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TOPICAL REVIEW

A review on the state of the art of dynamic voltage restorer: topologies, operational modes, compensation methods, and control algorithms

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Abstract

Enhancing and regulating power quality is a fundamental necessity in any industry reliant on power, aiming for the optimal utilization of resources. The power quality challenges, including sags, swells, harmonic distortions, and interruptions, have been acknowledged as critical issues. Among these, sags and swells are prevalent and can significantly impact electrical devices or machines, necessitating swift compensation to prevent malfunction or failure. Custom power devices such as the Unified Power-Quality Conditioner (UPQC), Distribution Static Synchronous Compensator (DSTATCOM), and Dynamic Voltage Restorer (DVR) are employed to address these issues. The DVR, a custom power device specifically designed for compensating voltage sags and swells, offers the advantage of active/reactive power control. A considerable body of literature over the past years has explored various DVR configurations and control techniques. This comprehensive review focuses on DVRs, presenting diverse power circuit topologies and control techniques available to address power quality issues. Noteworthy advancements in DVR technology include the incorporation of advanced control algorithms, facilitating more accurate voltage tracking and precise injection of compensating voltage. These algorithms can be implemented through digital signal processors (DSPs) or field-programmable gate arrays (FPGAs), ensuring rapid and precise DVR control. Furthermore, the adoption of high-frequency inverters in DVRs represents a significant development. These inverters operate at much higher frequencies than traditional counterparts, enabling quicker switching and the injection of a more precise compensating voltage. This review aims to assist in selecting optimal control strategies and power circuits for DVRs tailored to specific requirements, providing valuable insights for researchers in this field.

Abbreviations

AC	Adaptive Control
AC	Alternating Current
AF	Active Filter
ANN	Artificial Neural Network
BESS	Battery Energy Storage Systems
CPD	Custom Power Devices
CHB	Cascaded H-Bridge

DS	Distribution System
DSC	Distribution Series Capacitors
DSTATCOM	Distribution Static Synchronous Compensator
DVR	Dynamic Voltage Restorer
EM	Energy Minimization
FACTS	Flexible AC Transmission system
FC	Flying Capacitors
HESS	Hybrid Energy Storage Systems
IDVR	Interline Dynamic Voltage Restorer
IEC	The International Electromechanical Commission
IGCT	Integrated Gate-Commutated Thyristor
IGBT	Insulated Gate Bipolar Transistors
IPFC	Interline power flow controllers.
MLI	Multilevel Inverters
MV	Medium Voltage
LV	Low Voltage
NPC	Neutral-Point Clamped
PCC	Point of Common Coupling
PF	Power Factor
PQ	Power quality
PI	Proportional-Integral
PWM	Pulse Width Modulation
RTA	Real Twisting Algorithm
RTSMC	Real Twisting Sliding Mode Control
RMS	Root Mean Square
SETC	Static Electronic Tap Changers
SMC	Sliding Mode Control
ST	Super Twisting
STATCOM	Static Synchronous Compensator
SSB	Solid-State breaker,
SSCL	Solid-State current limiter
SSTS	Solid-State transfer switch
SEMI	Semiconductor Industrial Equipment Voltage Sag Immunity Standard
SSSC	Static Synchronous Series Compensators
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SSTS	Solid-State Transfer Switches
SA	Surge Arresters
TSC	Thyristor Switched Capacitors
SSFCL	Solid State Fault Current Limiter
SRF	Synchronous Reference Frame Theory
SVC	Static Var Compensator
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
VDVR	DVR Voltages

VS	Voltage Sag/Swell
VSC	Voltage Source Converter
V	State vector
v	State variable
$\dot{v}$	First derivative state variable V
Vref	Reference Volatge
S	Sliding Surface
$\mathbf{V_P}$	Pre fault voltage of peak
$\mathbf{V_{PSag}}$	Peak faulty voltage sag
Φ	Phase angle,
$\mathbf{t_1}$	Sag beginning time,
$\mathbf{t_2}$	Recovery of voltage to nominal value,
ω	Angular frequency.
Vs	Source voltage,
ZS	Source impedance,
ZL1	Load 1 impedance,
ZL2	Load 2 impedance
ITIC	Information Technology Industry Council
IEEE	Institute of Electrical and Electronics Engineers

1. Introduction

The issue of Power Quality poses significant challenges in contemporary power systems, casting adverse effects on both consumers and utility providers [1]. With a surge in demand and heightened competition among electric supply providers, there is a concerted effort to deliver high-quality electricity to end-users. Consequently, customers across residential and industrial sectors, especially those with sensitive loads, bear the brunt of poor power quality. The power system, comprising generation, transmission, and distribution, plays a pivotal role in this scenario [2].

On the distribution side, power is disseminated to diverse loads through transmission lines [3]. While the distribution network accommodates various types of loads, it is noteworthy that poor power quality exerts a more pronounced impact on sensitive loads. Equipment such as programmable logic controllers, digital computers, computer numerical control systems, and variable frequency motor drives are particularly vulnerable to the array of power quality issues prevalent in distribution systems [4].

The Distribution system (DS) emerges as the most vulnerable component within the power system, rendering it highly susceptible to the ramifications of power quality issues. The challenges faced by the Distribution system stem from factors such as faults, fluctuating load conditions, and the intricacies associated with interconnected or radial configurations. Furthermore, compared to power generation and transmission, the Distribution system typically operates at a lower voltage profile [5].

Flexible AC transmission system devices like Unified power flow controller (UPFC) [6], Static synchronous series compensators (SSSC) [7], Interline power flow controllers (IPFC) [8], and the Static synchronous compensators (STATCOM) [9], are generally customized to be employed in electrical distribution system known as Custom power devices (CPDs) such as Dynamic Voltage Restorer (DVR) [10], Active filter (AF) [11], Unified power quality conditioner (UPQC) [12], and Distribution static synchronous compensator (DSTATCOM) [13].

The DVR stands out as the optimal solution for mitigating power quality (PQ) issues due to its exceptional performance, surpassing other devices available in the market. Furthermore, as compared to other devices, DVR provides a cost-effective alternative [14]. DVR is often installed among a network and the sensitive load, with the help of a transformer providing supplemental power to mitigate for voltage instabilities that may harm the appliance. In figure 1, the generalized model of a DVR is presented, showcasing its integration with the grid. The DVR configuration primarily consists of an energy storage unit and a control system. It is connected to the grid via a voltage source inverter, which is linked in series with the grid through an injection electrical device and a low pass filter [10]. DVR control systems are categorized into four main components: detection, reference

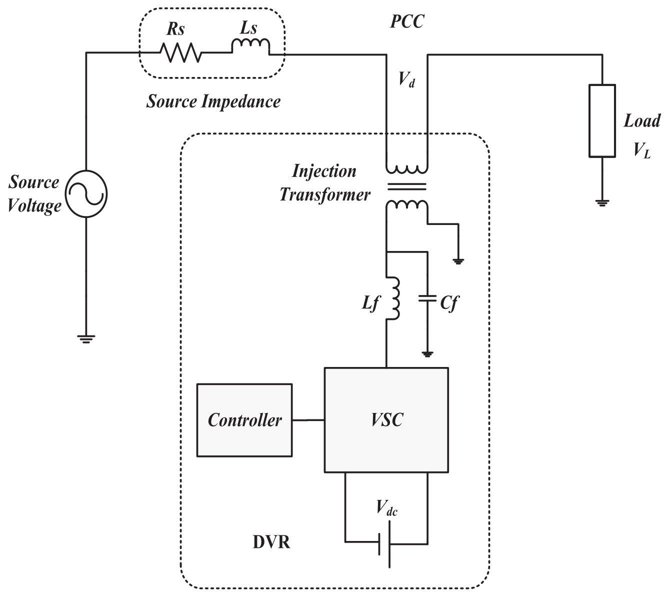


Figure 1. Block diagram of DVR.

generation, voltage/current control, and modulation [15]. There has also some Merit and demerit of DVR over other Custom devices [10, 14, 16, 17].

1.1. Merit

- Static VAR Compensator has no capability to control the real power stream along these lines DVR is still in Favor.
- DSTATCOM and other custom power gadgets are huge and expensive when contrasted with DVR.
- The DVR has more vitality capability when contrasted with UPS. Dynamic Voltage Restorer has numerous benefits over Uninterruptible Power Supply, for example low cost and less misfortunes.

1.2. Demerit

- It compensated for the PQ issues usually 50 percent.
- If the voltage to be injected exceeds the voltage rating of the protection, it becomes ineffective.
- DVR becomes more costly as the rating of power increases (when more than 50%).
- Unfeasible solution to power outage issues.
- The protection strategy is tough and expensive.

2. Power quality

Power quality in electrical systems is a significant and pressing challenge, impacting both utility providers and customers alike [1]. Power quality (PQ) remains a vital concern in modern power systems, particularly as they increasingly integrate large-scale renewable energy sources and incorporate numerous power electronics devices. The economic value of power quality is significant, as it directly impacts utilities, consumers, and load device vendors, all of whom may experience financial consequences as a result. For many users, power quality may have an immediate economic effect [18].

2.1. Issues of power quality

Power Quality concerns have many kinds of effects, causes and solutions that may be utilized power to enhance quality and their tool performance. Table 1 discusses the definitions, causes, and impacts of several issues such as voltage sag/swell, transients, voltage flicker, harmonics, voltage fluctuation, noise, voltage spikes, voltage imbalance and power frequency variation [19–30].

Table 1. Power quality issues and their causes and effects.

