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Fuzzy Logic Controlled DC-DC Converter Based Dynamic Voltage Restorer

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This paper presents fuzzy logic controlled dc-dc boost converter based Dynamic Voltage Restorer (DVR) to compensate severe voltage sag problems in an electrical system. DVR absorbs real power from battery to compensate voltage sags in the system. This condition causes reduction in voltage magnitude of dc-link capacitor. Additionally, DVR requires large dc capacitors to compensate long and severe voltage sags in the system. In this study, dc-dc boost converter is connected to DVR for keeping dc link voltage constant. For this propose, a control algorithm based on Fuzzy Logic (FL) control is developed for dc-dc boost converter. The main contribution of this study is that Fuzzy Logic (FL) is firstly used to generate reference signal for PWM signals of dc-dc converter applied in DVR. FL is a very flexible controller which keeps the dc link voltage constant during voltage sag. The performance results of proposed study are verified with PSCAD/EMDTC.

Keywords: fuzzy logic; DVR; voltage sag; dc link voltage

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1. Introduction

Voltage, current, frequency deviations and waveform distortions that cause equipment failure, economical loss and several negative effects are known as power quality problems. The most severe power quality problem in electrical systems is called as voltage sag. Voltage sag is a short duration reduction in the rms value of voltage. There are several custom power devices for voltage sag compensation. Among these devices, DVR is the most effective device to compensate this power quality problem.

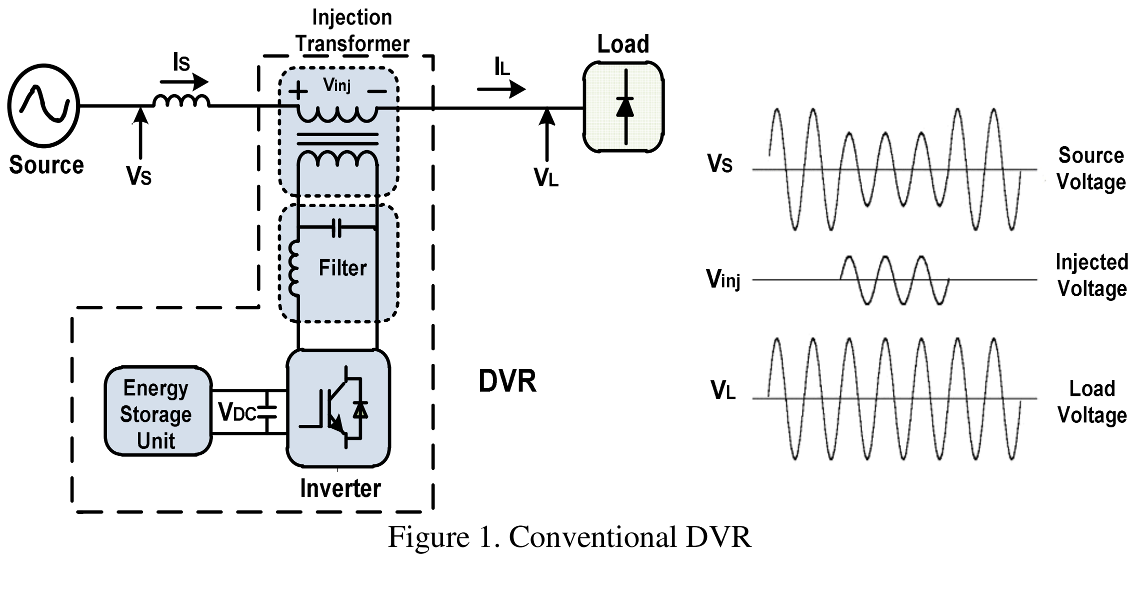

Figure 1. Conventional DVR

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DVR is located between sensitive load and grid in system, as shown in Figure 1. The basic structure of a conventional DVR consists of an inverter, dc-link capacitor, filter and injection transformer[1-6]. The function of DVR is to inject the voltage in series to compensate sag voltage and keep rms load voltage constant. DVR consumes active power to compensate this power problem under voltage sag condition. Voltage sag compensation causes reduction in voltage magnitude of dc link capacitor. In [7-11], dc-dc boost converter is connected to dynamic voltage restorer to improve performance. In this study, dc-dc converter is connected to DVR for keep dc link voltage constant. Dc-dc converter prevents voltage reduction at dc-link capacitor in the system. Owing to this condition, it can compensate long and severe voltage sag problems in system. In this wise, dc-dc converter in DVR uses PI control to keep dc link voltage constant in [8,10-11]. This study presents fuzzy logic controlled dc-dc converter based dynamic voltage restorer. The main contribution of this study is that Fuzzy Logic (FL) is firstly used to generate reference signal for PWM signals of dc-dc converter applied in DVR. FLC can incorporate a conventional design (PI, PID, state feedback) and fine tune it to certain plant nonlinearities due to universal approximation capabilities[12-14]. Additionally, FL is flexible controller which has advantages explained below:

- Uses linguistic variables
- Allows conradictory inputs
- Convenient user interface
- Easy computation
- Ambiguousness

This paper focuses on the implementation of fuzzy logic controller on dc-dc converter based DVR to compensate under voltage sag situations in the utility grid with improved control algorithm. This paper is therefore organized as follows: First, the configuration of proposed study is presented in Section II. Section III illustrates fuzzy logic control algorithm applied in the structure. Finally, in Section IV, analysis and performance results are discussed, which is followed by concluding remarks in Section V.

2. Notation

Indexes:

DVR	Dynamic Voltage Restorer
DC	Direct current
FL	Fuzzy Logic
PI	Proportional –Integrator
PID	Proportional Integrator and Differentiator
kVA	Kilo Volt Amperes
SRF	Synchronous Reference Frame
V_{dclink}	DC link capacitor side voltage of dc-dc converter applied in DVR
$V_{battery}$	Battery side voltage of dc-dc converter applied in DVR
D	Duty cycle
$\Delta\alpha$	Reference value
LD	Large Decrease
MD	Medium Decrease

SD Small Decrease
N Neutral
LI Large Increase
MI Medium Increase
SI Small Increase
w^l Weighted average of the outputs of all the rules in fuzzy logic control

3. The System Configuration

DVR generates controlled voltage in series to mitigate the impacts of upstream voltage disturbances on sensitive loads [4-8]. In proposed system, DVR is connected between three phase sources (380 Vpp) and sensitive load (15 kVA) as shown in Figure 2. In this study, DVR is designed using H bridge inverters to compensate balance and unbalanced voltage sags. Conventional SRF based control is implemented to generate PWM signals of solid-state devices used in H-bridge inverters. The compensation capability of DVR has a depth up to 30% for three phase balanced voltage sag. Therefore, the voltage magnitude of compensation is:

$$380x0.3=114\ V \tag{1}$$

To be continued, the magnitude value of dc link voltage must be:

$$Vdc=114x\sqrt{3}=160\ V \tag{2}$$

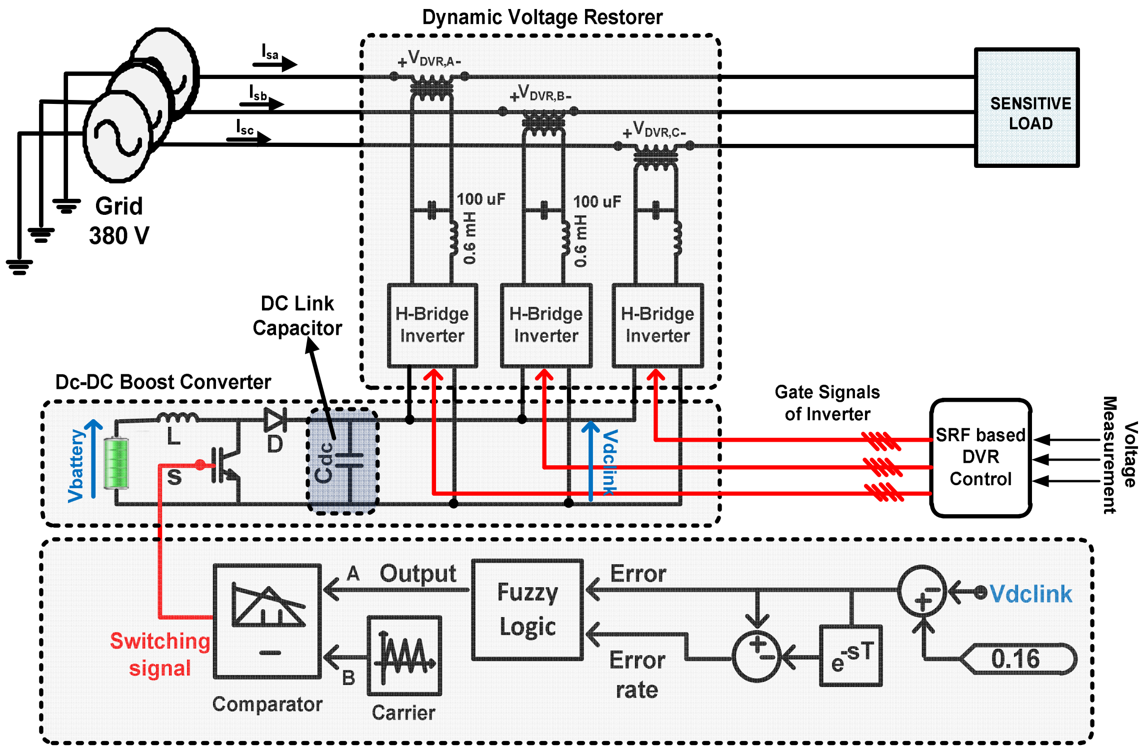

Figure 2. The schematics of proposed DVR based on FL controlled boost dc-dc converter

Figure 2 shows the system that dc link capacitor of DVR is connected to dc-dc converter supplied through battery. The rating of battery is selected as 100 V. Equation in (3) shows the duty cycle (D) of switching signal according to relationship between dc link voltage

(Vdclink) and battery voltage (Vbattery). According to (3), duty cycle of switch have to selected as ”0.6” to compensate three phase balanced 30% voltage sag in system.

$$D = \frac{(V_{dclink} - V_{battery})}{V_{battery}} \tag{3}$$

Cut off frequency f_0 should be between 500 Hz and 1500 Hz where grid frequency is 50 Hz and PWM inverter switching frequency is 3000 Hz. The values of capacitance and inductance in filter are selected according to (4).

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

4. Control Algorithm

Fuzzy logic controller is employed to generate reference signal of dc-dc boost converter. The fuzzy logic based control method is shown in Figure 2. The system considered in this study has two inputs which are the numerical difference (error) of dc link voltage and constant value and the error change (error_rate), and the reference value (Δα) is the only output. The inference mechanism of fuzzy logic controller is mathematically expressed by the set of rules. These rules are generated through the experience of operating the system, which may be feedback from the plant operator, design engineer, or the expert.

The block diagram of the proposed fuzzy logic control system is shown in Figure 3.

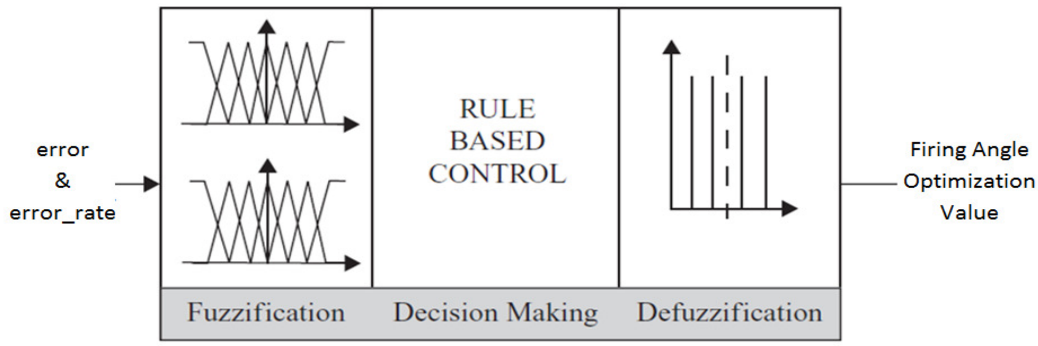

Figure 3. Proposed FL Control System Block Diagram

The design procedure of FL controller continues with the selection of membership functions for the inputs and the output of the controller. The non-fuzzy (numeric) input variables are transformed into the fuzzy set (linguistic) variables by fuzzification part, which is clearly defined boundary. The required input range of error is described as linguistic variables such as LD(Large Decrease), MD(Medium Decrease), SD(Small Decrease), N(Neutral), SI(Small Increase), MI(Medium Increase) and LI(Large Increase). The required input range of error_rate is described as linguistic variables such as LD, MD, SD, N, SI, MI, and LI. The membership functions of the inputs are shown in Figure 4. and Figure 5.

