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Voltage sag compensation using direct converter based DVR by modulating the error signal

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ABSTRACT

The aim of this paper is to present a modulation technique to achieve highest voltage sag compensation using direct converter based dynamic voltage restorer (DVR). The DVR topology proposed in this paper, has a direct converter and a series transformer. The direct converter is fabricated using only two bi-directional switches. The DVR is designed to compensate the sag in a phase by taking power from the same phase. The direct converter is connected between the series transformer and the line in which sag compensation is to be achieved. Conventionally, the PWM pulses for the direct converters are produced by comparing the error signal with the carrier signal. The error signal is obtained by comparing the amplitude of voltage in the line with the amplitude of the reference voltage. If the amplitude of the carrier signal is kept constant and the actual amplitude of error signal is used for PWM generation, it is possible to achieve only 22% of voltage sag compensation. But if the error signal amplitude is modulated according to the amplitude of existing voltage sag in the line, 52% of the voltage sag can be compensated with the THD less than 5%. Simulation results are presented for validating the analysis.

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1. INTRODUCTION

Though we have many power quality issues like voltage sag, voltage swell, flicker, harmonics, voltage sag is considered to be the severe issue as it affects the operation of sensitive loads like computer, micro controller, Digital Signal Processor, FPGA. As most of the industries are automated, the entire operation of the industries depends upon the operating condition of these sensitive loads. When sag or swell occurs in the industrial areas, these sensitive loads are getting affected, leading to immoral operation of the entire industry [1-8]. For the compensation of voltage sag, Dynamic Voltage Restorer (DVR) considered to be an effective device when compared to other devices like UPS, STATCOM [9-11]. The basic operation of DVR is to inject a voltage in series with the line voltage to mitigate power quality issues. Though many DVR topologies like DVR based on energy storage devices (like batteries, capacitors and super capacitors) have been proposed [12-16], in this paper DVR based on direct convert is presented [17-21]. The compensating range of the DVRs based on energy storage devices, depends upon the rating of the energy storage devices. But in the DVRs based on direct converters, it is based on the availability of voltage in the phase from which the power is taken for compensation and modulating techniques. Only a limited number of papers are available in the literature review for the DVRs based on direct converters. To begin with, the topology presented in [22] based on a matrix converter can mitigate only 25% of sag and 3 switches are to be modulated during compensation, making the generation of switching pulses somewhat complicated. The zero energy sag corrector without capacitors proposed in [23] can compensate 96% of voltage sags with 10 numbers of switches.

Yet another DVR based on an indirect matrix converter developed in [24] can compensate balanced voltage sags of 60%, but it needs a fly wheel energy storage systems with 4 switches. A computation intensive procedure, which runs throughout the cycle, has been described in [25] with 5 bidirectional switches. In spite of these, the compensation range for voltage sag is only 33%. Even though the topologies described in [26-29], can mitigate 50% sag, the generation of the switching pulses for the DVR is a bit complicated since 3 switches are to be modulated during compensation.

From the above literature survey it could be observed that to mitigate voltage sag either the topologies have more number of switches or more complicated procedures to mitigate voltage sag. In the proposed topology, only two bidirectional switches are used. In order to mitigate the sag, the error signal is obtained by comparing the peak value of the line voltage with the peak value of the reference voltage. Conventionally this actual error signal is compared with the carrier signal to generate PWM pulses for the direct converter to synthesis compensating voltage. This compensating voltage will be added to the line through the series transformer in order to mitigate the voltage sag. It is been shown in this paper that, if the actual error signal is used to generate PWM pulses, then it is possible to achieve only 22% of sag compensation. So in this paper, the amplitude of the error signal is modulated according to the percentage of existing sag, and voltage sag compensation of 52% is achieved.

2. PRINCIPLE OF OPERATION

The topology of the direct converter based DVR is shown in the Figure 1. It has a direct converter, a LC filters at the input side of the direct converter and another LC filter at the output side of the direct converter, and a series transformer. The LC filters are used to minimize the harmonics due to switching. The direct converter has two bidirectional switches S1 and S2 as shown in the Figure 1. The topology of the bidirectional switch is shown in the Figure 2.