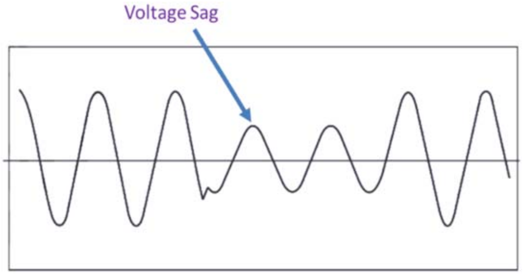
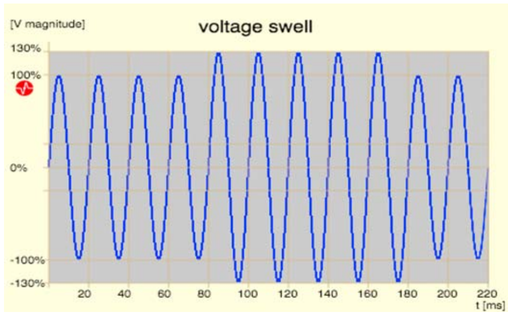
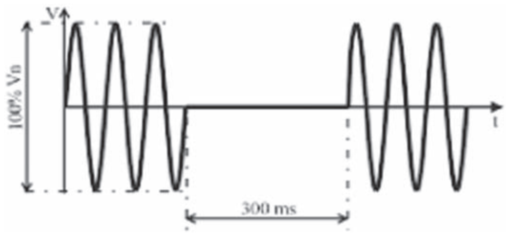
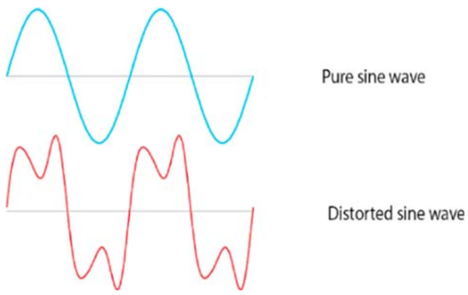
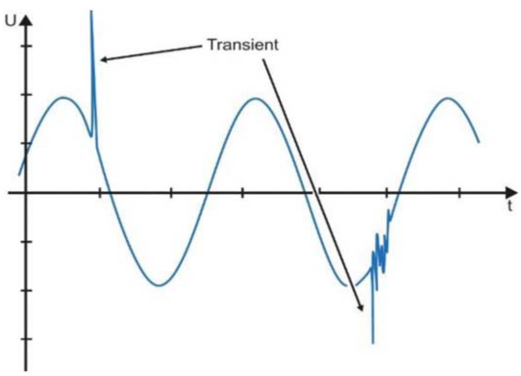
Issues of power quality		Causes	Effect
Voltage Sag: According to IEEE 1152–1995, voltage sag (VS) occurs when the AC voltage experiences an abrupt drop in the root mean square (RMS) value, from 0.1 to 0.9 p. u., anywhere from one half-cycle to one minute.		Turning over of huge motors. Energization of substantial burdens and false VAR compensation. Issues on the distribution station.	Memory disaster, Data blunder, Moderate lights and shrinking demonstrate screens, Apparatus shutdown.
Voltage Swell: The term 'voltage swell' refers to the rise in rated voltage that occurs when the load is suddenly disconnected or when a highly capacitive load is connected		Stimulating a enormous capacitor bank. Switching off an enormous load. False VAR compensation.	Bright lights. Data errors. The squinting of digital clock.
Voltage Interruption It is the moment at which the voltage and load current drop to less than.1 per unit and do not exceed one minute.		Short circuit, instrument failure, Insulator failures, Lightning	Effects are Hardware trips off Programming is vanished Disk drive crashes.
Harmonic Distortion: Harmonic distortion is the distorted waveform of normal waveform induced by the load. Harmonics are waveforms that have integral multiples of fundamental waveform's frequency.		IT apparatus, fluorescent illumination for example changeable frequency drives, SMPS.	Increments in line currents, Higher misfortunes Transformer, overheating of conductor, decreased hardware life range, equipment failing.
Transient: Transients are brief but large variations from normal voltage or current values. Transients generally endure between 200 millionths and half a second. Lightning, electrostatic discharges, and load switching are the most common causes of transients		More lightning, rotating significant tools on or off, consecutive empowerment of capacitor.	Stumbling, Processing mistake, Data misfortune, and Hardware reboot need, Components failure

Table 1. (Continued.)

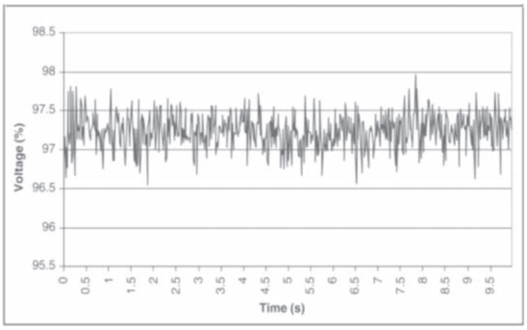
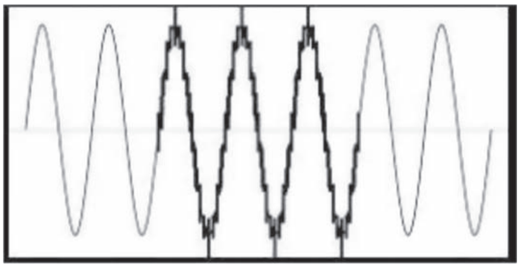
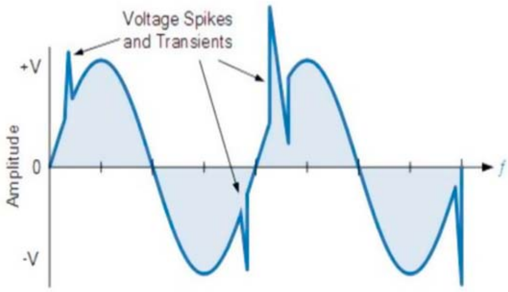
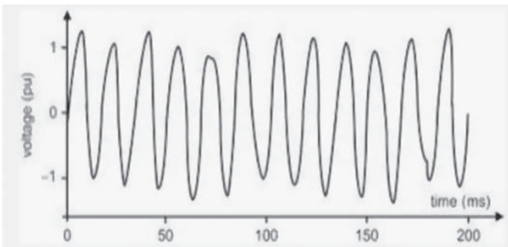
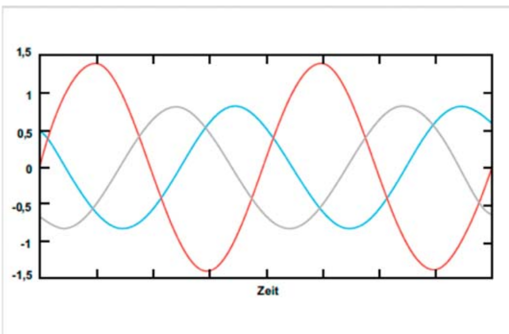
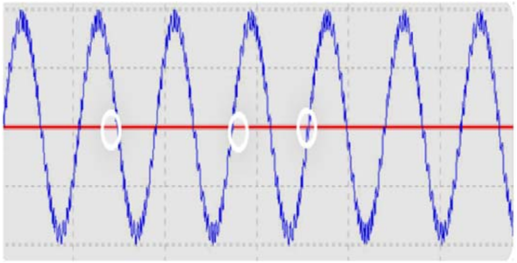
Issues of power quality		Causes	Effect
Voltage Flicker Flicker is described as tiny amplitude fluctuations in voltage levels occurring at fewer than 25 Hertz frequency. Large, quickly varying loads such as arc furnaces and electric welders, create flicker.		Transmission and the distribution systems of utility, arc furnaces and voltage variations	Irritation of the visuals, the inclusion of a significant number of harmonic components in the power supply and their associated equipment
Power frequency variation: The variation between the fundamental frequency of the electricity system and its nominal value.		Heavy loads (inductive loads, motors, and Transformer excitation)	Heating up, slow failure, inefficiency in motors and sensitive devices
Voltage Spikes: Variation in voltage value across timescales ranging from a few microseconds to a few milliseconds. Even at low voltage, these fluctuations can reach thousands of volts.		Internal voltage changes, lightning, static electricity, and magnetic fields.	current spike
Voltage Variation: Voltage value oscillation with amplitude modulation by a signal with a frequency of 0 to 30 Hz.		Connectors that are loose or rusted, either in the home or on the powerlines.	The power factor will be reduced. Temperatures are rising.
Voltage unbalance: In a three-phase system, a voltage fluctuation occurs when the magnitudes of the three voltages or the phase angle differences among them are not identical.		Mechanical strains in motors because of lower-than-normal torque output, as well as unbalanced current flowing in neutral conductors in three-phase wye systems	Noise, motor vibration and collapse

Table 1. (Continued.)

Issues of power quality		Causes	Effect
Noise: Superimposition of high-level signals on the power system frequency waveform.		welders, transmitters, and switchgear	Equipment failure, overheating, and premature wear are all possibilities.

2.2. IEEE PQ standard for DVR

Some initiatives have been taken to control the minimum PQ level that utilities must deliver to consumers, as well as the immunity level that equipment must have to operate effectively when the power delivered meets the standards. Nonetheless, the IEEE standards provide greater practical and academic information on the phenomenon, making it an extremely helpful reference. The following sections explain some of the IEEE power quality standards [24, 31].

2.2.1. 519–1992-IEEE

Recommendations and requirements for harmonic control in electrical power systems. In this standard, the restriction of voltage and current harmonics for PCC is less than 5%.

2.2.2. 1100–1992—IEEE

This standard applies to powering and grounding sensitive electrical equipment. It also contains design and installation suggestions, as well as electronic equipment maintenance. This standard describes the grounding procedure in detail.

