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RESEARCH ARTICLE

# Voltage Sag, Swell, and Interruption Compensation Using DVR Based on Energy Storage Device

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**ABSTRACT** Though we have many power quality issues, voltage sag, interruption and swell are considered to be very important ones as it occurs very frequently and affects the sensitive loads adversely. Though many topologies of DVR are presented in the literature, all the topologies have used P or PI or PID or fuzzy or neural network controllers to mitigate power quality issues. But in this paper, it is proved that it is possible to mitigate the voltage sag, swell and outages using Dynamic Voltage Restorer (DVR), without using any controllers like P, PI, PID, fuzzy or neural networks. The proposed DVR consists of a battery bank as an energy storage device, a Voltage Source Inverter (VSI), control circuitry to generate switching pulses, LC filter and a series transformer. The proposed DVR is connected immediately after the distribution transformer in order to protect the load from supply voltage deviations. The three phase supply voltages are always measured and converted into Direct-Quadrature-Zero (DQ0) quantities and compared with the reference value to generate error signals. When the supply voltage is at rated value, the error signal is zero. So, PWM will not be generated by the control circuitry and the VSI won't generate any compensating voltage. At this condition, the secondary winding of the series transformer will also be short circuited using a breaker. So, the voltage injected into the line by the DVR is zero. Thus, the load voltage is equal to supply voltage and maintained at rated value. Whenever a sag or swell or interruptions occurs at the supply side, the three phase voltages are not at rated value and also unbalanced. So, error signals will be generated in the DQ0 frame. These error signals in the DQ0 frame are again converted into three phase voltages using inverse DQ0 transformation. Using these three phase error signals, switching pulses are generated for the VSI. The generated compensating voltage is injected along with the supply voltage using the series transformer, in order to maintain the load voltage at rated value. MATLAB Simulink software is used for simulation and the presented results validate that the proposed DVR can effectively mitigate balanced and unbalanced voltage sag of 100%, balanced and unbalanced voltage swell of 100%, single phase outage and three outages.

**INDEX TERMS** Dynamic voltage restorer (DVR), sag, swell, short interruption, power quality, VSI.

## I. INTRODUCTION

Power quality is affected and degraded due to the disturbances occurring in the transmission as well as in the distribution sides. (Flexible AC Transmission System) FACTS devices are employed at the transmission side to overcome the power quality problems [1], [2]. Custom power devices are employed in the distribution side to compensate for the power quality disturbances like voltage sags, interruption, swells, and harmonic distortions, etc. The effect of a power quality issue depends upon the type of utility. Certain issues may pose a serious problem for a given utility class, but it may not be

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considered a big issue for another class. So, it is practically quite difficult to rank the above issues according to their severity [3], [4].

Generally unpredictable faults on the distribution and transmission systems cause voltage sag, interruption, and swell. The voltage sags are also caused by starting of large motors, switching of large loads, energizing of transformers and equipment faults. Most of these faults (70-80%) will be self-cleared within a few milliseconds as explained in [5], [6], and [7]. IEEE Standard 1100-1992 in IEEE Emerald Book defines voltage sag as, "a rms reduction in the AC voltage from 90% to 10% of nominal supply, at the power frequency, for durations from a half-cycle to a few seconds". Voltage swell is defined as, "a short duration increases in rms supply with an increase in voltage ranging from 110% to 180% of nominal supply". Highlighted that the main reasons for voltage swells are switching large capacitors or the sudden removal of large loads [8], [9], [10]. As the various issues originate both from utility and customer sides, the solution is also to be provided on both sides. While the FACTS devices are controlled by the utility, the custom power devices are installed, operated, and maintained by the customers at their premises. Hence, line conditioners have been developed to perform the role of regulating, conditioning, isolating, purifying, and distributing incoming power with adequate power quality standards.

All most all industries and automation systems use embedded systems like computers, micro controllers, microprocessors, digital signal processors, and field programmable gate arrays for the automation process. These embedded devices are very sensitive to supply voltage variations [11], [12]. If the magnitude of the supply voltage changes, then these embedded devices will get switched off and result in data, time, work and economic losses. For example, in a paper manufacturing industry, if the supply voltage deviation occurs, then speed of the motor will get changed or suddenly stopped. This, will lead to change in thickness of the paper or the paper will get ripped. This in turn results in rejection of the whole bundle of the paper, halting the entire process and restarting the whole system again. All these results into loss of economy, human resource and time [13], [14]. So, it is mandatory to maintain the power quality of the system in order to avoid process disturbances in the precision and automated industries, which employ many embedded systems that are very sensitive to power supply disturbances.