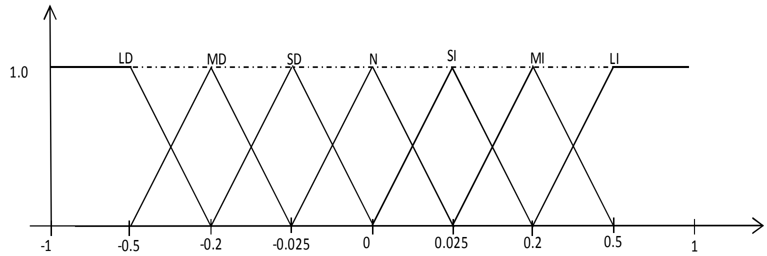

Figure 4. Membership Function of Input 1 - error

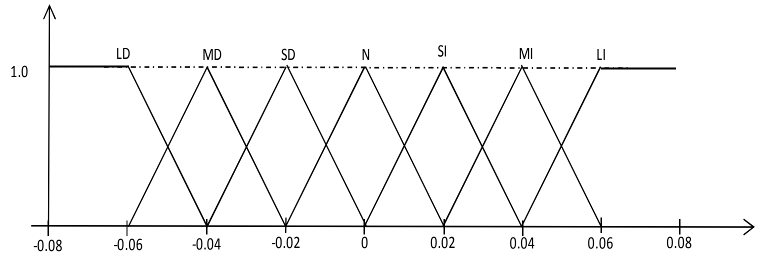

Figure 5. Membership Function of Input 2 - error_rate

The linguistic terms for membership functions that will be used in the rule base are labeled on each of the corresponding membership function[15]. These are given in Table 1.

Table 1 Linguistic terms for the Error, Error rate and Output

Error		**Error rate**		**Output**	
LD	Large Decrease	LD	Large Decrease	BN	Big Negative
MD	Medium Decrease	MD	Medium Decrease	MN	Medium Negative
SD	Small Decrease	SD	Small Decrease	SN	Small Negative
N	Neutral	N	Neutral	Z	Zero
SI	Small Increase	SI	Small Increase	SP	Small Positive
MI	Medium Increase	MI	Medium Increase	MP	Medium Positive
LI	Large Increase	LI	Large Increase	BP	Big Positive

For the designed controller, there are two inputs error and error_rate, which have 7 membership functions for each. Normally, there must be 49 rules from DS1 to DS49 in the rule base. Table 2 summarizes the fuzzy logic controller decision rules.

Table 2: FL Controller Decision Rules

		Error_rate						
		LD	MD	SD	N	SI	MI	LI
Error	LD	DS49	DS48	DS47	DS46	DS45	DS44	DS43
	MD	DS42	DS41	DS40	DS39	DS38	DS37	DS36
	SD	DS35	DS34	DS33	DS32	DS31	DS30	DS29
	N	DS28	DS27	DS26	DS25	DS24	DS23	DS22
	SI	DS21	DS20	DS19	DS18	DS17	DS16	DS15
	MI	DS14	DS13	DS12	DS11	DS10	DS9	DS8
	LI	DS7	DS6	DS5	DS4	DS3	DS2	DS1

According to the values of input signals, the fuzzy decision rule is arranged. The membership values of decision blocks at the intersection points are determined from the membership functions of input signals.

It is the process of converting the controller outputs in linguistic labels represented by fuzzy set to real control (analog) signals. Sugeno's wtaver (weighted average) method is selected for defuzzification and it is a special case of Mamdani model. For real valued inputs x1,..., xn, the output y of the fuzzy system is a weighted average (w^l) of the outputs of all the rules. The solution of defuzzification process results from this equation[16].

$$y = \frac{\sum_{i=1}^{M} w^l y^l}{\sum_{i=1}^{M} w^l} \tag{5}$$

Fuzzy output is used as a reference signal in dc-dc boost converter. It is compared to carrier for generation of PWM switching signals.

5. Performance Results

This section presents the performance results of FL controlled dc-dc converter-based DVR under voltage sag problems. The system parameters are given in Table 3. Sensitive load consists of resistors which has a capacity of 15 kVA. It is fed from 380 Vpp (peak value of phase voltage is 311V) three phase supply. The proposed DVR is designed to compensate up to over 30% three phase voltage sag. DVR in a three phase system is designed to protect 15 kVA sensitive load. The proposed DVR model is implemented in PSCAD/EMTDC to compensate voltage sag at the source side.

