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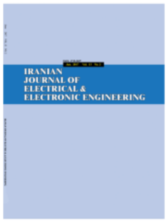
Research Paper



A Novel DVR Topology to Compensate Voltage Swell, Sag, and Single-Phase Outage

S. A. Rahman*$^{(C.A.)}$, S. Birhan*, E. D. Mitiku*, G. T. Aduye*, and P. Somasundaram**

Abstract: Aim of this paper is to attain the highest voltage sag and swell compensation using a direct converter-based DVR topology. The projected DVR topology consists of a direct converter with bidirectional switches, a multi winding transformer with three primary windings and secondary winding and a series transformer. When voltage swell occurs in a phase, the same phase voltage can be utilized to mitigate the swell as huge voltage exists in the phase where swell has occurred. So it is possible to mitigate an infinite amount of swell. In all the DVR topologies, the converter is only used to synthesize the compensating voltage. The range of voltage sag mitigation depends upon the magnitude of input voltage available for the converter. If this input voltage of the direct converter is increased, then the range of voltage compensation could also be increased. Input voltage of the direct converter is increased using the multi winding transformer. The direct converter is synthesizing the compensating voltage. This compensating voltage is injected in series with the supply voltage through the series transformer and the sag is mitigated. In this proposed topology, the input voltage for the direct converter is increased by adding the three phase voltages using a multi winding transformer. Thus the voltage sag compensating range of this topology is increased to 68% and the swell compensating range is 500%. Ordinary PWM technique has been used to synthesize the PWM pulses for the direct converter and the THD of the compensated load voltage is less than 5%. This topology is simulated using MATLAB Simulink and the results are shown for authentication.

Keywords: Dynamic Voltage Restorer (DVR), Direct Converter, Bidirectional Switch, Multi Winding Transformer, Ordinary PWM, MATLAB Simulink.

1 Introduction

VOLTAGE sag (or dip), Very short interruptions, Long interruptions, Voltage spike, Voltage swell, Harmonic distortion, Voltage fluctuation, noise, and voltage unbalance are the common power quality problems. But voltage sag and swell are considered to be the most severe issues as they will affect all the sensitive and nonlinear loads. In this era, all industries are automated with sensitive devices like computers, DSP, FPGA, etc. If a voltage sag or swell occurs, the entire industry will get shut down or maloperate due to the sensitive devices. This will result in data or economical loss or both [1-6]. To avoid these losses, flat voltage profiles should be maintained in the industry. Though we have many devices like uninterruptible power supply, active filters, generators and static transfer switch, DVR is one of the best devices to mitigate voltage sag and swell. Because the UPS should be active always and there is a double conversion process like AC/DC and DC/AC. In active filters, the current carrying capacity of the device should be huge to mitigate a small magnitude of sag or swell. Generators and static transfer switches are bulky, uneconomical, requirement of more maintenance, etc. So Dynamic Voltage Restorer (DVR) is one of the best devices, for voltage sag and swell mitigation, when

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Iranian Journal of Electrical and Electronic Engineering, 2021.
Paper first received 17 November 2020, revised 18 February 2021, and accepted 02 March 2021.

* The authors are with the Department of Electrical and Computer Engineering, Institute of Technology, University of Gondar, Ethiopia.
E-mails: msajce.abdulrahman@gmail.com, shumyeb9@gmail.com, est7eced@gmail.com, and gebrie.415@gmail.com.
** The author is with the College of Engineering Guindy, Anna University, India.
E-mail: somuau77@gmail.com.
Corresponding Author: S. A. Rahman.

https://doi.org/10.22068/IJEEE.17.4.2036

compared to other available devices [7-11]. DVR is a device which will add a voltage in phase with or out of phase with the supply voltage in order to mitigate voltage sag or swell at the load side. It works, when there is an occurrence of sag or swell. Otherwise, it will not work. DVRs could be classified into two categories. DVRs using energy storing devices and DVRs using direct converters. The DVRs using energy storing devices are using batteries or capacitors or supercapacitors to store the DC power (or the rectified AC power from the supply-side). From the energy storage device, the compensating AC voltage is synthesized using an inverter. This compensating voltage added is series with the line voltage using a series transformer to mitigate voltage sag or swell. This DVR topology which is based on energy storage devices, has disadvantages like double conversion, huge current consumption, bulky, uneconomical, huge maintenance and need of DC-link capacitor [12-16]. Recently DVRs are proposed, based on direct converters. But the DVR based on direct converters does not have any disadvantages like double conversion, huge current consumption, bulky and uneconomical [17-20]. Since the available AC power in the grid is used for compensation, no energy storing devices are required. So far in the literature, very few publications are available for the DVRs using direct converters. In the DVRs which use direct converters, the voltage sag compensating range is based on, the modulating techniques and the availability of input voltage for the direct converter [21-23]. So far a maximum voltage sag compensation of 50% had been achieved, using the DVR topologies based on matrix converter [24]. Though it is possible to mitigate the sag and swell using a single-phase matrix converter, it can mitigate a voltage sag of 50% and cannot mitigate single-phase outage as it takes power from the same phase to mitigate sag. A DVR topology in [25] is mitigating voltage sag of 33% and voltage swell of 100% but cannot mitigate single-phase outage. With less number of switches in [26], 50% sag and 100% swell was mitigated but the same topology cannot mitigate single-phase outage. Carrier modulation-based DVR in [27], can mitigate 33% of voltage sag and 100% of swell. A DVR topology based on two winding transformers can mitigate only balanced sag, single-phase outage and 100% swell and it cannot mitigate unbalanced sag [28]. From the literature survey, it is found that almost all the topologies of DVR based on direct converters, require at least 4 bidirectional switches per phase. During compensation, PWM signals have to be generated for at least three switches. If the power is taken from the same phase to mitigate voltage sag, then the maximum sag compensation is 50% and that topology cannot mitigate single-phase outage. If the power is taken from the other phases to mitigate voltage sag, then that topology can mitigate only 33% of voltage sag. To mitigate single-phase outage using DVRs based on direct converters, power should be taken from the other phases. A multi winding transformer is necessary to take the power from the other phases and to add the other phase voltages. By adding the two-phase voltages of the same magnitude, it is possible to get the third phase voltage using the multi winding transformer. The range of voltage sag mitigation depends upon the input voltage available for the direct converter. If the input voltage for the direct converter is increased, then the range of voltage compensation could also be increased. So far, from the literature survey, it is observed that with the presented DVRs based on direct converter, the maximum voltage sag compensation is only 50% and that topologies cannot mitigate single-phase outage or otherwise it cannot mitigate unbalanced sag. Otherwise, if the DVR is able to mitigate single-phase outage then it cannot achieve 50% voltage sag compensation. But the topology presented in this paper, can mitigate single-phase outage, balanced voltage sag of 68%, unbalanced voltage sag (by properly adding the three-phase voltages using a multi winding transformer) and swell.