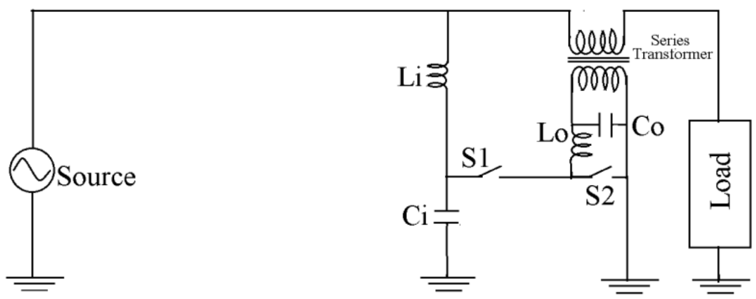

Figure 1. Topology of the DVR

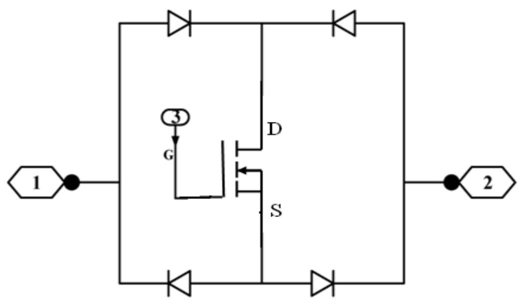

Figure 2. Topology of the bidirectional switch

When the supply voltage is at rated value, the switch S1 is open and switch S2 is closed. In this condition, the secondary of the series transformer is short circuited which results in zero voltage injection and the load voltage is maintained at its rated value. When the sag occurs, the DVR will synthesis the compensating voltage by taking power from the same phase and operating the switches S1 and S2 alternatively. The compensating voltage is added in phase with the supply voltage through the series transformer. The turns ratio of the series transformer is 1:1.

3. CONTROL ALGORITHM

Conventional method of generating the PWM pulses for the DVR is shown in the Figure 3. Uref is the peak value of the reference voltage and Ugmax is the peak value of the supply voltage. The supply side voltage is measured and the peak value of the instantaneous voltage is calculated by single phase dq theory [30]. It is compared with the peak value of the reference voltage to generate the error signal. The error signal is compared with the carrier to generate PWM for controlling the switches as shown in the Figure 3.

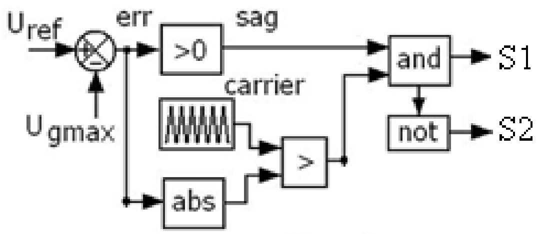

Figure 3. Conventional PWM generation to mitigate sag

In order to generate the PWM, the amplitude of the carrier is signal is kept at 1 unit. The actual error signal in per unit is compared with the carrier signal. As per the IEEE standard the load voltage should be maintained with in the limit of ±5% of the rated value. It is been observed from the Table 1that in the conventional PWM generation technique, it is possible to achieve only 22% of sag compensation since the actual error signal is used to generate the switching pulses. When the sag is more than 22%, for example when the sag is 24%, the supply voltage is 76% of the rated value. For this 24% of sag, the PWM on time is only 24%. The compensating voltage synthesized by the direct converter is 24% of this 76%, which is 18.24% only. By adding this compensating voltage in the line through the series transformer, the load voltage will be 94.24% which is not at par with IEEE standard. This is explained in the Table 1. The same is the case with 40%, 50% and in general, for more than 22% of sag as proved in Table 1.