Though many CUPS devices like UPS, DSTACOM are available to improve the power quality in distribution side, DVR is a recent and effective device to improve the power quality [15], [16], [17]. Uninterruptible Power Supply converts the AC to DC and stores the energy in the battery. This stored DC is converted to AC and delivered to the utilities. It mitigates most of the power quality problems with a double conversion process [18]. Solid State Transfer Switch doesn't need an energy storage device for mitigation. When a power quality disturbance occurs, it disconnects the faulty feeder and connects to a healthy feeder [19]. Compared to UPS, DVR is cost effective and more efficient since UPS needs to operate all the time whether the power quality disturbance occurs or not. Dstatcom is a shunt controller, which needs a high-power rating transformer which has to withstand large shunt injection current, to mitigate voltage sag, swell or interruption [20], [21]. The Dynamic Voltage Restorers (DVR) is a recent series active controller developed to compensate power quality issues for the entire duration of their occurrence, maintaining a clean regulated voltage at critical loads. In this paper, the power quality issues like voltage sag, swell and interruption had been identified, and it is mitigated using the DVR.

Many DVR topologies are presented in the literature survey. DVRs based on direct converters are presented in [6] and [7], in which power required for compensation is taken from the AC supply side and AC/AC direct converters are used to generate compensating voltage for mitigating voltage sag and swell. In this topologies, single phase outage or three phase outages can't be compensated as there is no voltage available at the supply side during outage. Moreover, these topologies can compensate only 50% of voltage sag or depending upon the voltage availability at the supply side. DVRs based on energy storage devices are using either battery banks or capacitor banks for storing DC power and a voltage source inverter (VSI) is used to synthesis the compensating voltage from the DC power stored in the battery banks. As the compensating voltage is synthesized from the DC power stored in the battery banks, these topologies can mitigate 100% of voltage sag, swell and also outages.

Cuckoo search algorithm is used in [22] to mitigate power quality problems using DVR based on energy storage device. Zero Active Power Tracking Technique is presented in [23] for DVR capability enhancement. A hysteresis voltage control loop is implemented along with the synchronous reference frame technique in [24]. Harris Hawks Optimization Algorithm is implemented for enhancing the DVR control system in [25]. A discrete time control method is applied for fast transient voltage sag compensation in DVR in [26]. An adaptive neuro-fuzzy control strategy based on soft computing is used for power quality improvement in [27]. In [28], in order to improve the transient responses of the three-phase load voltage and the DC-link voltage under the sudden grid voltage distortion conditions, a novel recurrent compensation petri fuzzy neural network controller is used. For power quality enhancement using DVR, a predictive space vector transformation with proportional resonant controller, is presented in [29]. Improved instantaneous reactive power theory-based control of DVR for compensating extreme sag and swell is presented in [30] and both line current and supply side voltages are sensed in order to generate the compensating voltage. But in the proposed control technique, compensating voltage is generated only by sensing the supply side voltage. Moreover, all the above-mentioned DVR topologies are using some algorithms or special control loops or intelligent controllers or P controller or PI controller or PID controller for voltage sag and swell compensations. But the proposed topology is not using any algorithm or any PI controller or current measurement or artificial intelligence or neuro or fuzzy technique for the compensation. The proposed topology is simply measuring the supply side voltage and expressing it in DQ0 quantities. The obtained DQ0 quantities are compared with the reference values to generate the error signals. The switching pulses are generated from the error signal in order to synthesis the compensating voltage.

## II. TOPOLOGY OF THE PROPOSED DVR

As the DVR is a custom power device, it is installed immediately after the distribution transformer in order to protect the loads from the supply voltage deviations. The topology of the proposed DVR is shown in the figure 1. The proposed DVR has a battery bank as an energy storage device. The battery is connected to the VSI in order to supply DC power to the VSI. The output voltage of the VSI is fed to the primary winding of series transformer through LC filters. A breaker is connected across the secondary winding of the series transformer. The supply voltage is continuously measured and compared with the rated reference value. When the supply voltage is at rated value, no error signals will be produced. No switching pulses will be generated for the VSI. So, the compensating voltage generated by the DVR will be zero. At this condition, the breaker will be in closed condition. The secondary winding of the series transformer will be short circuited. Load voltage will be equal to the supply voltage and at rated value.