2 Proposed Topology of the DVR

Each phase is provided with a DVR as shown in Fig. 1. Each DVR has a direct converter with seven bidirectional switches, a multi winding transformer to add the three-phase voltages, an LC filter to minimize the harmonics, and a series transformer to inject the compensating voltage. Ordinary pulse width-modulation (PWM) technique is employed to operate the switches. The multi winding transformer has totally four windings. The primary of the multi winding transformer has three windings and the secondary side has one winding with the turns ratio of 1:1:1:3. Each primary winding has a turns ratio of 1 and the secondary winding has the turn ratio of 3. The turn ratio of the series transformer is 1:1 and its secondary is connected in such a way that the compensating voltage injected at the primary is added 180 degrees out of phase with the primary voltage. Under normal condition, i.e. while the supply voltage is without any sag or swell, all the switches are in open condition except the switches Sga, Sgb, and Sgc. These three switches Sga, Sgb, and Sgc should be in closed condition so that the series transformer secondary side is shorted. The voltage added with the supply voltage is zero. So the load voltage is maintained at the rated voltage.

Whenever and whichever phase voltage swell occurs, the power is taken from the same phase as more voltage is available at that phase due to swell. For example, when phase ‘a’ has voltage swell, the switches Saa and Sga are used to generate the compensating voltage. The compensating voltage is injected 180 degrees out of phase with respect to the supply voltage using the series transformer to mitigate the swell. Thus the voltage swell will be mitigated.

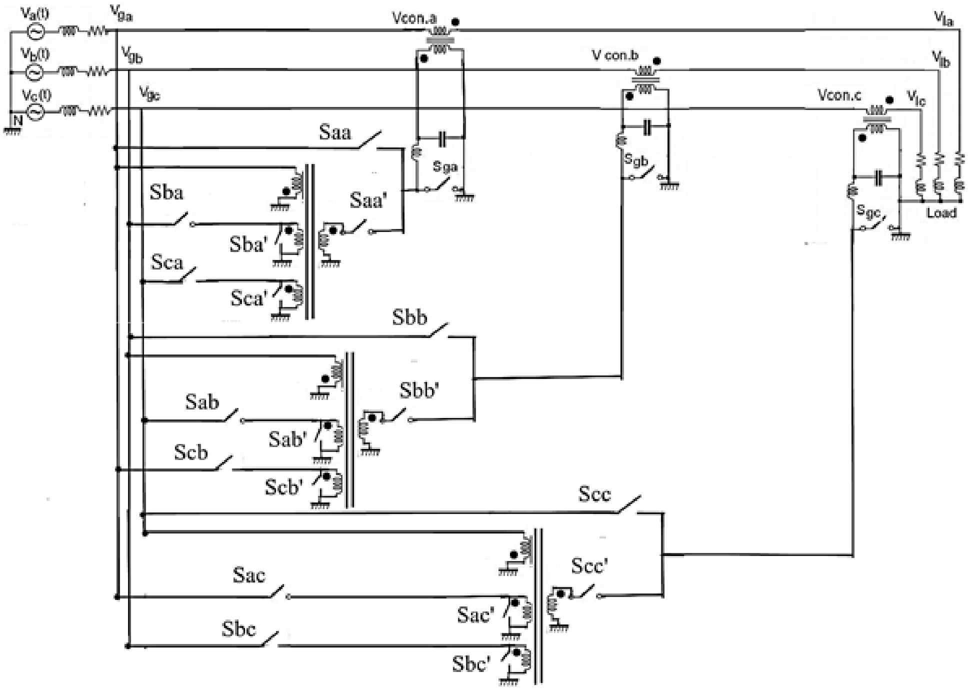


Fig. 1 Proposed DVR topology.