Table 1. Possible compensation without modulating the error signal

Supply Voltage in Volts	% of Sag	Error	Duty Cycle of PWM in %	Compensating voltage generated by the DVR = Supply Voltage * Duty Cycle	Load Voltage = Supply Voltage + Compensating Voltage
100	0	0	0	0	100
98	2	2	2	1.96	99.96
96	4	4	4	3.84	99.84
94	6	6	6	5.64	99.64
92	8	8	8	7.36	99.36
90	10	10	10	9	99
88	12	12	12	10.56	98.56
86	14	14	14	12.04	98.04
84	16	16	16	13.44	97.44
82	18	18	18	14.76	96.76
80	20	20	20	16	96
78	22	22	22	17.16	95.16
76	24	24	24	18.24	94.24
74	26	26	26	19.24	93.24
72	28	28	28	20.16	92.16
70	30	30	30	21	91
68	32	32	32	21.76	89.76
66	34	34	34	22.44	88.44
64	36	36	36	23.04	87.04
62	38	38	38	23.56	85.56
60	40	40	40	24	84
58	42	42	42	24.36	82.36
56	44	44	44	24.64	80.64
54	46	46	46	24.84	78.84
52	48	48	48	24.96	76.96

But it is possible to improve the range of sag compensation, as sufficient voltage is available at the supply side. It could be observed from the Table 1 that, for a sag of 22%, the duty cycle of the PWM is only 22% but the available voltage is 78%. Likewise for voltage sag of 30%, 40% and even for 52%, the available voltage at the supply side is 70%, 40% and 48% respectively. With this much available voltage at the supply side, it is possible to maintain the load voltage within the IEEE standard, by increasing the duty cycle of the PWM. But the duty cycle has to be modulated according to the percentage of available sag. The error signal is not modulated, if the sag is 0 to 22%. The actual error is compared with the carrier to generate the PWM to control the switches. From the Table 1, it could be observed that up to 22% of sag, the load voltage is maintained at 95.16% of rated value. If the sag increases beyond 22%, then using the actual error signal the sag can't be compensated as shown in the Table 1. So for the sag of more than 22%, the error signal is modulated according to the percentage of sag. For a sag of more than 22% and less than or equal to 32%, the error signal is amplitude modulated for a gain of 1.25 as shown in Table 2, such that the on time of the PWM is also increased by 25% compared to its original on time. Due to increase in the on time of PWM pulses, the load voltage is maintained at the minimum of 95.2% of its rated value. It could be observed from Table 2 that if the error signal is modulated by the same gain of 1.25, then the sag can't be compensated beyond 32%, since the load voltage is less than 95% of rated value. So if the sag is more than 32% and less than or equal to 41%, the error is modulated by the gain of 1.5, in order to keep the load voltage to a minimum value of 95.3% as shown in the Table 3. The block diagram for PWM generation with modulated error signal si shown in the Figure 4.