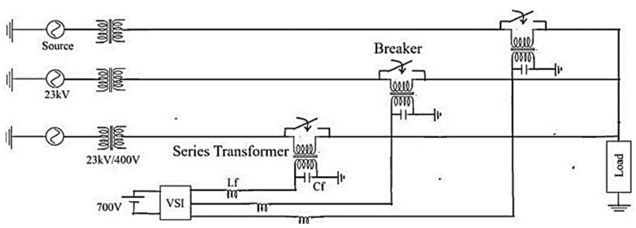


**FIGURE 1.** Topology of the Proposed DVR.

Whenever a voltage sag or swell or interruption occurs, the supply voltage will not be equal to rated value. So, error signals will be generated. The DVR will generate the required compensating voltage using the control circuitry. The breaker across the series transformer will be opened. The compensating voltage will be added to the line, along with the supply voltage through the series transformer in order to mitigate the voltage sag, swell and interruption. The supply voltage is continuously measured and monitored.

## III. CONTROL ALGORITHM

The supply voltage from the grid is continuously monitored by the control circuit. The proposed DVR and the control circuits are installed immediately after the distribution transformer. The control system's job is to continuously monitor and identify any disruptions in the supply voltage by comparing it with the predetermined reference value and synthesis the required PWM switching pulses for VSI in order to generate the required compensating voltage.

It is very well known that the three phase voltages can be expressed in direct quadrature voltages using Clarks and parks transforms. It is also known that when the three phase voltages are at rated value, their corresponding direct axis voltage and the quadrature axis voltage will have the values as 1 and zero. So, the reference values in DQ0 frame are 1 for $V_{sd}$ and 0 for $V_{sd}$ and $V_{s0}$. Based upon these very well-known facts, the supply voltages $V_{sa}$, $V_{sb}$, and $V_{sc}$ are first transformed to the $V_{sd,}$ $V_{sq\ \mathrm{and}}$ $V_{s0}$, using the equation (1).

$$\begin{bmatrix} V_{so} \\ V_{sd} \\ V_{sq} \end{bmatrix} = \frac{2}{3} \begin{vmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \sin wt & \sin\left(wt - \frac{2\pi}{3}\right) & \sin\left(wt + \frac{2\pi}{3}\right) \\ \cos wt & \cos\left(wt - \frac{2\pi}{3}\right) & \cos\left(wt + \frac{2\pi}{3}\right) \end{vmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (1)$$

Under rated condition, let, Vsa as Vmsinwt, Vsb as Vmsin(wt-120) and Vsc as Vmsin(wt-240). Then from equation (1), we will get Vso and Vsq as zero and Vsd as Vm (which is nothing but 1 per unit). The obtained supply voltages $V_{s0}$, $V_{sd}$ and $V_{s0}$ in DQ0 frame, are compared with the reference values. The control circuit block diagram is shown in the figure 2. $V_{sd}$ will be compared with 1. $V_{s0}$ and $V_{sq}$ will be compared with 0. If the supply voltage is at rated value, then the $V_{sd}$ will be equal to 1, both $V_{s0}$ and $V_{sq}$ will 0. Then the error value will be zero. So, no PWM pulses will be generated and the compensating voltage generated by the VSI is zero. In this condition the breaker will be closed. This will short circuit the secondary side of the series transformer and the compensating voltage added will be zero. So, the load voltage will be equal to rated supply voltage.

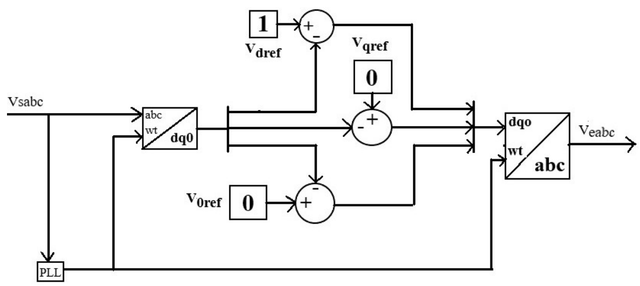


**FIGURE 2.** Control Circuit Block Diagram.

Whenever a voltage sag swell or interruption occurs, the supply voltages are unbalanced and not at rated value. So, neither $V_{sd}$ will be equal to 1, nor $V_{s0}$ and $V_{sq}$ will be equal to 0. So, an error voltage will be generated when compared with the reference DQ0 values. This error DQ0 voltages are $V_{e0}$, $V_{ed}$ and $V_{eq}$. The error voltages $Ve_0$, $V_{ed}$ and $V_{eq}$ in DQ0 frame, will again convert into three phase voltages $V_{ea}$, $V_{eb}$ and $V_{ec}$ using equation (2).