When voltage sag occurs at phase ‘a’, phase ‘a’ voltage, modulated phase ‘b’ voltage, and modulated phase ‘c’ voltage, are added by the multi winding transformer. The resultant secondary winding voltage of the multi winding transformer is 180 degrees phase shifted with respect to phase ‘a’ voltage. From this resultant voltage, the compensating voltage is obtained by operating the switches Saa’ and Sga alternatively and added along with the supply voltage using the series transformer to mitigate the sag. As the output voltage of the multi winding transformer is already 180 degrees phase shifted with respect to phase ‘a’ voltage and the secondary of the series transformer is connected in such a way to add the compensating voltage 180 degrees out of phase with the supply voltage, the compensating voltage will be added in phase with the supply voltage as sum of 180 degrees and 180 degrees is zero degrees.

3 Sag Compensation

Using the single-phase dq theory, the peak value of the supply-side voltage is measured. This measured value is compared with the reference value to identify the voltage sag or swell and also to generate the error signal as explained in [24]. The multi winding transformer consists of three primary windings and a single secondary winding. The multi winding transformer primary windings are connected in such a way that the first winding voltage is subtracted from the addition of second and third winding primary voltages. The winding polarity of the primary winding of the multi winding transformer could be explained by taking phase ‘a’ multi winding transformer as an example. To mitigate the voltage sag at one phase, the power from all the three phases are utilized. To mitigate voltage sag at phase ‘a’, phase ‘a’ is connected directly to the first primary winding. The phase ‘b’ is connected to the second primary winding but through two bidirectional switches Sba and Sba’ for supplying power from phase ‘b’ to phase ‘a’. Likewise, the phase ‘c’ is connected to the third primary winding but through two bidirectional switches Sca and Sca’ for supplying power from phase ‘c’ to phase ‘a’. Now the second and third winding voltages will be connected in additive polarity and the first winding voltage will be connected to get subtracted from the additive polarity. So the primary windings voltage connection is written as $(v_b + v_c) - v_a$ for phase ‘a’. The voltage sag compensation is analyzed in three different conditions.

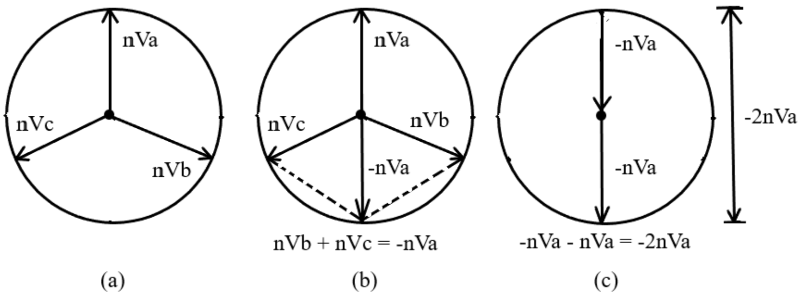
3.1 Balanced Sag Compensation

When a balanced sag occurs at the supply-side, voltages of all the phases are equal in magnitude and displaced by 120 degrees. As equal voltage magnitudes exist at phase ‘b’ and phase ‘c’ the switches Sba and Sca are closed and the switches Sca’ and Sba’ are opened. The second and third primary windings are connected in additive polarity. So under balanced conditions, we know that,

$$v_a + v_b + v_c = 0 \tag{1}$$

The multi-winding transformer adds the equal magnitude phase ‘b’ and phase ‘c’ voltages as given by (2).

$$(v_b + v_c) = -v_a \tag{2}$$

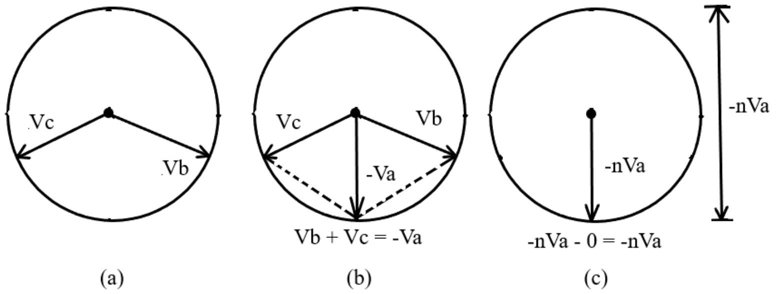


(a) (b) (c)

Fig. 2 Voltage phasors at balanced voltage sag condition; a) Balanced sag, b) Addition of two-phase voltages, and c) Output voltage of multi winding transformer.

Table 1 DVR switches to be modulated for balanced sag compensation.

Phase ‘a’			Phase ‘b’			Phase ‘c’		
ON	OFF	Modulating	ON	OFF	Modulating	ON	OFF	Modulating
Sba & Sca	Sba’ & Sca’	Saa’& Sga	Scb & Sab	Scb’ & Sab’	Sbb’ & Sgb	Sac & Sbc	Sac’ & Sbc’	Scc’ & Sgc



(a) (b) (c)

Fig. 3 Phasor diagram for single-phase outage compensation; a) Single-phase outage, b) Addition of two phases, and c) Output voltage of multi winding transformer.

Table 2 DVR switches to be modulated for single-phase outage compensation.