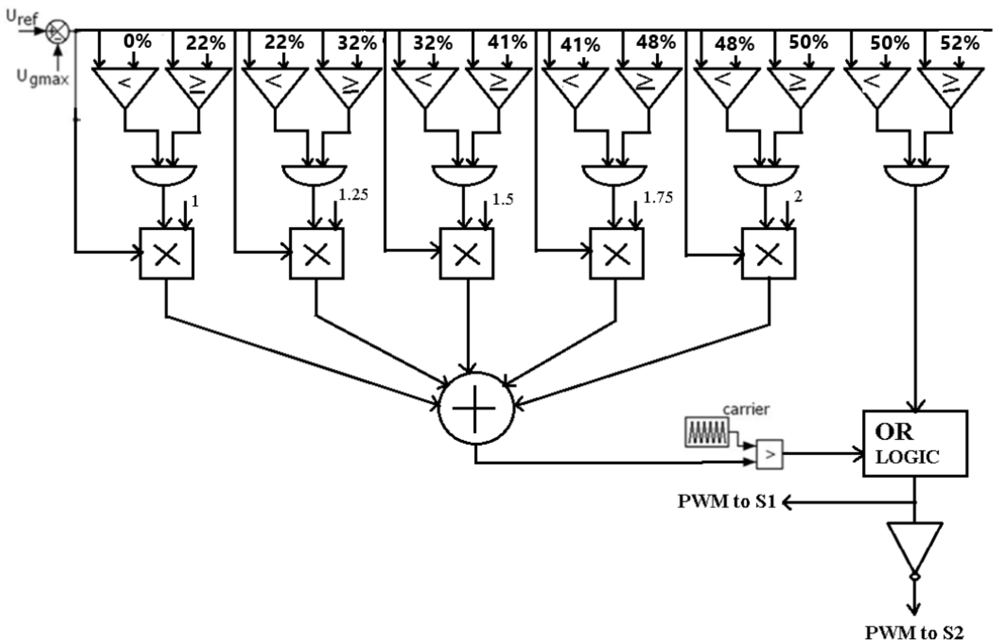

Figure 4. Block diagram for PWM generation with modulated error signal

Table 2. Possible compensation by modulating the error signal by a gain of 1.25

Supply Voltage in Volts	% of Sag	Error	Duty Cycle of PWM without Modulation	Modulated Error = 1.25 * error	Modulated PWM	Compensating voltage generated by the DVR = Supply Voltage * Modulated Duty Cycle	Load Voltage = compensating Voltage + Supply Voltage
77	23	23	23	28.75	28.75	22.1375	99.1375
76	24	24	24	30	30	22.8	98.8
75	25	25	25	31.25	31.25	23.4375	98.4375
74	26	26	26	32.5	32.5	24.05	98.05
73	27	27	27	33.75	33.75	24.6375	97.6375
72	28	28	28	35	35	25.2	97.2
71	29	29	29	36.25	36.25	25.7375	96.7375
70	30	30	30	37.5	37.5	26.25	96.25
69	31	31	31	38.75	38.75	26.7375	95.7375
68	32	32	32	40	40	27.2	95.2
67	**33**	**33**	**33**	**41.25**	**41.25**	**27.6375**	**94.6375**

Table 3. Possible compensation by modulating the error signal by a gain of 1.5

Supply Voltage in Volts	% of Sag	Error	Duty Cycle of PWM without Modulation	Modulated Error = 1.5 * error	Modulated PWM	Compensating voltage generated by the DVR = Supply Voltage * Modulated Duty Cycle	Load Voltage = compensating Voltage + Supply Voltage
67	33	33	33	49.5	49.5	33.165	100.165
66	34	34	34	51	51	33.66	99.66
65	35	35	35	52.5	52.5	34.125	99.125
64	36	36	36	54	54	34.56	98.56
63	37	37	37	55.5	55.5	34.965	97.965
62	38	38	38	57	57	35.34	97.34
61	39	39	39	58.5	58.5	35.685	96.685
60	40	40	40	60	60	36	96
59	41	41	41	61.5	61.5	36.285	95.285
58	42	42	42	63	63	36.54	94.54

For the sag of more than 41% and less than or equal to 48%, the error is modulated by the gain of 1.75 such that the load voltage is maintained at least at 95.7% as shown in the Table 4. For the sag of more than 48% and less than or equal to 50%, the error is modulated by the gain of 2 such that the load voltage is maintained within the IEEE standard as shown in the Table 5. It could be observed from the Table 2 to Table 5 that the load voltage is maintained within the IEEE standard value by modulating the error signal according to the percentage of available sag. If the sag is more than 50% and less than or equal to 52%, then the switch S1 is fully on and the switch S2 is off such that even for 52% sag the load voltage will be maintained at 96% of rated value.