Table 3: System Parameters

Source Parameters	
Fundamental Frequency	50 Hz
Source Voltage	380 V (line-line, peak) or 311 V (phase voltage)
Load Parameters	
Resistive	3x10 ohm
DVR (Voltage Source Inverter)	
Compensation Rating	30%
Power Rating	5 kVA
Filter inductor (Lf)	0.5 mH
Filter Capacitor (Cf)	100 µF
Filter Resistance (Rf)	0.05 Ω
DC-DC Converter	
Transformer Rating	5 KVA
Output Capacitor (Cdc)	1 mF
Inductor	10 uH

Fuzzy logic controller is employed to generate reference signal of boost dc-dc converter. The simulation results of fuzzy logic control method used in dc-dc converter is presented in Figure 6. In control method, reference signal (FL output) is compared to carrier signal. Frequency of carrier signal has been selected as 10 kHz.

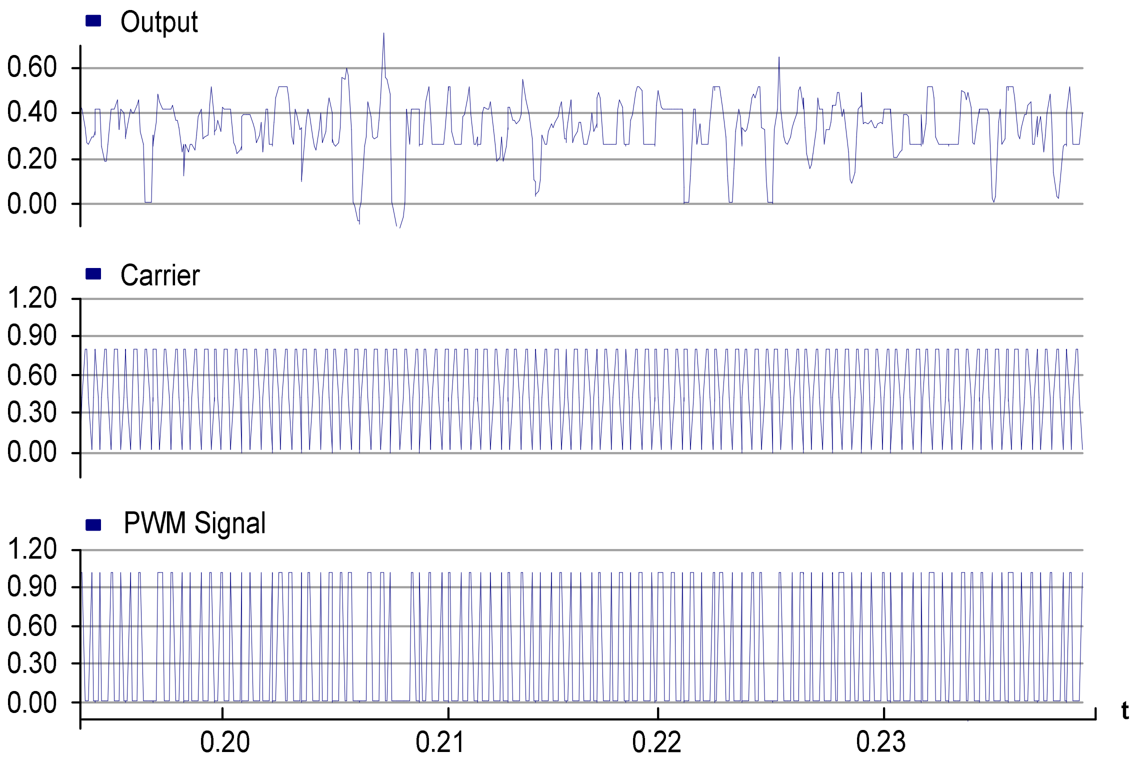

Figure 6. Fuzzy logic output (reference), carrier and PWM signal

Figure 7 shows the performance results of FL controlled dc-dc converter based DVR under voltage sag situations. Three phase source, load and injected voltages, dc link and battery voltages are presented in Figure 7, respectively. The magnitude of balanced voltage sag is 30% for three phases. During the fault, rms value of the supply voltages with 30% sag are reduced to 154 Vrms from 220 Vrms. It is demonstrated that proposed FL controller keeps dc link voltage effectively during sag. Vdclink is maintained under 3% voltage limit. Vdclink nearly kept at 155-160 V limits during three phase voltage sag. As soon as the sag is finished, Vdclink returns to its steady state value (=160 V).