Phase ‘a’			Phase ‘b’			Phase ‘c’		
ON	OFF	Modulating	ON	OFF	Modulating	ON	OFF	Modulating
Sba & Sca	Sba’ & Sca’	Saa’& Sga	Scb & Sab	Scb’ & Sab’	Sbb’ & Sgb	Sac & Sbc	Sac’ & Sbc’	Scc’ & Sgc

The first primary winding is connected to subtract the phase ‘a’ voltage from the resultant voltage of the second and third primary winding voltage. So

$$(v_b + v_c) - v_a = -2v_a \tag{3}$$

From (2) and (3)

$$(-v_a) - v_a = -2v_a \tag{4}$$

The output voltage on the secondary side will be double the time of the phase ‘a’ voltage but phase shifted by 180 degrees. The phasor diagram for adding the three-phase voltages is shown in Fig. 2. The balanced voltage sag condition at the supply-side is shown in Fig. 2(a). All the phase voltages are equal to the magnitude of nV with n < 1. In Fig. 2(b), phase ‘b’ and phase ‘c’ voltages are added and the resultant voltage which is phase shifted by 180 degrees with respect to phase ‘a’ voltage is shown. This resultant voltage is subtracting the phase ‘a’ voltage using the first primary winding and the output voltage is double the phase ‘a’ voltage as shown in Fig. 2(c). From this output voltage, the compensating voltage is synthesized using switches Saa’ and Sga and injected along with the supply voltage using the series transformer.

3.2 Single-Phase Outage Compensation

When anyone of the three phases has no power, it is called single-phase outage. The proposed topology can mitigate the single outage also. Consider a single-phase outage at phase ‘a’ as shown in Fig. 3. The multi winding transformer will add the voltages of phase ‘c’ and phase ‘b’ as shown in Fig. 3. As per (2), the resultant voltage magnitude is equal to the phase ‘a’ rated voltage but phase shifted by 180°. This resultant voltage is injected using the series transformer, in phase with the supply-side phase ‘a’ voltage by closing the switch Saa’ and opening the switch Sga.

3.3 Unbalanced Voltage Sag Compensation

When an unbalanced sag occurs, still the compensation is possible. Unbalanced sag could be analyzed in two different conditions. In the first case, the phase in which the sag occurs has a magnitude which is different from the other two phase voltages magnitude but the other two phases have equal magnitude. In the second case,

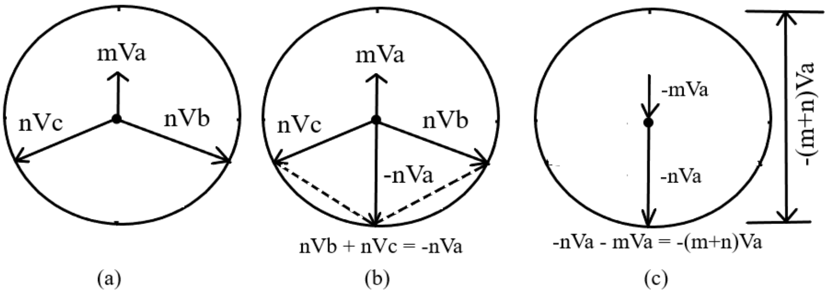


Fig. 4 Phasor diagram unbalanced sag compensation: Case 1; a) Unbalanced sag, b) Addition of two phases, and c) Output voltage of multi winding transformer.

Table 3 DVR switches to be modulated under unbalanced voltage sag: Case 1.

Phase ‘a’			Phase ‘b’			Phase ‘c’		
ON	OFF	Modulating	ON	OFF	Modulating	ON	OFF	Modulating
Sba & Sca	Sba’ & Sca’	Saa’& Sga	Scb & Sab	Scb’ & Sab’	Sbb’ & Sgb	Sac & Sbc	Sac’ & Sbc’	Scc’ & Sgc

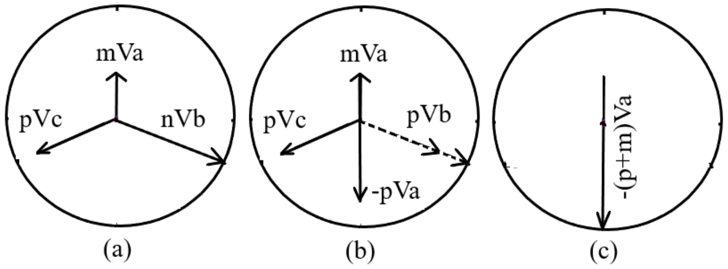


Fig. 5 Phasor diagram unbalanced sag compensation: Case 2, a) Unbalanced sag, b) Addition of two phases, and c) Output voltage of multi winding transformer.

none of the three-phase voltages are equal to each other.

Case 1: Consider voltage sag occurs at phase ‘a’ with a magnitude mVa where m<1. The other two phase voltages are equal in magnitude. i.e. $nVb = nVc$ and $m < n < 1$ as shown in Fig. 4. As the voltages of phase ‘c’ and phase ‘b’ are equal, they could be added, without any modulation by the switches Sba, Sba’, Sca, and Sca’. It is enough to close the switches Sba, Sca and to open the switches Sba’ and Sca’. The resultant voltage –nVa will be 180 degrees phase shifted with respect to phase ‘a’. The phase ‘a’ voltage mVa, will be subtracted from this resultant voltage –nVa, so that the output voltage is 180 degrees phase shifted with respect to phase ‘a’ voltage, which is given by –(m+n)Va. From this voltage –(m+n)Va, the compensating voltage is generated by operating the switches Saa’ and Sga.