2.2.3. 142–2007—IEEE

This standard specifies the grounding and power requirements for industrial manufacturing machinery with extremely high ratings. It also includes specific industrial equipment grounding difficulties and solutions. It also contains issues with neutral connections, as well as their remedies, as well as the benefits and drawbacks of grounded and ungrounded circumstances. This standard also addresses the difficulty of connecting equipment frames to the ground, which is connected to bounding.

2.2.4. 141–1993—IEEE

This IEEE standard governs the installations and distribution of industrial machinery and plants. This standard address some of the most important aspects of industrial plant design and distribution. This standard is included in the color book. Proper installation and dispersion of the industrial plants. It also covers the protection of the industrial machinery and workers in industry.

2.2.5. 241–1990 - IEEE

This standard governs the design and installation of electrical power systems in commercial structures. It is a full-color book that covers the sources, necessary protection, relay coordination, load characteristics, electrical spacing, wiring system, and other topics. It just contains references, yet it is quite useful for commercial building. This is the position we must take when it comes to commercial construction.

2.2.6. C57.110–1986—IEEE

When delivering non-sinusoidal load currents, it's a good idea to build transformer capabilities. The Standard's purpose is to establish standardized processes for assessing a transformer's capacity to deliver non-sinusoidal load currents while preserving normal life expectancy. Two methods are mentioned. The first is for those who know a lot about loss density distribution in transformer windings.

The second method is less accurate and should be utilized only by those who have accessibility to transformer approved test report information. The first method is anticipated to be mostly utilized by transformer design engineers, whereas the second method is expected to be primarily used by customers. This

Table 2. PQ issues compensating devices.

CPD devices	Issues of power quality								
	Sag	Swell	Transient	Flicker	Noise	Harmonics	Frequency deviation	Interruption	Voltage spikes
Voltage regulator	Yes	Yes	No	No	No	No	No	No	No
Filter	No	No	No	No	Yes	yes	No	No	No
UPS	yes	Yes	Yes	yes	Yes	yes	yes	yes	yes
Passive filter	No	No	No	No	No	No	yes	No	No
Fixed capacitor	yes	No	No	No	No	No	No	No	No
Surge Suppressor	No	No	Yes	No	No	No	No	No	No
HAPE	No	No	No	No	No	yes	No	No	No
Isolation transformer	No	No	Yes	No	Yes	No	No	No	No
SVC	yes	Yes	Yes	No	No	No	yes	No	No
UPQC	yes	Yes	Yes	yes	Yes	yes	yes	yes	yes
STATCOM	yes	Yes	Yes	No	No	No	yes	No	No
Power Conditioner	yes	Yes	Yes	No	Yes	No	No	No	No
SPS	No	No	No	No	No	No	No	yes	No
Active power filter	No	No	No	No	No	Yes	No	No	Yes
DSTATCOM	yes	Yes	Yes	yes	Yes	yes	yes	yes	yes
DVR	yes	Yes	Yes	yes	Yes	yes	yes	No	yes
SSFCL	No	No	No	No	No	yes	No	No	No
BESS/SMES	yes	Yes	No/Yes	No	No	Yes/No	No	No	No

best practice will be useful in determining whether existing transformers can handle non-sinusoidal load currents, as well as in defining new transformers to handle non-sinusoidal loads [30].

2.3. Others alternative CPD for power quality improvement

Each special power device has its possess advantages and the limitations, Static Electronic Tap Changers (SETC) [32], Static VAR Compensator (SVC) [33], Battery Energy Storage Systems (BESS) [34], Super conducting Magnetic Energy Systems (SMES) [35], Distribution Series Capacitors (DSC) [36], Solid-State Transfer Switches (SSTS) [37], Capacitor-FC [38], Surge Arresters (SA) [39], Thyristor Switched Capacitors (TSC) [40], Solid State Fault Current Limiter (SSFCL) [41], unified power-quality conditioner(UPQC) [42], Uninterruptible Power Supply (UPS) [43], Power Conditioner Filters [44], Distribution-STATCOM (DSTATCOM) [45], Hybrid Active Power filters [44] and Filter-HAPF Fixed [43].

The DVR is regarded as a specific power supply that is effective and efficient in reducing voltage distortion-sensitive loading effects. Table 2 discusses the properties of these various types of devices [46].

3. Dynamic voltage restorer

DVR is series compensator that inserts voltage into the distribution system to regulate load side voltage. It is linked between the supply and sensitive load to compensate for line voltage harmonics, transient reduction, voltage sags and swells. The fundamental working idea is to inject a voltage of the proper amplitude and frequency to restore the load voltage when there is voltage sag, as shown in figure 1 [47].

The power circuit, which injects the necessary voltage, and the control circuit, which manages the load voltage of the system within set limits, are critical components of DVR [48]. It is made up of the following primary components, each of which is described in section 3.1.

3.1. Structural element of DVR

3.1.1. Energy storage and DC link

The active power need of DVR during 'compensation' is met by the DC connection and energy storage devices. For load voltage correction during dips, the required vitality can be drawn from an auxiliary supply or the network grid itself [47]. When the DVR grid is weak, the auxiliary supply system is employed to boost performance. The energy source can be SMES (Superconducting magnetic energy storage) [49], fly wheel [50], Auxiliary power supply [51], Hybrid energy storage systems [52], super capacitors [53], fuel cell [51] and lead-acid for most DVR applications. If the grid is strong, the leftover voltage on the supply or load side is used to deliver needed power to the DVR; an AC/DC/AC converter is employed in this technique [54].

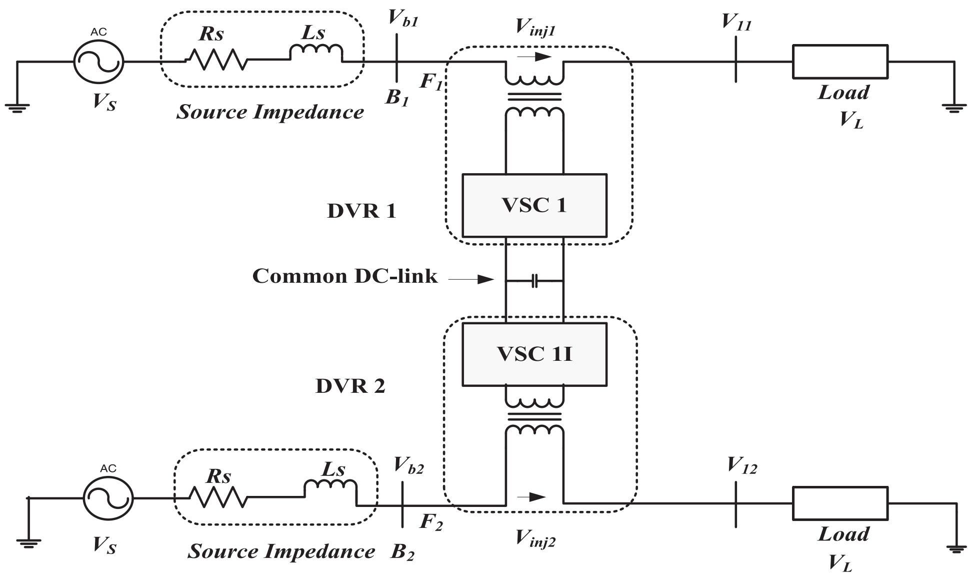


Figure 2. Two-line IDVR.

3.1.2. Voltage source inverter

This is a power-generating electric gadget made up of a switching device that can create a 'Sinusoidal voltage' with the requisite frequency, magnitude, and phase edges [55]. The VSI's primary function is to convert DC voltage from any DC storage to AC voltage. In DVR, VSI inverters such as Thyristor (GTO), matrix converter with flywheel, Integrated Gate-Commutated Thyristor (IGCT), Bidirectional converter, Type-dc-ac/ac-ac converter, Connection-series, MOSFET, and Insulated Gate Bipolar Transistors (IGBT) are used [56–61].

3.1.3. Filters circuit

As a result of the inherent nonlinear characteristics of the semiconductor switches used, the output of the DVR's inverter exhibits distortion and a significant number of harmonics. The primary objective of the DVR's filtering system is to mitigate and eliminate the harmonics generated by the Voltage Source Inverter (VSI), ensuring that the adjusted voltage remains of high quality [62]. The fundamental types of filtering schemes include harmonic filtering units, line side filtering, two schemes-inverter side filtering, LC filters, RCL and RC filters [63–65].

3.1.4. Injected transformer

The transformer's principal duties are to enhance the voltage generated by the VSI and to isolate and connect the DVR to the distribution system. Only by carefully selecting the electrical characteristics of the injection transformer can optimum efficacy and dependability be achieved When the ground fault situation is at its most severe [47]. The importance of subsequent positive chain recovery and voltage compensation cannot be emphasized. In the DVR, secondary windings in series with load and supply, step up, delta-star transformer, and earthed star-star distribution circuit transformer can all be employee [66, 67].

3.1.5. By-pass switch

Generally, Use of by-pass switch as a protective circuit to ensure an alternate route for the loads current in the event of a failure, maintenance, and overload. The reason for this, the DVR is not constantly in injection mode since voltage disruptions are transitory and occur only temporarily [68]. The DVR seems to be in standby mode if the power supply is in excellent working condition, thus the bypass switch bypasses the DVR for safety. The bypass switch has a power outage, which should be recognized. This power loss occurs while the supply is in regular operation. Because the DVR's efficiency is measured in injection mode, the bypass switch's power loss may be negligible [69].