Table 4. Possible compensation by modulating the error signal by a gain of 1.75

Supply Voltage in Volts	% of Sag	Error	Duty Cycle of PWM without Modulation	Modulated Error = 1.75 * error	Modulated PWM	Compensating voltage generated by the DVR = Supply Voltage * Modulated Duty Cycle	Load Voltage = compensating Voltage + Supply Voltage
58	42	42	42	73.5	73.5	42.63	100.63
57	43	43	43	75.25	75.25	42.8925	99.8925
56	44	44	44	77	77	43.12	99.12
55	45	45	45	78.75	78.75	43.3125	98.3125
54	46	46	46	80.5	80.5	43.47	97.47
53	47	47	47	82.25	82.25	43.5925	96.5925
52	48	48	48	84	84	43.68	95.68
51	49	49	49	85.75	85.75	43.7325	94.7325

Table 5. Possible compensation by modulating the error signal by a gain of 2

Supply Voltage in Volts	% of Sag	Error	Duty Cycle of PWM without Modulation	Modulated Error = 2 * error	Modulated PWM	Compensating voltage generated by the DVR = Supply Voltage * Modulated Duty Cycle	Load Voltage = compensating Voltage + Supply Voltage
51	49	49	49	98	98	49.98	100.98
50	50	50	50	100	100	50	100
49	51	51	51	102	100	49	98
48	52	52	52	104	100	48	96

4. SIMULATION RESULTS

For easy understanding, the rated value of supply voltage is set with the amplitude of 100V, 50Hz. The DVR operates with the filter inductance of 1mH and filter capacitance of 15uF at the carrier frequency of 4 KHz. In the Figure 5(a), it could be observed that the supply voltage has a sag of 20% as the amplitude of the supply voltage is 80V. Even though the supply voltage has 20% sag, the load voltage is maintained at the rated voltage of 100v as shown in the Figure 5(b) and the corresponding compensating voltage synthesized by the DVR is shown in the Figure 5(c).

When the supply voltage is at 60V with a sag of 40% as shown in the Figure 6(a), the DVR is compensating the sag and the load voltage is maintained at 100V as shown in the Figure 6(b), by generating compensating voltage as shown in the Figure 6(c). In the Figure 7(a), it could be observed that the supply voltage has a sag of 50% as the amplitude of the supply voltage is 50V. Even though the supply voltage has 50% sag, the load voltage is maintained at the rated voltage of 100v as shown in the Figure 7(b) and the corresponding compensating voltage synthesized by the DVR is shown in the Figure 7(c). When the supply voltage is at 48V with a sag of 52% as shown in the Figure 8(a), the DVR is compensating this maximum sag and the load voltage is maintained at 100V as shown in the Figure 8(b), by generating compensating voltage as shown in the Figure 8(c).