Case 2: Consider that in all three phases, the magnitudes of the voltages are different as shown in Fig. 5(a). As m, n, and p are less than one, and not equal to each other, all the three phases have voltage sag. The mitigating technique of the DVR could be explained by taking phase ‘a’ as an example. As phase ‘b’ and phase ‘c’ voltage are not equal, they cannot be added directly. So the DVR, find the higher phase voltage out of the phase ‘b’ and phase ‘c’ and modulate it using the switches such that the modulated voltage will be equal to the other phase voltage. For example, if phase ‘b’ voltage is more than phase ‘c’ voltage (such that $mVa < pVc < nVb$) , then only the switches Sba and Sba’ are alternatively modulated in order to bring the voltages of phase ‘c’ and phase ‘b’ equal. The switching pulse generation block diagram is shown in Fig. 6 which is self-explanatory. Phase ‘c’ rms voltage value is subtracted from the Phase ‘b’ rms voltage value to get the error value. This error value is divided by the phase ‘b’ rms voltage value to express the error in per unit. PWM pulses for the switches Sba and Sba’, are produced by comparing the error signal with the carrier signal. Phase ‘c’ voltage will not be modulated as its magnitude is less than phase ‘b’. As phase ‘c’ voltage is not modulated, the switch Sca is closed and Sca’ is opened as observed from Fig. 6.

Now the voltages of modulated phase ‘pVb’ and unmodulated phase ‘pVc’ voltages are added. So the resultant voltage is –pVa, as shown in Fig. 5(b). As explained already, the ‘a’ phase voltage ‘mVa’ is subtracted from this resultant voltage –pVa, and the output voltage is –(p+m)Va which is shown in Fig. 5(c).

The peak value of the multi winding transformer secondary voltage –(p+m)Va, is measured. From the supply-side and the phase ‘a’ peak voltage is subtracted from the reference voltage to get the voltage sag value. To synthesize the required compensating voltage, it is mandatory to express the error signal in terms of the voltage from which the compensating voltage will be generated. Here the compensating voltage is generated from the output voltage of the multi winding

Table 4 DVR switches to be modulated under unbalanced voltage sag: Case 2.

Phase ‘a’	Phase ‘b’	Phase ‘c’
Sba, Sba’, Sca, Sca’, Saa’& Sga	Scb, Scb’, Sab, Sab’, Sbb’ & Sgb	Sac, Sac’, Sbc, Sbc’, Scc’ & Sgc

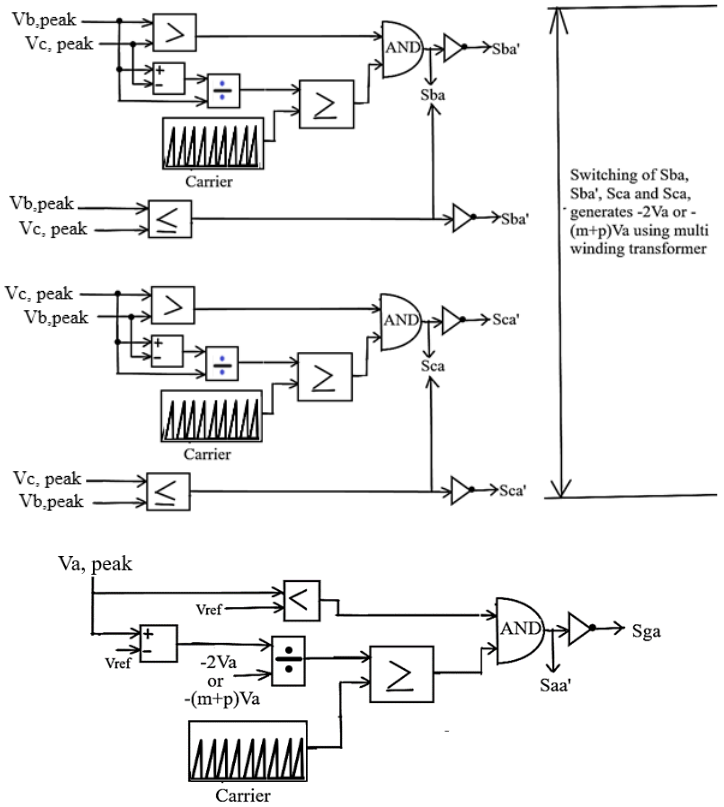


Fig. 6 Switching pulse generation for swell mitigation.

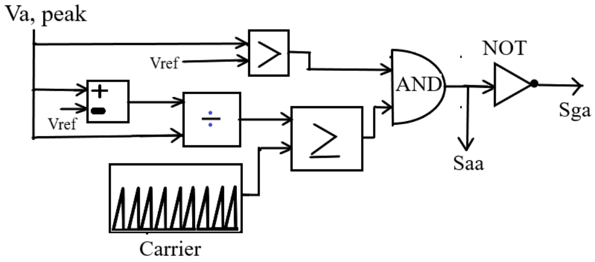


Fig. 7 Switching pulse generation for swell mitigation.

Table 5 DVR switches to be modulated under-voltage swell.

Phase ‘a’	Phase ‘b’	Phase ‘c’
Saa & Sga	Sbb & Sgb	Scc & Sgc

transformer. So the voltage sag value is divided by the peak value of the multi winding transformer output voltage –(p+m)Va, to get the error signal in per unit. Using this error signal PWM pulses for the switches are generated. The compensating voltage is produced by operating the switches Saa’ and Sga. Switching pulse generation for sag compensation is presented in Fig. 6. The generated compensating voltage is injected using the series transformer in order to mitigate the sag at phase ‘a’. In this manner, the voltage sag in other phases also mitigated. Table 4, shows the active switches in each phase during unbalanced voltage sag compensation.