4. DVR topologies

4.1. Interline DVR

Active power ability of the DVR is administered by the limit of the vitality storage component and the utilized compensated procedure. Be that as it may, cost and size requirements of vitality storage frameworks constrain their ability hence the DVR real power infusion capacity. IDVR comprises of a few DVRs on various circulation outline sharing a typical DC connect, it empowers real power trade among at least 2 DVR as illustrated in figure 2

[69]. It would chop down the expense of tradition power gadget as sharing a typical Direct Current -connect, lessens the DC-interface storage limit altogether and size also [70]. Since the feeders in Interline Dynamic Voltage Restorer framework are exuding by various network stations, then these feeders could be of a similar extent or distinctive voltage size. To conquer these cutoff points, sustainable power sources and additionally vitality storage components can be associated with the normal DC-connection to share necessary active power [71].

4.1.1. DVR without energy storage
Supply-side DVRs without energy storage often use a power converter connected in parallel to the supply or the load to provide the necessary energy, as shown in figure 3 [72]. Energy and load power are both maintained through the supply voltage. Figure 4 shows how the possible system configurations may be broken down into systems 1 and 2 [72]. A supply-side connected DVR design is described in the literature; it employs a half-bridge inverter for single-phase voltage compensation and a three-phase voltage compensator with fewer switches and lower costs. Due to advantages including low device stress, decreased THD, and low switching losses [15], the latter is more popular than the former two- and three-level inverters.

4.1.2. DVR with energy storage
When the DVR grid is unstable, the backup generator boosts performance. In most DVR applications, a combination of energy sources, including SMES (Superconducting magnetic energy storage), source battery, fly wheel, hybrid energy storage systems, super capacitors, Fuel cell, auxiliary power supply, and lead-acid are used [47, 49–51]. Energy storage may be expensive, but it might improve the DVR's functionality by mitigating voltage disturbances like voltage imbalance. System 3 illustrates the storage topologies using a changeable DC-Link Voltage, where the energy is stored in a DC Link Capacitor (figure 5; [15, 74]. This simple topology can function with a wide range of dc-link voltages. Activating a DVR requires a quantity of energy storage proportional to the square of the rated dc-link voltage, System 4, as seen in figure 5 [74], employs this design with a constant DC-Link Voltage.

4.1.3. Without isolation based DVR (Transformer less DVR)
This Dynamic Voltage Restorer has been additionally announced for voltage compensation. That technique disposes of the infusion transformer utilized in the fundamental setup of Dynamic voltage restorer [75]. The noteworthy components of the imbuement transformer consolidate voltage implantation and electrical partition. In any case be it can be issues, for example relating to the immersion and in rushed flows related with the transformer polarization wonder in any event, when it is sensibly planned [76, 77]. The block diagram of transformer less DVR is shown in the figure 6 [46]. Points of interest and drawbacks with DVR as beneath.

4.1.3.1. Benefits [78–80]

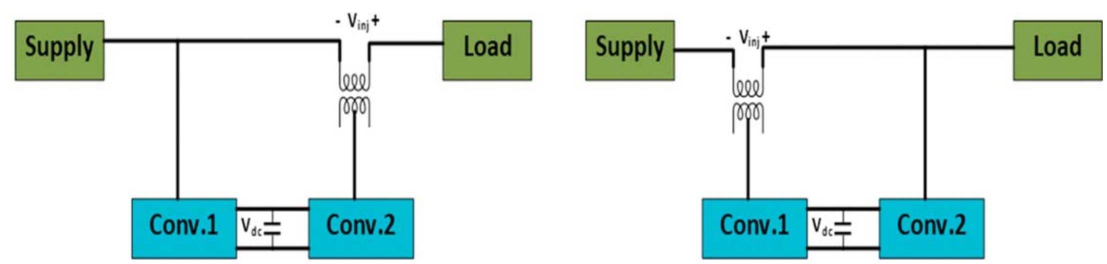
- Impact of 'non-linear' that is immersion and drop of voltage by 'transformer' is evacuated, just a little drop of voltage because of exchanging part is available, which is typically insignificant.
- Bulky transformer can be stayed away from, a minimized arrangement low volume, low weight is accomplished.

4.1.3.2. Drawbacks

- Converter topology is increasingly unpredictable, and more no. of segments is relied upon to utilized.
- Safety of intensity devices is progressively muddled, and the essential protection level (BIL) must be guaranteed all more effectively.

4.1.4. Topologies of DVR power converter
From the power converter point of view, the DVR converter can be distributed into two Categories, single and three phase converters as shown in the figure 7 [15].

Three-phase DVRs commonly employ three power converter topologies, namely four-leg inverters, two-level inverters, and three full-bridge inverters. These are the most prevalent configurations utilized in power converters for three-phase DVR applications [81]. For low-voltage (LV) grid applications, DVR topologies incorporating two-level power converters are often favored due to their switching approach. The use of two-level power converters is prevalent in these cases, primarily due to their suitability and effectiveness in LV grid applications [82]. PWM (Pulse Width Modulation) is a basic technique that is less expensive than MLIs.



(b)

Figure 3. DVR without energy storage (a) Supply side (b) load side.

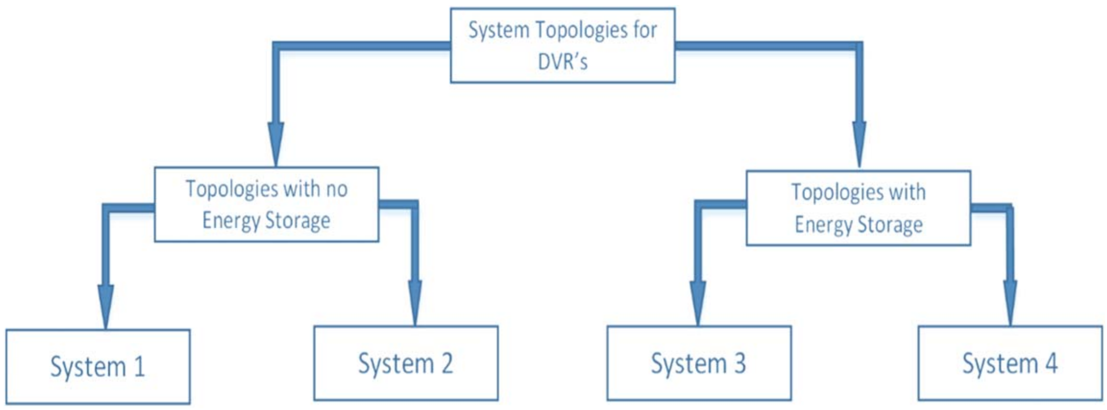
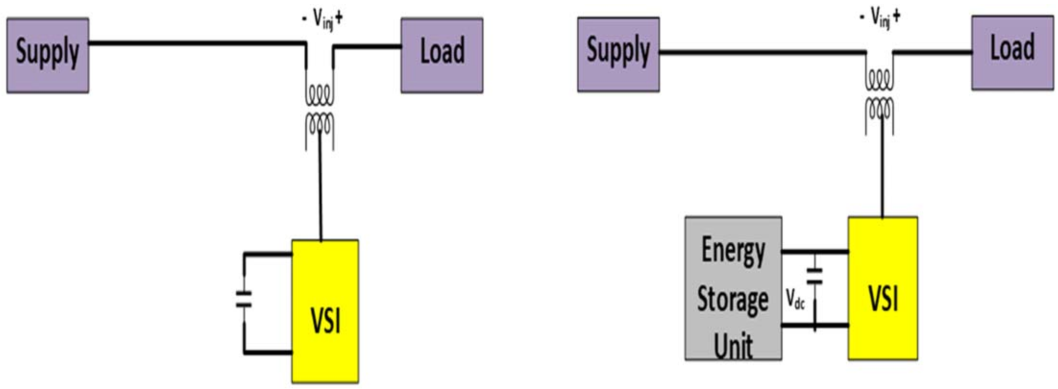


Figure 4. DVR system topology.



(a) (b)

Figure 5. DVR with energy storage (a) capacitor, (b) with external energy storage system, Merit and demerit of DVR with and without energy storage are given below on table 3 [15, 73].

Table 3. Merit and demerit of DVR with and without energy storage.

Topologies	Merit	Demerit
DVR without energy storage	Suitable in strong grids Saving is achievable, mitigation of higher voltage sag, Economical, No internal storage.	On the grid more Comparatively strain Complex control system
DVR with energy storage	Suitable in weak grids Voltage of dc- link is constant. Less control complexity Less strain	Decays of energy Decrease of compensation complexity Expensive Injected voltage must be controlled.