$$\begin{bmatrix} V_{ea} \\ V_{eb} \\ V_{ec} \end{bmatrix} = \frac{2}{3} \begin{vmatrix} \frac{1}{2} & \sin wt & \cos wt \\ \frac{1}{2} & \sin(wt - \frac{2\pi}{3}) & \cos(wt - \frac{2\pi}{3}) \\ \frac{1}{2} & \sin(wt + \frac{2\pi}{3}) & \cos(wt + \frac{2\pi}{3}) \end{vmatrix} \begin{bmatrix} V_{e0} \\ V_{ed} \\ V_{eq} \end{bmatrix} \tag{2}$$

$V_{ea}$, $V_{eb}$ and $V_{ec}$ error signals are compared with the carrier signals and the PWM switching pulses are generated for the VSI. A phase locked loop circuit is used to track the phase of the supply voltages in order to generate the compensating voltage according to the three different phases of the supply voltage. The compensating voltage generated by the DVR is injected in the line along with the supply voltage through the series transformer in order to maintain the load voltage at rated condition at all the time.

## IV. SIMULATION RESULTS

To verify the proposed algorithm, the supply voltage from the grid is chosen as 23kV. This supply voltage is stepped down using a 6.25 kVA distribution transformer of 23kV/400 V. A RL load of 5 kVA with 0.8 power factor lag is chosen. The DVR is connected immediately after the distribution transformer. The voltage of the battery bank is 700 volts. A voltage source inverter is constructed with 6 IGBT switches with anti-parallel diodes. A LC filter of 2 milli Hendry and 15 micro farad is connected at the output of the VSI. The filtered output voltage is added to the supply voltage using a 6.25 kVA series transformer of 1:1 turns ratio. The proposed DVR is able to mitigate voltage sag, swell, single phase outage and three phase outages successfully. The simulation results are presented below in per unit value. As the results are expressed in per unit value, the results are self- explanatory and easy to understand the effectiveness and reliability of the proposed DVR.

Mitigation of single-phase voltage sag of 50% in phase 'a' is shown in the figure 3. Mitigation of balanced voltage sag of 20% and 50% is shown in the figure 4 and figure 5 respectively. Mitigation of unbalanced voltage sag of 20% in phase 'a', 50% in phase 'b' and 25% in phase 'c' is shown in the figure 6.