4 Swell Compensation

During voltage swell, the phase in which swell occurs has more than the rated voltage. This surplus voltage which is available is used for swell compensation. When a voltage swell takes place at phase ‘a’ then switches Saa and Sga are operated to generate the compensating voltage. This compensating voltage is injected along with the supply-side voltage using the series transformer to alleviate the voltage swell. The series transformer connection is fixed in such a way that, always (whether it is sag or swell or normal condition) the series transformer is adding the compensating voltage 180 degrees out of phase with the supply voltage.

5 Simulation Outcomes

To simulate this proposed system MATLAB/Simulink software is used. The amplitude of the desired load voltage is 325 V (1 p.u) at a frequency of 50 Hz with a load of 2.4 kVA per phase at 0.8 lagging power factor. The direct converter is operated at a carrier frequency of 5 kHz with LC filters of values 1 mH and 15 µF. Series transformers have a turn ratio of 1:1. Balanced voltage sag compensation of 68% is shown in Fig. 8. Unbalanced voltage sag compensation of 68% in phase ‘a’ and phase ‘c’ and voltage sag of 40% in phase ‘b’ (Case 1) is shown in Fig. 9. In Fig. 10, the DVR is compensating an unbalanced voltage sag of 70% in phase ‘a’, 40% in phase ‘b’ and 10% in phase ‘c’ (Case 2). Compensation of single-phase outage is shown in Fig. 11, where the phase ‘a’ has no voltage at the supply-side but at the load side, the phase ‘a’ voltage is maintained at the rated value by the DVR.

Mitigation of 100% voltage swell at all the phases is shown in Fig. 12. Compensation of unbalanced voltage swell of 25% at phase ‘a’, 50% at phase ‘b’ and 100% at phase ‘c’ (Case 1) can be observed from Fig. 13. Fig. 14 shows the mitigation of unbalanced voltage swell of 100% at phase ‘a’, 300% at phase ‘b’ and 500% at phase ‘c’ (Case 2).

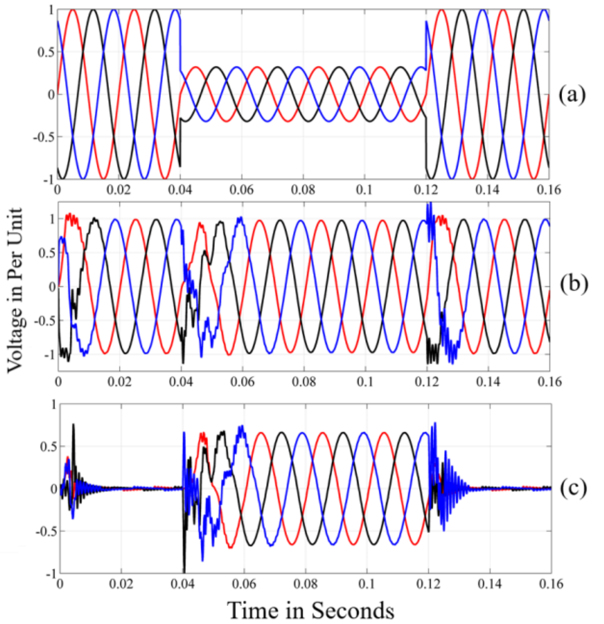


Fig. 8 Balanced voltage sag compensation; a) Supply-side voltage, b) Load side voltage, and c) Compensating voltage.

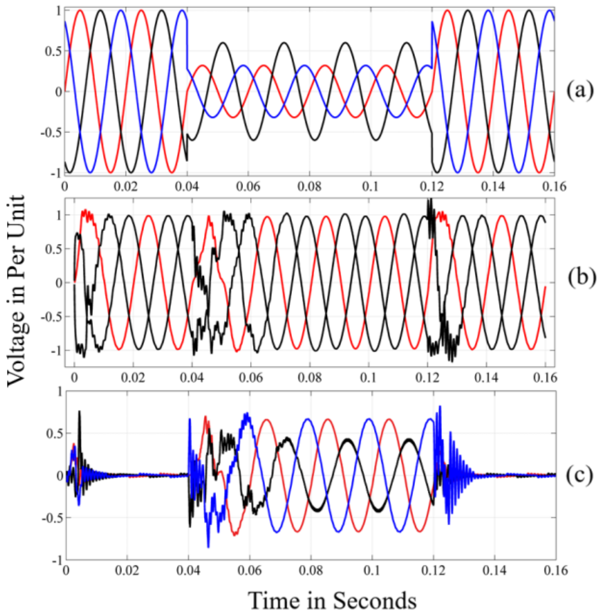


Fig. 9 Unbalanced voltage sag compensation: Case 1; a) Supply-side voltage, b) Load side voltage, and c) Compensating voltage.