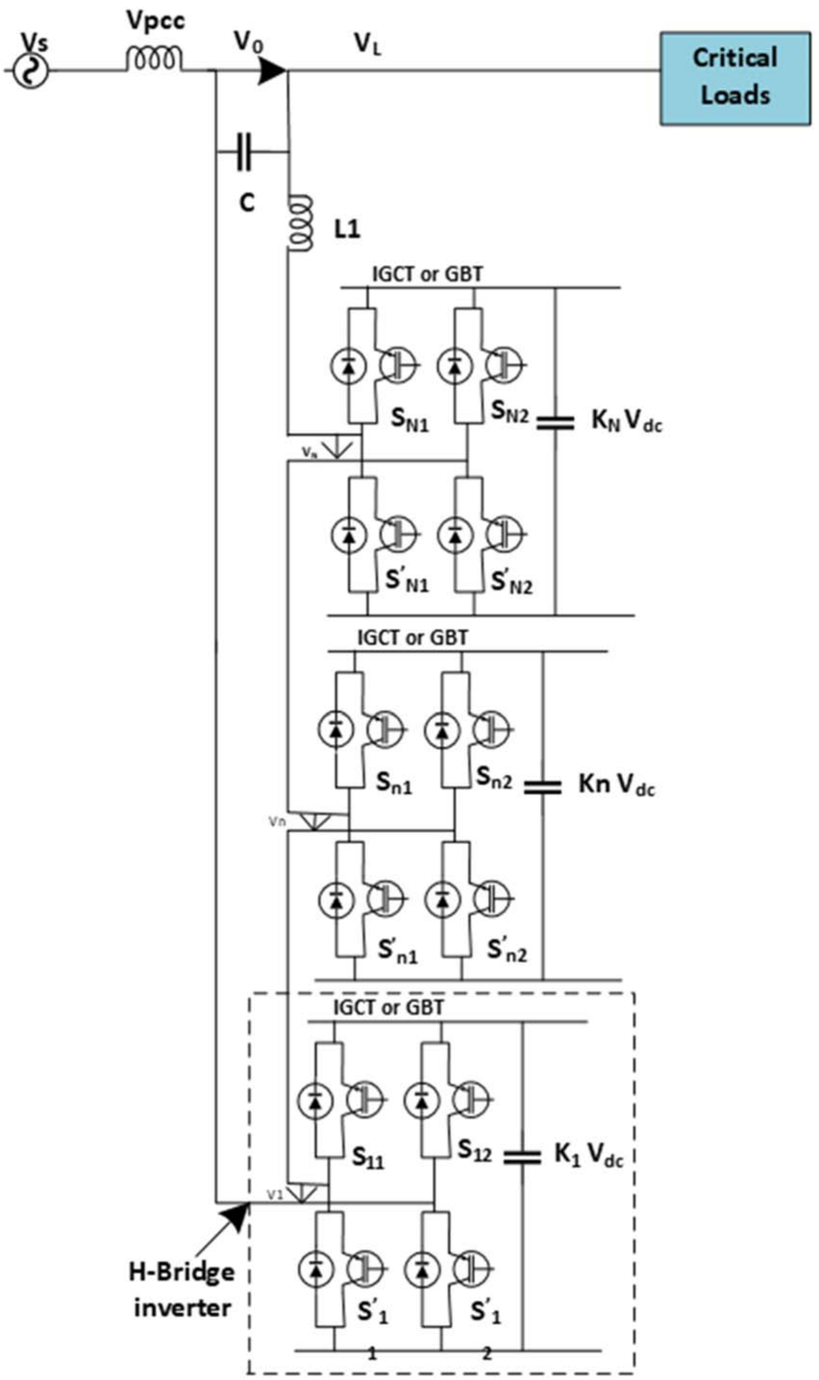


Figure 6. Transformer less DV.

4.1.5. Converter topologies of two level

Due to the high voltages on switches, they cannot be utilized in Medium-Voltage (MV) grid applications, which is why electronic devices are often employed in medium voltage grid connections. Switches that linked in series or parallel are one solution to this problem [82]. Using MLIs, on the other hand, is a superior alternative.

4.1.5.1. Multilevel converter topology

Reduced harmonics component, improved power quality, dependable operation at higher voltage levels, and less switching stress across the switches are all features of the MLIs. The three kinds of MLIs are Flying Capacitor [78], Cascaded H-Bridge and Diode-Clamped [79]. The most well-known MLI topology is the Cascaded H-Bridge topology. When the voltage levels in the NPC MLI architecture exceed three, balancing the voltage of the capacitors becomes difficult, that is why the three level NPCMLI is used. Not only is the switch selection more adjustable in the FC MLI design, but the capacitor voltage balance is also more customizable. As a result,

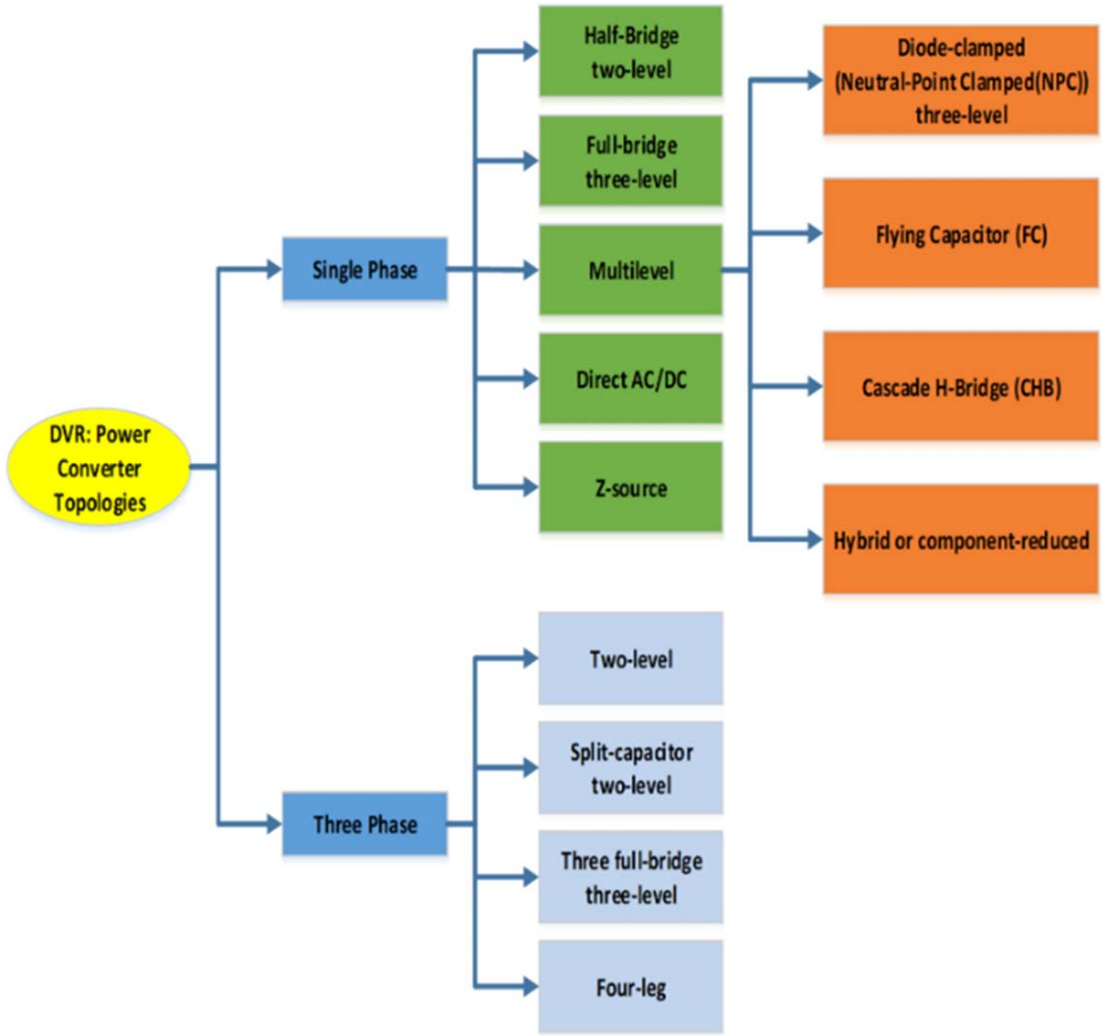


Figure 7. Power converter topologies.

unlike the NPC MLI structure, higher voltage level applications are not difficult. The FC MLI, on the other hand, has the drawback of increasing the number of capacitors as the voltage level rises [80, 83]. The CHB MLI topology, which is the most prevalent MLI topology, features a modularity characteristic, which increases its dependability. The sole downside of the CHB MLI design is that each H-bridge requires independent DC sources. One method is to connect each H-bridge output to a low-frequency transformer [79].

4.1.5.2. Direct AC to AC conversion-based topology

The topology dispenses with the requirement of Direct current-interface storage component [84]. The DVR topology depends on both regular (DC-interface) change and (AC connect) direct transformation. Regular (DC-interface) topologies sorted into two categories. Firstly, the important direct current voltage given throughout a transformer from the lattice by means of rectifier. Secondly the essential vitality for damages of voltage is in use from the vitality storage component through an inverter [85]. Adjacent to the customary geographies, few topologies have introduced for DVRs which DC-interface without requirement for storage components and dc interface [86]. Conventional topologies of DVR are Voltage Source inverter. In Conversion of Ac to Ac, matrix converter and Vector switching converters are used [87, 88]. The benefits and drawback of AC-to-AC conversion are given below [19].

4.1.5.3. Benefits

- Cheaper
- Compensation cannot be cultivated for a short time.
- decreased establishment territory.

