rendered while the FLC amplitude phasor estimation is varying. Hence, the FL controller is combined with a technique for detecting whether the estimation for the amplitude reached a constant value. This ensures that the compensating voltage is always at a proper level. In some cases, this is performed at a cost of not completely compensating the sag for a certain period of time. Yet, this is a compromise solution to be applied to loads which can withstand some level of sag within a limited period. The method has been put on test by simulations of different scenarios of voltage sags.

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