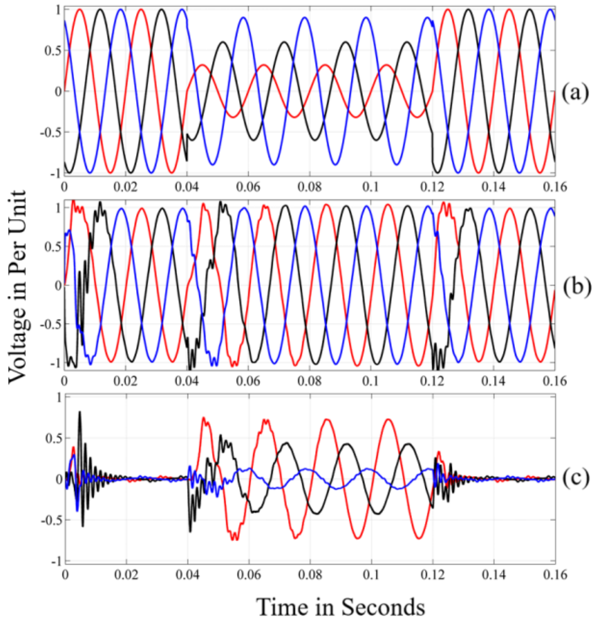


Fig. 10 Unbalanced voltage sag compensation: Case 2; a) Supply-side voltage, b) Load side voltage, and c) Compensating voltage.

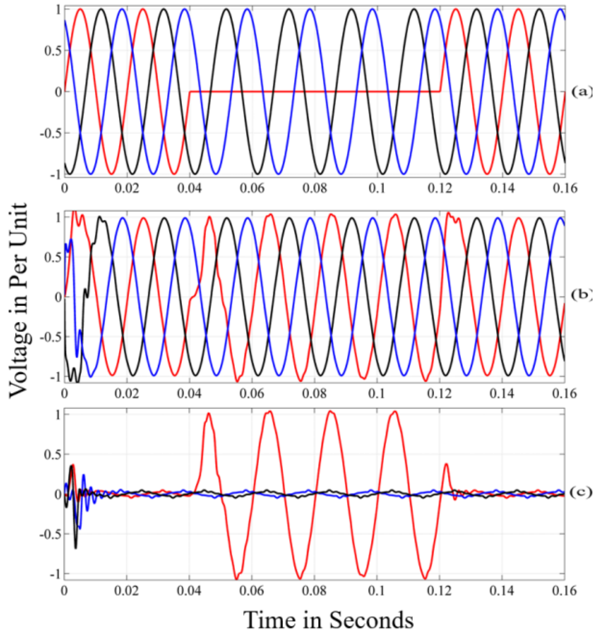


Fig. 11 Single-phase outage compensation; a) Supply-side voltage, b) Load side voltage, and c) Compensating voltage.

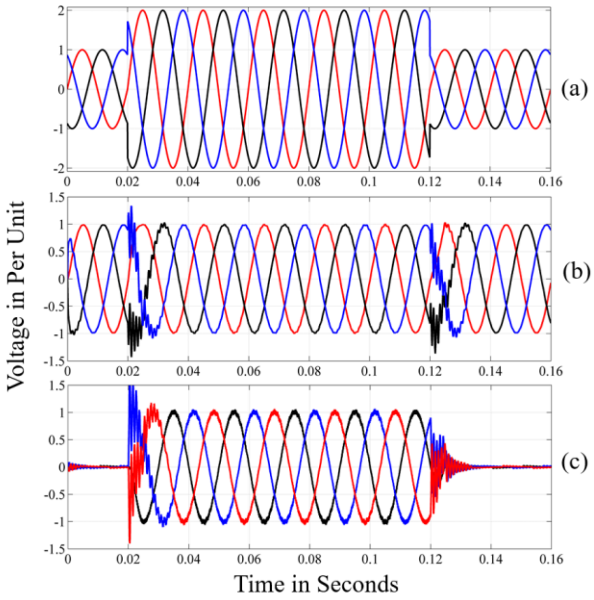


Fig. 12 100% balanced voltage swell compensation; a) Supply-side voltage, b) Load side voltage, and c) Compensating voltage.

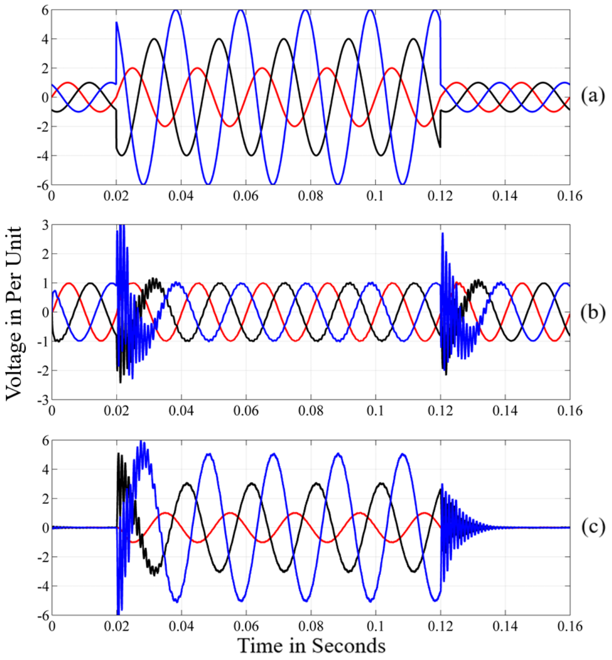


Fig. 12 Unbalanced voltage swell compensation: Case 2; a) Supply-side voltage, b) Load side voltage, and c) Compensating voltage.