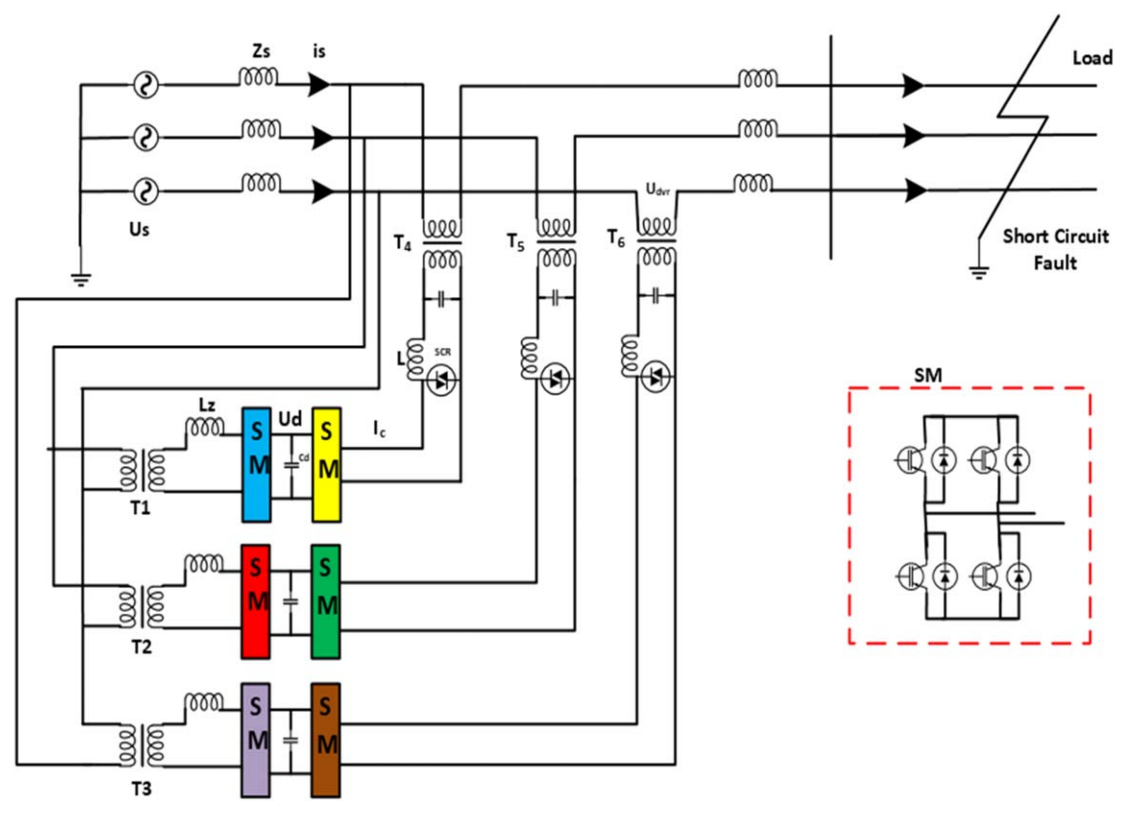


Figure 8. Fault current limit (FCL).

Table 4. Three phase converter topologies.

Topology	Merit	Demerit
AC-AC converter	Extending voltage disturbances minimization by eliminating energy storage	Falls to minimize voltage sag in weak grid station.
NPCMLI	output voltages (Multilevel)	Limit to level of three.
Two level inverter (Four wire Inverter)	Simple, Lower cost	Fails to eliminate the unbalanced Voltage disturbances
Split capacitor	Mitigation of unbalanced voltage disturbance	Hard to balanced Capacitors
ZSI	Higher voltage gain Lower strain	Extra passive Components
Four leg inverters	Lower DC- link Voltage Ripples	More switching frequency
CHB MLI	Modulatory, higher reliability Deep sag mitigation	Required several DC sources
H-Bridge	Unbalanced voltage disturbance elimination.	Extra semiconductor switches
FC-MLI	Increased the output voltages	flying capacitors needs for restriction of charging.

4.1.5.4. Drawbacks

- Number of switches are high

Table 4 lists the DVR topologies, as well as their pros and limitations, from the perspective of the three-phase power converter [15].

4.1.6. Fault Current Limit (FCL) for grid connected DVR

The bidirectional crowbar thyristor became inactive when the FCLDVR is set to voltage compensation mode. As shown in figure 8, the FCLDVR operates in the same way as a voltage-controlled source converter [89]. Control of fault current limitation, DVR achieved by the voltage compensation, if any voltage unbalance/fluctuations occur, resulting in improved power quality and voltage across load [90]. Input module of back-to-back

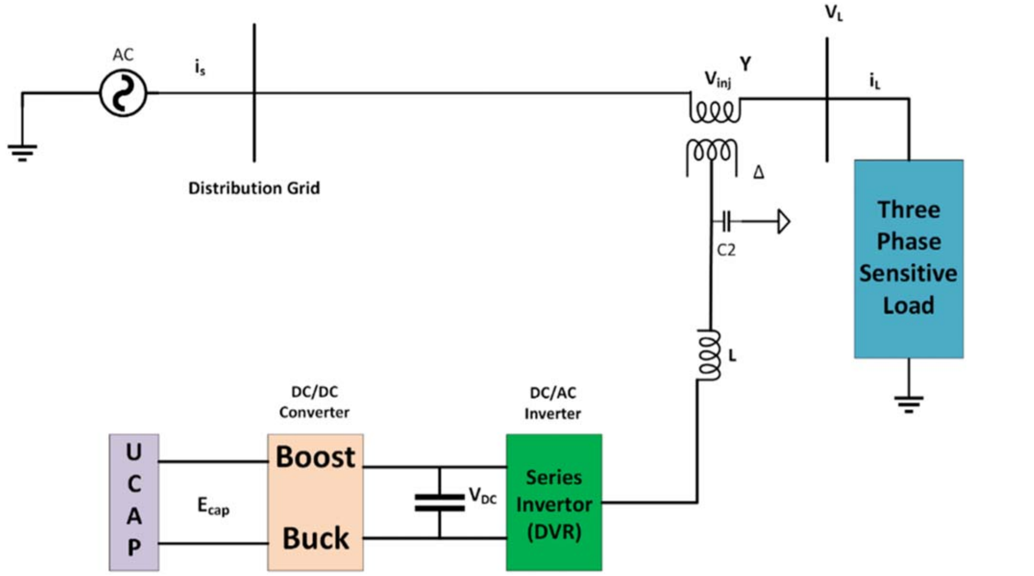


Figure 9. Distribution grid with ultra-capacitor.

converter used to deliver the voltage across the DC-link. When a short circuit fault occurs, the defective phase of the inverter turned off, and the crowbar bidirectional thyristor switched on. At this time, on the secondary side of a series-connected transformer, reactor L inserted to limit the fault current. Using the damaged component removed, the DVR can return to its regular state by sustaining the voltage supply with series linked transformer and the back-to-back converter [91].

4.1.7. DVR in distributed grid with ultra capacitor

As illustrated in figure 9 [5] ultra-capacitors are the best-suited technology for active power support and rechargeable energy storage at milliseconds to second timeframes. Ultra-capacitor inclusion in the DVR system is perfect due to the milliseconds to seconds range duration of instant sags/swells. In general, ultra-capacitors have a lower energy density are better suited for voltage sag/swell correction with high power density, as these processes need a large amount of power in a short amount of time [5].

Ultra-Capacitors, as compared to other energy storage components, have a huge charge/discharge cycle, even for modules of same size, resulting in simplicity of integration [92]. The following are examples of DVR applications with ultra-capacitors [93, 94].

I. The capacity of providing actual power to the system completed for correcting voltage sag/swell in line.

II. A basic demonstration of a dc-to-dc converter, an inverter interfacing with control, and ultra-capacitors is possible.

III. The development of inverters and DC-DC converters can be used to adjust for voltage swell/ sag in the distribution grid.

IV. Ultra-capacitor DVR's system hardware integration and their performance verification.

4.1.8. Renewable energy sources (RES) integration with DVR

It is unavoidable for the researchers and engineers to integrate RES in the creation of improvements in power system studies. The integration of renewable energy sources into the power system poses significant difficulties to the power system community. This tendency does not exclude the development of DVR. The feedforward vector control approach is used by the researchers in [95] to create the firing angle for voltage disturbance reduction in VSI.

Actual wind farm data acquired at Chinnaputhur substation in India during a voltage sag and swell event proves the usefulness of the recommended strategy [96]. Describe a PV-based DVR as enhancing power quality following a system outage. PV serves two tasks here: it provides power to the load as well as the DVR DC-link. To identify any power quality issues and turn the PV systems obligation into a DVR, a switching control based on wavelet transform is provided. The authors discuss how the DVR utilized with a mix of feedforward and

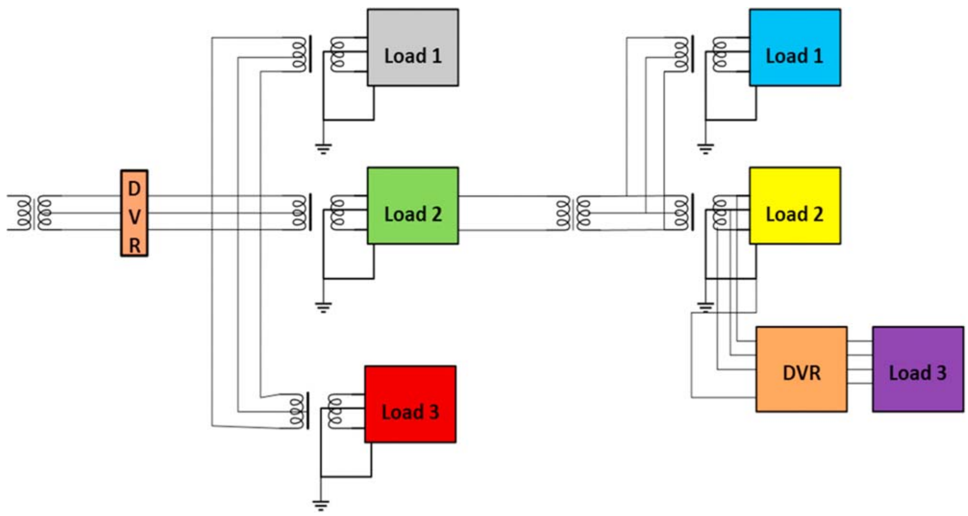


Figure 10. DVR location at three and four wire system.