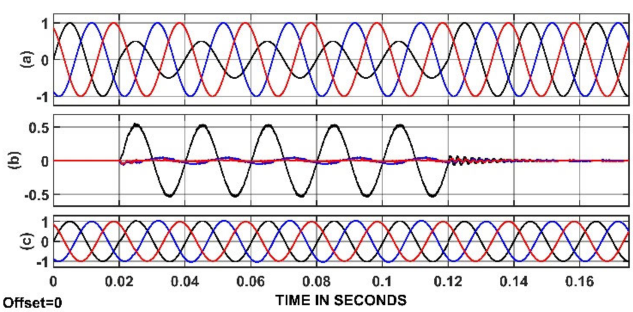


**FIGURE 3.** Single phase voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

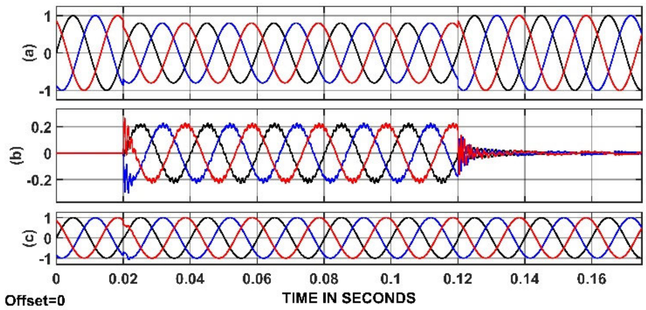


**FIGURE 4.** Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

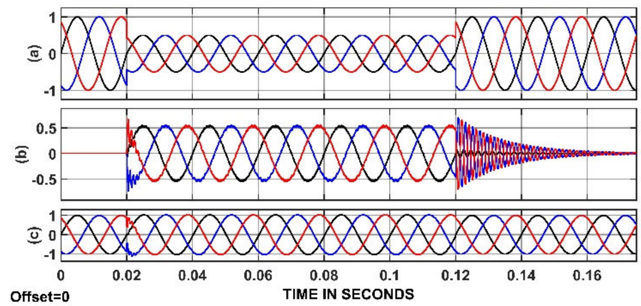


**FIGURE 5.** Balanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

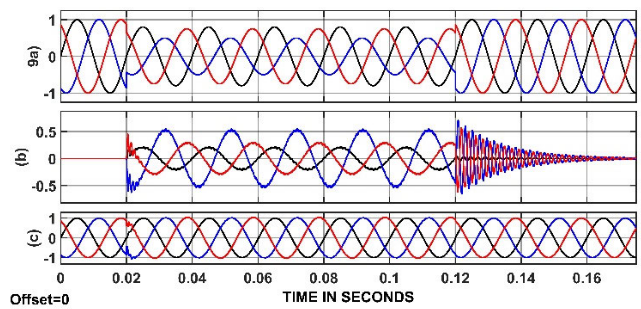


**FIGURE 6.** Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

Mitigation of single-phase outage in phase 'c' and unbalanced voltage sag of 20% in phase 'a' and 50% in phase 'b' is shown in the figure 7. Three phase outage mitigation is shown in the figure 8. The ability of the proposed DVR to compensate balanced voltage swell of 100% and single-phase swell of 100% in phase 'a' are shown in the figures 9 and 10 respectively. Unbalanced voltage swell of 100% in phase 'a', 75% in phase 'b' and 50% in phase 'c' is shown in the figure 11.

## V. PERFORMANCE COMPARISON

DVR control based on Cuckoo search algorithm presented in [22], uses two DC link capacitors to maintain the DC link voltage constant and the DC voltage is maintained constant by using the cuckoo search algorithm. But in the proposed

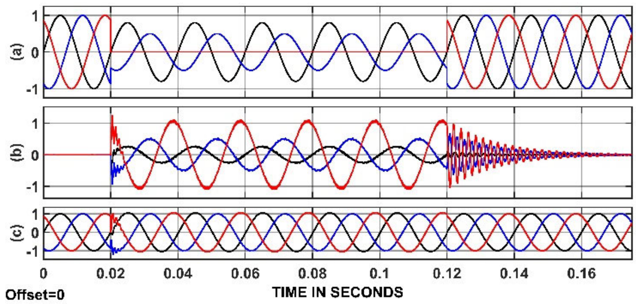


FIGURE 7. Single phase outage and Unbalanced voltage sag mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

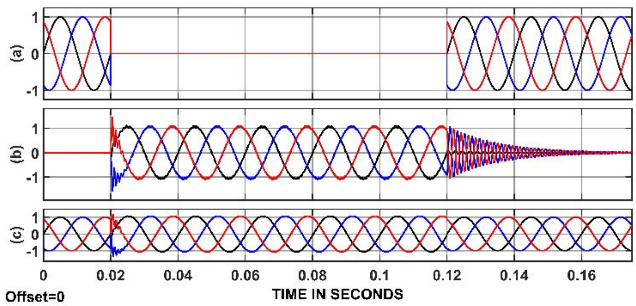


FIGURE 8. Three phase outage mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

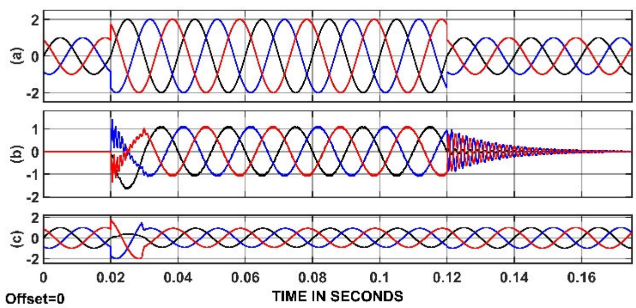


FIGURE 9. Balanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

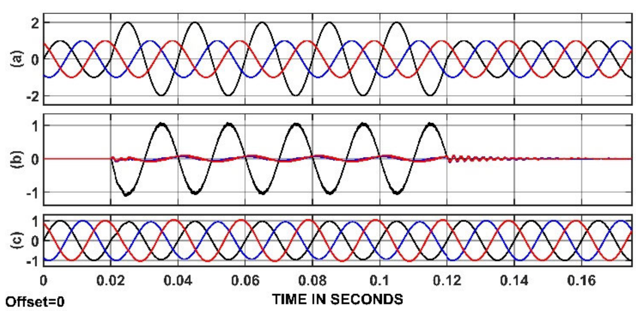


FIGURE 10. Single phase voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

topology, no DC link capacitors are used but the Dc link voltage is maintained constant without using any algorithm.

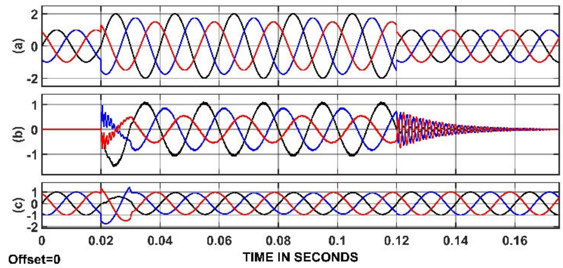


FIGURE 11. Unbalanced voltage swell mitigation (a)Source Voltage in Per Unit (b) Compensating voltage generated by the DVR in Per Unit (c) Load voltage in Per Unit.