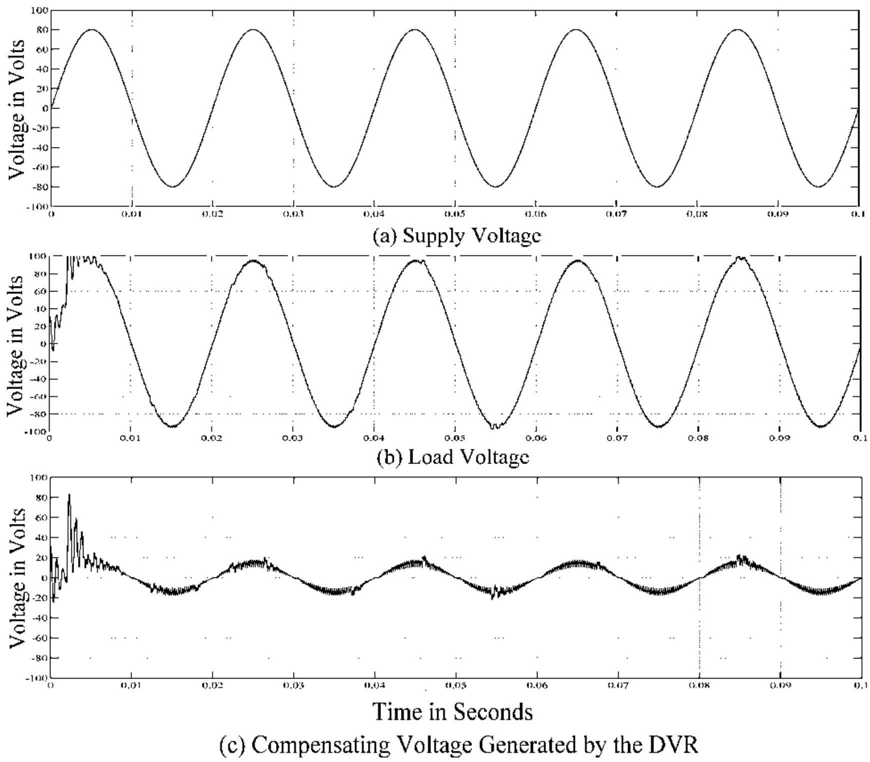

Figure 5. Sag Compensation of 20%

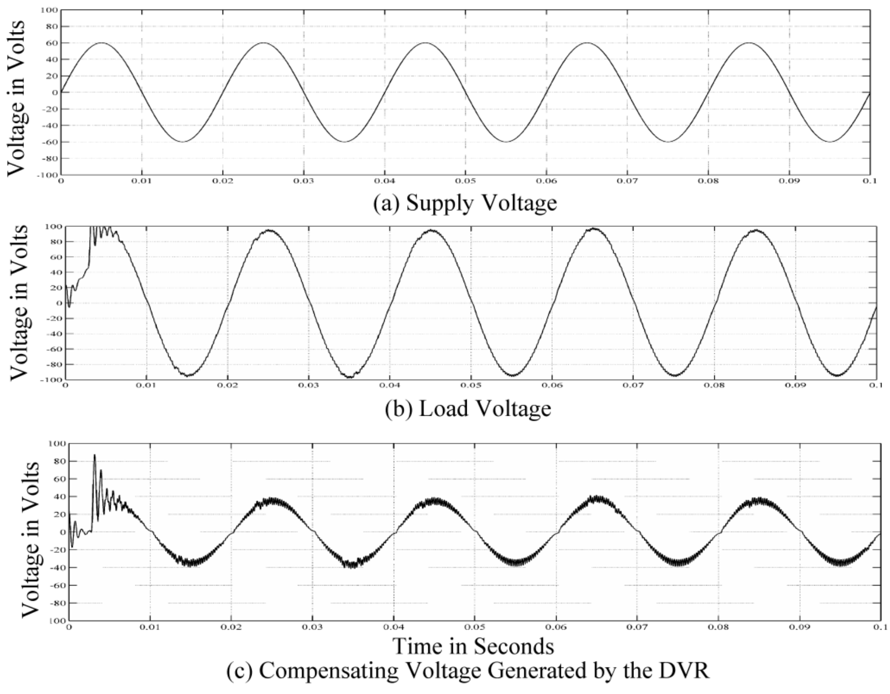

Figure 6. Sag Compensation of 40%

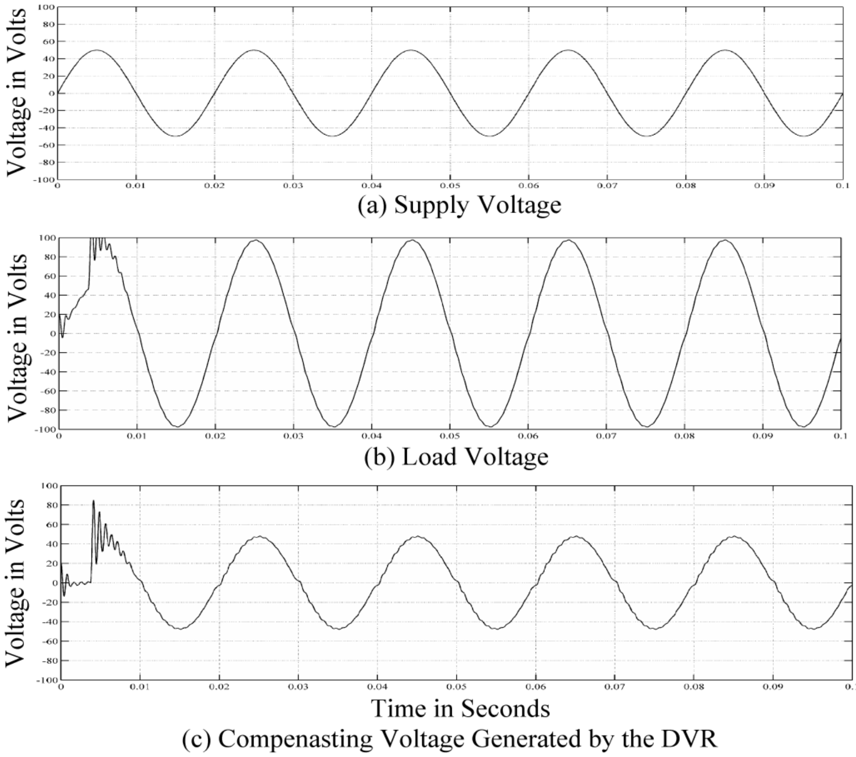

Figure 7. Sag Compensation of 50%

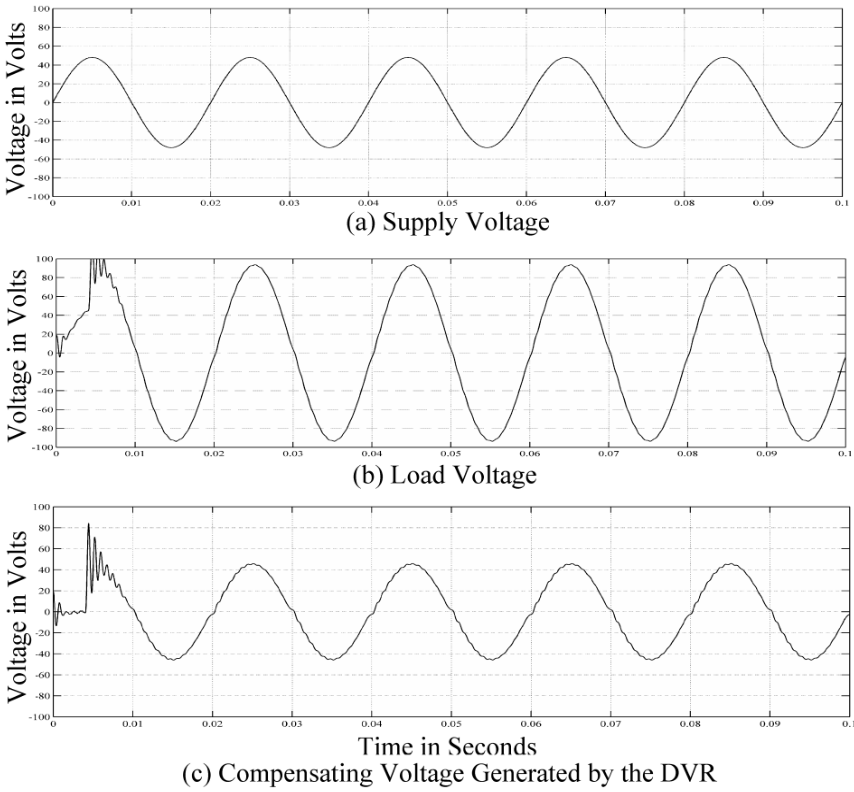

Figure 8. Sag Compensation of 52%

5. CONCLUSION

Though it is possible to mitigate voltage sag using DVR of various topologies, a detailed and easy procedure for obtaining highest sag compensation is not discussed in the literature so far. In this paper highest voltage sag compensation is achieved with the simple topology of DVR based on direct converter and controlled with an easy modulation technique. The DVR topology presented in this paper has got only two bidirectional switches. When the DVR is compensating the voltage as only two switches are operated to mitigate the sag, the switching losses are minimum. The PWM generation is also very easy as these two switches are modulated alternatively. It is been proved in this paper that if the actual error signal is used to generate the PWM for compensating the sag, it is possible to achieve only 22% of sag compensation. In order to achieve the highest sag compensation, the error signal is amplitude modulated according to the percentage of voltage sag and the PWM is generated according to the modulated error signal. With this modulated error PWM generation, the direct converter based DVR presented in this paper mitigated 52% of voltage sag with the THD less than 5%.

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