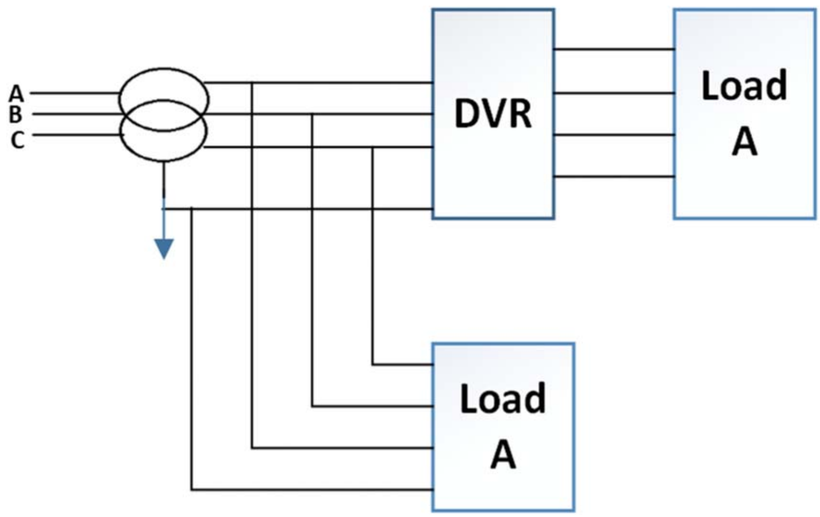


Figure 11. DVR location in low distribution network.

feedback control to minimize voltage sag under unbalanced fault scenarios in [97]. The control of the DVR based on wind turbine is crucial for increasing fault ride-through performance in doubly fed induction generator.

5. Location of DVR

DVR aim is to secure just a single consumer or group of significant worth included consumers. It is frequently conceivable to apply a DVR to a medium voltage circulation framework or low voltage. The principal distinction among MV to DVR and LV to DVR link is the arrangement of zero sequences voltages and the zero-order current stream [98].

As shown in figure 10, in a 4-wire LV power distribution network, DVR must provide a low impedance for zero sequence current and the zero sequence can flow either in the power converter or in the injection transformer delta winding and impedance because of DVR arrangement on the LV side is high [99].

The 3-wire medium level distribution framework appeared in figure 10 uses a basic DVR geography in many nations and is therefore simple to control because of the absence of zero-sequence segments. The injector transformer in a DVR requires a significant level of protection, and the short out level is additionally high at the medium level [100].

But figure 11 depicts the DVR location at low voltage electrical distribution radial system [74]. The implementation of DVR in a low voltage radial distribution network as shown in the figure 12 [74].

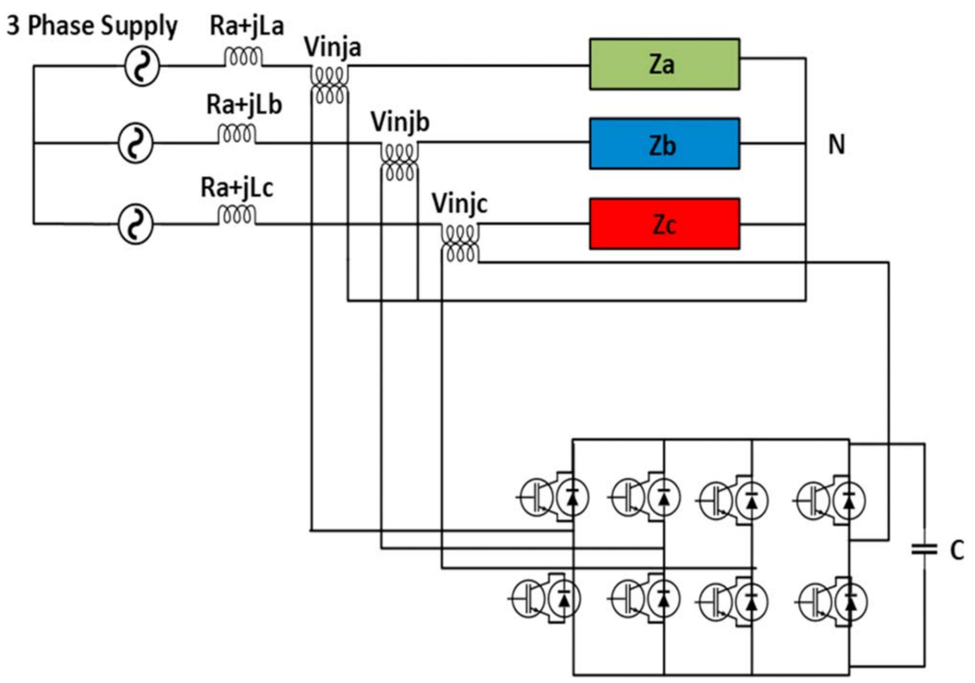


Figure 12. 3-phase four wire DVR.

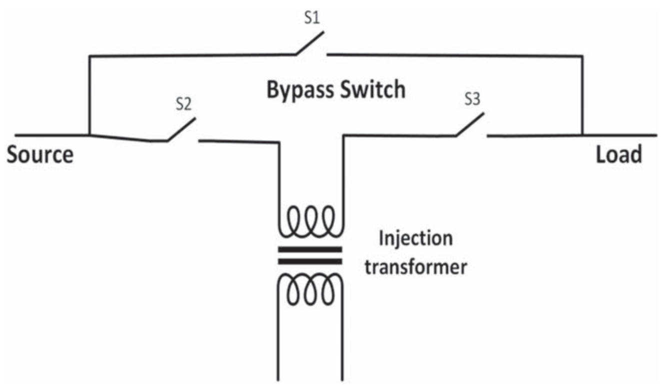


Figure 13. DVR protection mode.

In [101], listed the following benefits of using DVR in low voltage applications [102]:

i. The DVR may be used to target voltage imbalance and voltage fluctuations loads with more precision.

ii. Because several power users share a single LV system, DVRs could be installed by either the utility or consumers.

iii. In LV system, distribution transformer reduces short circuit faults significantly, and DVR prevention is simple.

6. DVR operation modes

The DVR's primary function is to inject voltages through a booster transformer to the load voltage to mitigate the power quality faults [47]. Protection mode, standby mode, and injection/boost mode are the three operating modes of the DVR.

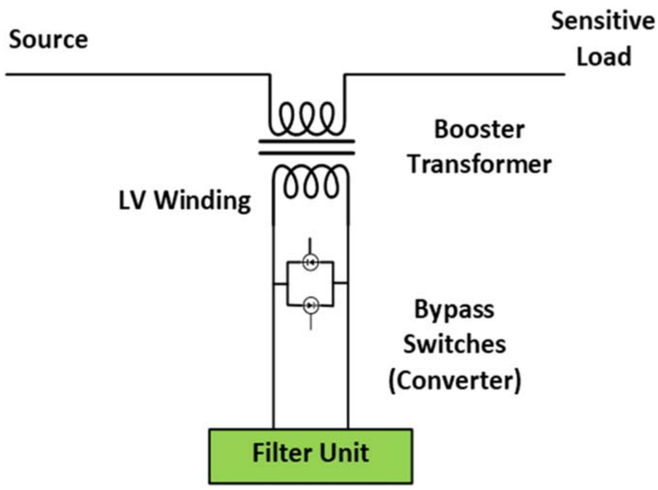


Figure 14. Standby mode.

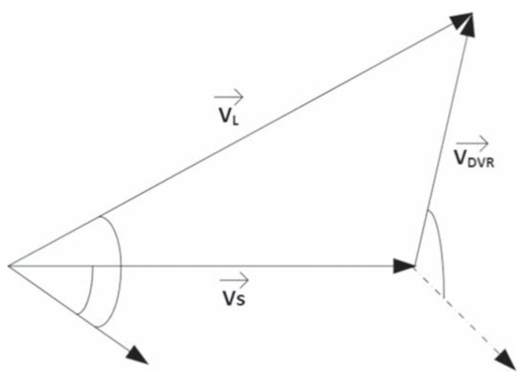


Figure 15. Phasor diagram of pre-sag compensation.

6.1. Protection (safety mode)

In the event of a short circuit on the load or a substantial inrush current exceeding the permissible limit, the DVR will be disconnected from the system. This disconnection is achieved by opening the bypass switches (S2 and S3) and closing another channel for the current through the operation of switch S1, as illustrated in figure 13 [15]. will open) and providing another channel for current (S1 will closed) as shown in figure 13 [15].

6.2. Standby mode

In this DVR operation mode, grid voltages properly regulated and within allowable limits. To arrange the battery performance, the best strategy required. The main goal of this strategy is to keep the Battery State of Charge (SOC) within acceptable limits so that the battery is ready for any coming disturbances while also increasing battery life. Under typical grid circumstances, the phase angle of the reference load-voltage has a significant impact on the battery mode. When in standby mode, inappropriate selection of this angle could result in continuous battery drain [15, 18, 103]. DVR Standby mode illustrated in figure 14.

6.3. Injection mode

In the event of a voltage sag, the Dynamic Voltage Restorer (DVR) will switch to injection mode and utilize a booster transformer to inject a compensated voltage. This injection of the compensated voltage is triggered in response to any disturbance or disruption in the supply voltage [18].

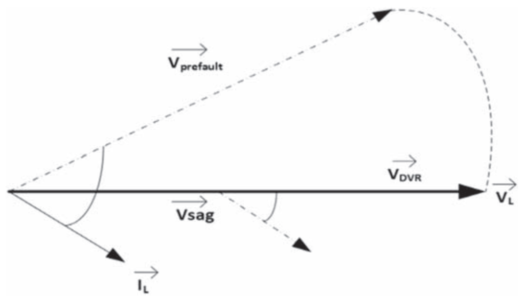


Figure 16. In phase compensation method.