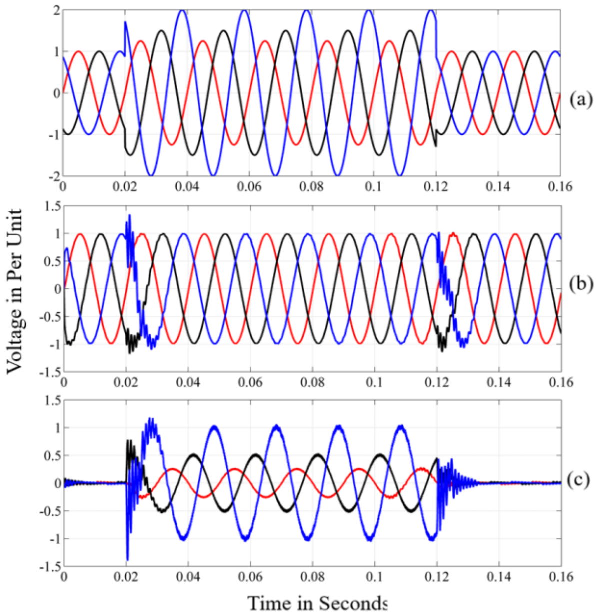


Fig. 13 Unbalanced voltage swell compensation: Case 1; a) Supply-side voltage, b) Load side voltage, and c) Compensating voltage.

6 Conclusion

Though many DVRs based on direct converters have been proposed, the maximum voltage sag compensation achieved is only 50%. The best topology in the literature survey, with the 4 bidirectional switches per phase, can only mitigate 50% of sag and 100% of swell but it cannot compensate for single-phase outage. Though this proposed topology is using a multi winding transformer with 7 bidirectional switches per phase, its ability to compensate both balanced and unbalanced sag, swell, and also single-phase outage, proves the importance and efficiency of this topology. Using this proposed topology, it is proved that by adding all the three-phase voltages using a multi winding transformer and by properly modulating the direct converters, voltage sag of 68%, single-phase outage, and voltage swell of infinite quantity can be compensated. The control procedure is very simple and rugged as the ordinary PWM technique is used to mitigate the disturbances.

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S. A. Rahman was born in 1978, in Tamilnadu, India. He completed his under graduation in the field of Electrical & Electronics Engineering in 1999 at the University of Madras, India, post-graduation in Power Electronics & Drives in 2007 at Anna University, India, and Ph.D. in the field of Electrical Engineering, in 2014 at Anna University, India. He was working as an Assistant Professor at King Khalid University, Saudi Arabia. Now he is working as an Assistant Professor at the University of Gondar, Ethiopia. His fields of research interests are power quality improvement, direct converters, and modulating techniques.

S. Birhan was born in 1988 in central Gondar in the Amhara region, Ethiopia. He received his B.Sc. degree in Electrical and Computer Engineering at Haramaya University in 2010 and he got his M.Sc. degree from Addis Ababa Institute of Technology in Electrical Power Engineering in 2016/17 academic year. Now he is working at the University of Gondar as a Lecturer since 2012. He has served as a research and publication coordinator of the Institute of Technology in this university. He is currently the chair of the Electrical Power Engineering stream. I am a senior member of the Department Unit Council of the Electrical and Computer Engineering Department. He is interested in the research area of power electronics application in power systems, DC transmission and distribution technology, smart grid technology, and renewable energy technologies.

E. D. Mitiku was born in 1990, Gondar, Amhara, Ethiopia. He has received his B.Sc. degree in Electrical and Computer Engineering from Bahir Dar Institute of Technology, Bahir Dar, Ethiopia in 2012 and M.Sc. degree in Electrical Power Engineering from Addis Ababa Institute of Technology, Addis Ababa, Ethiopia in 2015. He has worked as a Lecturer and Researcher in the Department of Electrical & Computer Engineering, Gondar Institute of Technology, University of Gondar, Gondar, Ethiopia since 2012. Presently, he is working as a Head of the Department for Electrical and Computer Engineering. He has attended international and national conferences during his stay at the University of Gondar. He is actively involved in research, technology transfer, and community service projects for the past five years. His area of interest is power quality improvement and renewable energy technologies.

G. T. Aduye was born in 1982, Gondar, Amhara, Ethiopia. He has received his B.Sc. degree in Electrical Engineering from Mekelle University, Ethiopia, and M.Sc. degree in Electrical Power Engineering from Bahirdar University, Ethiopia. He is working as a Lecturer, Researcher in the Department of Electrical & Computer Engineering, Gondar Institute of Technology, University of Gondar, Gondar, Ethiopia since 2016. He has served as a community service coordinator of the Institute of Technology in this university. He has attended international and national conferences during his stay at the University of Gondar. He is actively involved in research, technology transfer, and community service projects for the past four years. His area of interest is power quality improvement and renewable energy technologies.

P. Somasundaram was born on 24th May 1977, at Kurumbanur, Tamil Nadu, India. He got his Undergraduate Degree in Electrical and Electronics Engineering in 1998 from the University of Madras, India. He obtained the Postgraduate degree in Power System Engineering in 2000 from Annamalai University, India. He completed his Ph.D. in 2005 at Anna University, India. His area of interest is application of artificial intelligence techniques to power system optimization problems, hybrid microgrids, renewable energy, and power quality improvement. At present, he is working as a Professor in the Department of Electrical and Electronics Engineering, College of Engineering-Guindy, Anna University, India.