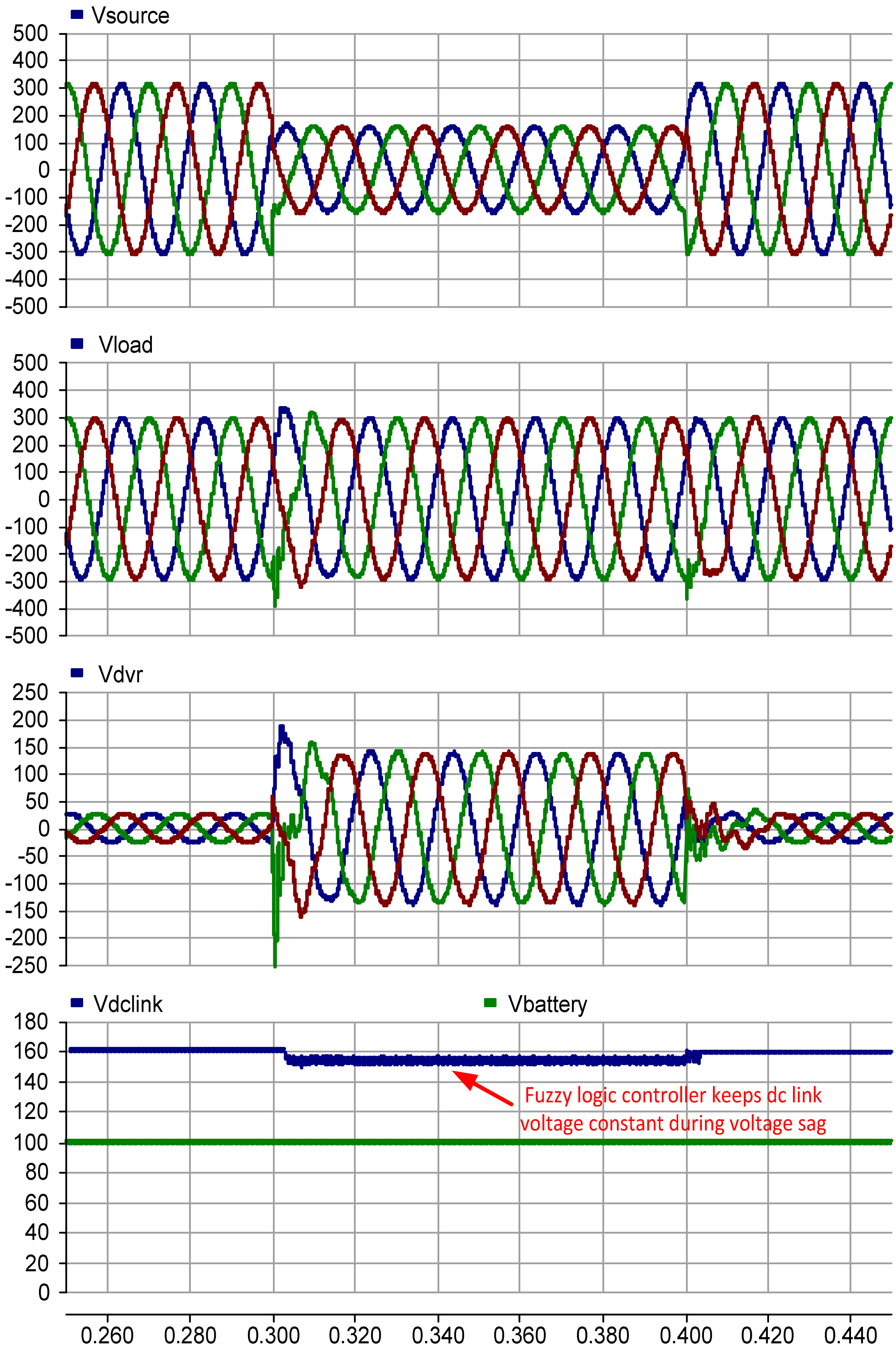

Figure 7. Performance Results: Source Voltage, Load Voltage, Injected Voltage, and dc link Voltage, respectively

6. Conclusion

In this paper, FL controlled dc-dc converter based DVR is presented. The proposed DVR is designed to protect 15 kVA sensitive load and compensate up to over 30% three phase voltage sag. FL controlled dc-dc boost converter is applied to keep dc link voltage constant under voltage sag situations. It is demonstrated that proposed FL controller keeps dc link voltage effectively during sag. It is very good result to keep voltage variation under 3%. The proposed topology is modelled and simulated using PSCAD/EMDTC. The performance results verify the efficacy of the proposed DVR topology and its control strategy to compensate voltage sag.

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