Zero Active Power Tracking Technique based DVR is presented in [23] has used 12 switches for implementing voltage source inverter. But the proposed topology has used only 6 switches for the VSI.

Synchronous Reference Frame based DVR in [24] and soft computing adaptive Neuro-Fuzz controllers-based DVR presented in [27] have also used a DC link capacitor for maintain the DC link voltage constant and also used 3 switches around the series transformer. One breaker across the series transformer to short circuit when the supply voltage is at rated value. Two switches on both the side of the transformer, to connect the series transformer along the line when a voltage fluctuation occurs. In the proposed topology, only one breaker is used to short circuit the secondary side of the transformer when the supply voltage is at rated condition. As the series transformer is permanently connected in the line, it is enough to open the breaker when the supply voltage has fluctuations.

Harris Hawks Optimization Algorithm based DVR proposed in [25] has not used any breaker across the series transformer to make the compensation voltage zero when the supply voltage is at rated condition. Moreover, this topology also uses a DC link capacitor across the battery and the series transformer turns ration is 3:1. But the proposed topology didn't use any DC link capacitor and has used series transformer with the turns ration of 1:1 to mitigate 100% sag, swell and outages.

A discrete time control method is applied for fast transient voltage sag compensation in DVR in [26]. This topology has used a series transformer of rating 20kVA for a load of 5 kVA. This is a very high value. But the proposed topology has used a series transformer of 6.25 kVA for a load of 5 kVA.

In [28], in order to improve the transient responses of the three-phase load voltage and the DC-link voltage under the sudden grid voltage distortion conditions, a novel recurrent compensation petri fuzzy neural network controller is used. In this presentation, no breaker is used across the series transformer in order to short circuit the secondary side of the transformer when the supply voltage is at rated condition. The control algorithm is highly complex to implement. But the proposed topology is very simple rugged and easy to implement.

For power quality enhancement using DVR, a predictive space vector transformation with proportional resonant controller, is presented in [29]. This topology has used a DC link capacitor for maintaining the DC link voltage and no breaker is used across the series transformer.

Improved instantaneous reactive power theory-based control of DVR for compensating extreme sag and swell is presented in [30] and both line current and supply side voltages are sensed in order to generate the compensating voltage. In this topology no braker is used across the series transformer and DC link capacitor is used. But in the proposed control technique, compensating voltage is generated only by sensing the supply side voltage and no DC link capacitor is used.

All the above-mentioned topologies didn't show any results regarding mitigation of single-phase outages and three phase outages. In this paper the mitigation of single-phase outage and three phase outages using the proposed DVR is shown.

All the above-mentioned DVR topologies are using some algorithms like cuckoo search algorithm or special control loops or intelligent controllers like neuro or fuzzy or at least P or PI or PID controller for compensations. But the proposed topology is not using any algorithm or P or PI or PID controller or current measurement or artificial intelligence or neuro or fuzzy technique for the compensation. The proposed topology is simply measuring the supply side voltage and expressing it in DQ quantities. The obtained DQ quantities are compared with the reference values to generate the error signals. Th error signal obtained in the DQ0 frame is again expressed in three phase quantities using inverse DQ0 transform. The switching pulses are generated from the error signal in order to synthesis the compensating voltage and mitigating 100% voltage sag, swell and outages without using any controllers or algorithm.

## VI. CONCLUSION

From the above simulation results, it is proved that the proposed DVR based on energy storage device as battery banks, can mitigate balanced voltage sag, unbalanced voltage sag, single phase outage, three phase outage, balanced voltage swell and unbalanced voltage swell of 100%, using DQ0 theory. The control is very simple, rugged and easy to implement, as voltage source inverter with only six IGBT switches are used for three phase system. In the literature, many topologies were presented to mitigate voltage sag, swell and interruption using DVR but they all have used controllers like P or PI or PID controllers or fuzzy logic controllers or neural network controllers or some algorithms. But, in the proposed model, it is proved to mitigate voltage sag, swell and outage, no controller is needed. With out any controller and algorithms, just by using DQ theory, the proposed system has generated the PWM pulses needed for generating compensating voltage to mitigate the sag, swell and outages. The simulation results validated the ability of the proposed system for the compensation of 100% voltage sag, swell, single phase outage and three phase outages without any controllers using DVR based on energy storage device.

## REFERENCES


[1] Y. Han, Y. Feng, P. Yang, L. Xu, Y. Xu, and F. Blaabjerg, "Cause, classification of voltage sag, and voltage sag emulators and applications: A comprehensive overview," *IEEE Access*, vol. 8, pp. 1922–1934, 2020, doi: 10.1109/ACCESS.2019.2958965.

[2] S. Rahman, S. B. Mule, E. D. Mitiku, G. T. Aduye, and C. Gopinath, "Highest voltage sag and swell compensation using single phase matrix converter with four controlled switches," *Przeglad Elektrotechniczny*, vol. 97, no. 4, pp. 134–138, Mar. 2021, doi: 10.15199/48.2021.04.24.

[3] A. Rahman, "Realization of single phase matrix converter using 4 controlled switches," *Int. J. Eng., Appl. Manag. Sci. Paradigms*, vol. 54, no. 7, pp. 1–4, 2019.

[4] M. A. E. Mitiku, G. Aduye, and S. Rahman, "Performance comparison of harmonic filters in an industrial power system for harmonic distortion reduction," *Przeglad Elektrotechniczny*, vol. 98, no. 3, pp. 50–53, Mar. 2023, doi: 10.15199/48.2022.03.12.

[5] G. Tan and Z. Wang, "Stability analysis of recurrent neural networks with time-varying delay based on a flexible negative-determination quadratic function method," *IEEE Trans. Neural Netw. Learn. Syst.*, early access, Nov. 3, 2023, doi: 10.1109/TNNLS.2023.3327318.

[6] S. A. Rahman, S. Birhan, E. D. Mitiku, G. T. Aduye, and P. Somasundaram, "A novel DVR topology to compensate voltage swell, sag, and single-phase outage," *Iranian J. Elect. Electron. Eng.*, vol. 17, no. 4, pp. 1–10, 2021, doi: 10.22068/IJEEE.17.4.2036.

[7] A. R. S. Abuthahir, S. Periasamy, and J. P. Arumugam, "Mitigation of voltage sag and swell using direct converters with minimum switch count," *J. Power Electron.*, vol. 14, no. 6, pp. 1314–1321, Nov. 2014.

[8] J. Hu, G. Tan, and L. Liu, "A new result on $H_\infty$ state estimation for delayed neural networks based on an extended reciprocally convex inequality," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 71, no. 3, pp. 1181–1185, Mar. 2024, doi: 10.1109/TCSII.2023.3323834.

[9] S. A. Rahman and P. Somasundaram, "Mitigation of voltage sag and swell using dynamic voltage restorer without energy storage devices," *Int. Rev. Elect. Eng.*, vol. 7, no. 4, pp. 4948–4953, 2012.

[10] S. A. Rahman, P. A. Janakiraman, and P. Somasundaram, "Voltage sag and swell mitigation based on modulated carrier PWM," *Int. J. Electr. Power Energy Syst.*, vol. 66, pp. 78–85, Mar. 2015.

[11] A. Moghassemi, S. Padmanaban, V. K. Ramachandaramurthy, M. Mitolo, and M. Benbouzid, "A novel solar photovoltaic fed TransZSI-DVR for power quality improvement of grid-connected PV systems," *IEEE Access*, vol. 9, pp. 7263–7279, 2021, doi: 10.1109/ACCESS.2020.3048022.

[12] S. A. Rahman and P. Somasundaram, "Voltage sag and swell compensation using AC/AC converters," *Austral. J. Electr. Electron. Eng.*, vol. 11, no. 2, pp. 186–194, 2014.

[13] S. A. Rahman, "Direct converter based DVR to mitigate single phase outage," *Int. J. Recent Technol. Eng.*, vol. 8, no. 3, pp. 85–88, Sep. 2019.

[14] A. Rahman, "Mitigation of voltage sag, swell and outage without converter," *Int. J. Latest Trans. Eng. Sci.*, vol. 8, no. 1, pp. 1–6, 2019.

[15] E. M. Molla and C.-C. Kuo, "Voltage sag enhancement of grid connected hybrid PV-wind power system using battery and SMES based dynamic voltage restorer," *IEEE Access*, vol. 8, pp. 130003–130013, 2020, doi: 10.1109/ACCESS.2020.3009420.

[16] A. Rahman, "Mitigation of single phase voltage sag, swell and outage using voltage controlled voltage source," *Global Sci. J.*, vol. 7, no. 10, pp. 195–201, 2019.

[17] S. A. Rahman and G. Teshome, "Maximum voltage sag compensation using direct converter by modulating the carrier signal," *Int. J. Electr. Comput. Eng.*, vol. 10, no. 4, pp. 3936–3941, Aug. 2020.

[18] S. A. Rahman and E. Dagnew, "Voltage sag compensation using direct converter based DVR by modulating the error signal," *Indonesian J. Electr. Eng. Comput. Sci.*, vol. 19, no. 2, pp. 608–616, 2020.

[19] S. A. Rahman, E. D. Mitiku, S. B. Mule, G. T. Aduye, M. A. Huluka, and S. Mesfin, "Voltage sag mitigation using direct converter based DVR without error signal," *PRZEGLĄD ELEKTROTECHNICZNY*, vol. 97, no. 12, pp. 34–37, Dec. 2021, doi: 10.15199/48.2021.12.05.

[20] E. Hossain, M. R. Tür, S. Padmanaban, S. Ay, and I. Khan, "Analysis and mitigation of power quality issues in distributed generation systems using custom power devices," *IEEE Access*, vol. 6, pp. 16816–16833, 2018, doi: 10.1109/ACCESS.2018.2814981.

[21] P. A. Janakiraman and S. A. Rahman, "Linear pulsewidth modulation under fluctuating power supply," *IEEE Trans. Ind. Electron.*, vol. 61, no. 4, pp. 1769–1773, Apr. 2014, doi: 10.1109/TIE.2013.2263776.

[22] S. G. Reddy, S. Ganapathy, and M. Manikandan, "Three phase four switch inverter based DVR for power quality improvement with optimized CSA approach," *IEEE Access*, vol. 10, pp. 72263–72278, 2022, doi: 10.1109/ACCESS.2022.3188629.
[23] M. Danbumrungtrakul, T. Saengsuwan, and P. Srithorn, "Evaluation of DVR capability enhancement-zero active power tracking technique," *IEEE Access*, vol. 5, pp. 10285–10295, 2017, doi: 10.1109/ACCESS.2017.2706275.
[24] S. F. Al-Gahtani, A. B. Barnawi, H. Z. Azazi, S. M. Irshad, J. K. Bhutto, H. M. Majahar, and E. Z. M. Salem, "A new technique implemented in synchronous reference frame for DVR control under severe sag and swell conditions," *IEEE Access*, vol. 10, pp. 25565–25579, 2022, doi: 10.1109/ACCESS.2022.3151919.
[25] Z. Elkady, N. Abdel-Rahim, A. A. Mansour, and F. M. Bendary, "Enhanced DVR control system based on the Harris hawks optimization algorithm," *IEEE Access*, vol. 8, pp. 177721–177733, 2020, doi: 10.1109/ACCESS.2020.3024733.
[26] A. P. Torres, P. Roncero-Sánchez, J. Vázquez, Fco. J. López-Alcolea, and E. J. Molina-Martínez, "A discrete-time control method for fast transient voltage-sag compensation in DVR," *IEEE Access*, vol. 7, pp. 170564–170577, 2019, doi: 10.1109/ACCESS.2019.2955177.
[27] N. Abas, S. Dilshad, A. Khalid, M. S. Saleem, and N. Khan, "Power quality improvement using dynamic voltage restorer," *IEEE Access*, vol. 8, pp. 164325–164339, 2020, doi: 10.1109/ACCESS.2020.3022477.
[28] K.-H. Tan, J.-H. Chen, and Y.-D. Lee, "Intelligent controlled dynamic voltage restorer for improving transient voltage quality," *IEEE Access*, vol. 11, pp. 74686–74701, 2023, doi: 10.1109/ACCESS.2023.3293823.
[29] V. Babu, K. S. Ahmed, Y. M. Shuaib, and M. Manikandan, "Power quality enhancement using dynamic voltage restorer (DVR)-based predictive space vector transformation (PSVT) with proportional resonant (PR)-controller," *IEEE Access*, vol. 9, pp. 155380–155392, 2021, doi: 10.1109/ACCESS.2021.3129096.
[30] S. F. Al-Gahtani, E. Z. M. Salem, S. M. Irshad, and H. Z. Azazi, "Improved instantaneous reactive power (PQ) theory based control of DVR for compensating extreme sag and swell," *IEEE Access*, vol. 10, pp. 75186–75204, 2022, doi: 10.1109/ACCESS.2022.3185662.

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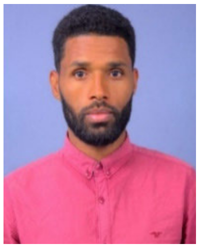

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