7. DVR compensation methods

7.1. Compensation via pre sag

The main goal of this method, as depicted in figure 15, is to restore the load voltages to their original phase angle and magnitude [15, 104]. To achieve this objective, the injected voltage needs to be precisely equal to the voltage vector difference between the sagged and pre-sagged states. Moreover, it is crucial to maintain the same phase angle of the reference load voltage regardless of the presence of supply jumps or phase shifts [104]. This approach proves highly advantageous for loads susceptible to phase-angle jumps, especially those controlled by thyristors, as it incorporates an optimal compensation technique. However, for specific severe sags, it becomes necessary to employ a higher-rated voltage injecting transformer and energy storage device to meet the compensation requirements [15]. Angular compensation, on the other hand, mandates that the equipment built to withstand greater voltage levels than In-Phase correction. DVR voltage is given in equation (1) [105]:

$$V_{DVR} = V_{Prefault} - V_{sag} \tag{1}$$

7.2. In phase compensation methods

In the case of magnitude-sensitive loads, the most suitable compensation technique is the in-phase voltage compensation approach. This approach ensures that the load voltage is aligned in phase with the source voltage during the correction process [105]. When a voltage sag occurs and the supply voltage experiences a phase shift, the load voltage also undergoes a phase jump. Consequently, upon restoration, the load voltage aligns in phase with the sagging voltage. However, if the supply voltage undergoes changes in phase angle or jumps during the sag, a phase shift arises between the load voltages before and during the sag. Thus, this compensation method is only appropriate for loads unaffected by phase-angle jumps [106]. The load voltage given below in equation (2):

$$V_L = V_{Prefault} \tag{2}$$

The injected voltage with the supply voltage is always in phase, active power correction requires energy storage. The phase jumps are not addressed by this strategy. To restore load voltage, in-phase correction uses both real and reactive power as shown in figure 16 [19].

7.3. Compensation of reactive power

Reactive power compensation typically requires a minimal amount of energy storage, meaning no active power is necessary. In the depicted scenario, where the injected voltage is in phase with the load current, the DVR provides reactive power correction without the need for any real power consumption. The purpose of correcting the reactive power is to adjust the power factor and maintain the voltage stability of the system [107].

7.4. Energy optimization compensation method

In this scenario, the injected voltage serves to elevate the voltage level, resulting in a perpendicular orientation between the phasor of the injected voltage and the line current. However, the energy storage device's capacity can become a limiting factor during compensation when the DVR needs to supply real power into the affected line in cases of pre-sag or in-phase conditions. The storage of real power occurs in the DVR's DC connector, which happens to be one of its costlier components [52]. The main goal of the energy optimization technique is achieved when the phasor of the injected voltage is perpendicular to the phasor of the load current. In this configuration, the injected real power component becomes zero, emphasizing the desired outcome of the optimization process [105].

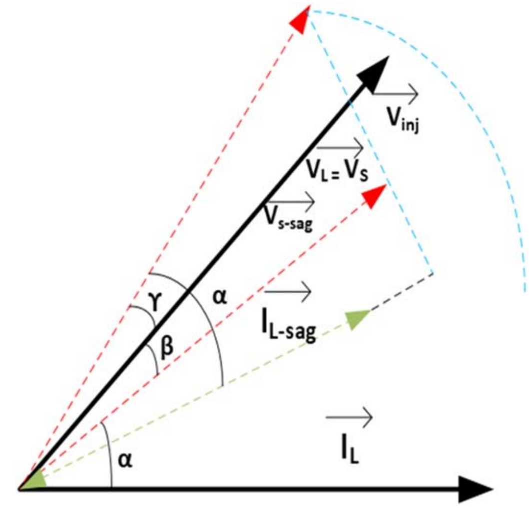


Figure 17. EM for balanced sag.

It employs only reactive power, which is generated electronically inside the voltage source inverter (VSI), for compensation, hence a higher VSI rating is required. However, as not all sags may be reduced without actual power, this method can only be used for a subset of sags. Keeping the voltage constant throughout the energy storage unit is essential due to the DVR's need for actual power from the external network, and only the energy-saving approach based on the zero-power injection strategy has been shown to do so. The following must be considered within the scope of the DVR's restrictions [101].

7.4.1. Voltage restriction
To keep costs low and decrease the voltage sag across the device in standby mode, DVR's injection capability has been reduced.

7.4.2. Power limit
Even though power is kept in the DC-link, most of the power is often transferred from the supply or a larger DC storage. To ensure a steady DC-link voltage, an extra converter with restricted rating is frequently utilized.

7.4.3. Energy limit
To save money, storage is usually kept as small as feasible. Some sags may quickly drain storage, and proper regulation can help to limit the danger of load tripping due to inadequate energy storage. As indicated in the figures, there are two forms of energy minimization: EM for balanced Sag and EM for unbalanced Sag.

EM has two types for compensation, one is EM for Balancing Sag and other one is EM for Unbalance sag to explain this further process as shown in the figures.

7.4.4. EM for balanced sag
The γ angle is load voltage phase change after the sag as shown in in figure 17 [19, 104, 105] which shows the EM compensation technique. To avoid trading the active power P injected is zero, as mentioned above. However, the phasor of the injected voltage is orthogonal to the phasor of the load current. In addition, under voltage sags render this approach useless. One method is connecting a thyristor-switched inductor in parallel with the DVR [101, 105]. For convenience, the formulae to calculate the injected voltage data can be expresses as:

$$V_{inj} = \sqrt{2}.\sqrt{(V_L)^2 + (V_{s-sag})^2 - 2.V_L.V_{s-sag}.\cos(\beta + \gamma)} \quad (3)$$

$$V_{inj,j} = \tan^{-1}\left(\frac{V_L.\sin(\alpha + \gamma) - V_{s-sag}.\sin(\alpha - \beta)}{V_L.\cos(\alpha + \gamma) - V_{s-sag}.\cos(\alpha - \beta)}\right) \quad (4)$$

7.4.5. EM for unbalanced sag
As depicted in figure 18, the inserted voltage phasor is not perpendicular to the load current phasor, indicating that there is a non-zero power transfer between the phases [19, 105]. Consequently, if the active power of one phase is negative, it follows that the active power of the other two phases will also be negative. Consequently, no

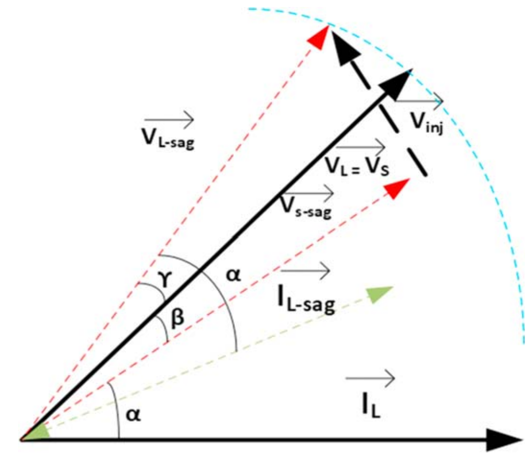


Figure 18. EM for unbalanced sag.

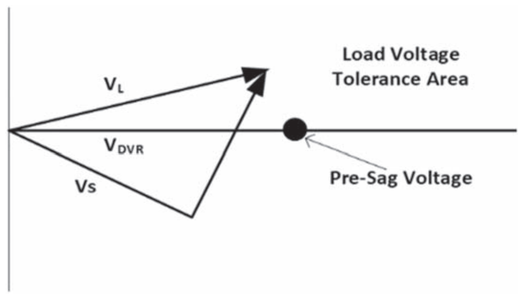


Figure 19. Voltage tolerance method.

net active power is exchanged overall [106]. The injected voltage data may represent using the formulae below given in equations (5) and (6).

7.5. Voltage tolerance method with minimum energy injection

Within the acceptable range of load voltage tolerance, the modified load voltage experiences changes in both phase angle and magnitude. The load is designed to withstand slight voltage drops and phase jumps. However, different loads may respond differently to phase angle jumps and voltage magnitude variations. Control of magnitude and phase is essential in this approach to minimize the required energy input. The phase advance technique just considers phase difference; however, this approach takes into account both control parameters as shown in figure 19 [108].

$$V_{inj} = \sqrt{2}.\sqrt{(V_L)^2 + (V_{s-sag,j})^2 - 2.V_L.V_{s-sag,j}.\cos(\beta_j + \gamma)} \tag{5}$$

$$< V_{inj,j} = \tan^{-1}\left(\frac{V_L.\sin(\alpha + \gamma) - V_{s-sag,j}.\sin(\alpha - \beta)}{V_L.\cos(\alpha + \gamma) - V_{s-sag},\ j.\cos(\alpha - \beta)}\right) \tag{6}$$

7.6. Hybrid voltage compensation methods

To create a hybrid voltage compensation approach, the benefits of pre-sag and in-phase compensation methods combined. This approach avoids huge dc-link capacitors and over modulation without limiting the operation range. A hybrid compensation methodology is created by integrating three compensation methods: reactive power management, minimum energy injection, and maximum voltage injection [109].

This compensation approach recovers the load voltage by using pre-sag compensation before switching to a minimal active power injection mechanism. The magnitude and phase of the inserted voltage controlled via a unique compensation approach known as elliptical compensation, allowing the DVR to achieve low voltage ride through capabilities. A correction mechanism based on voltage elliptical parameters developed for efficient DVR use [110]. DVR cannot correct phase jumps of voltage sag with imbalanced phase jumps after altering the compensation technique from pre-sage to in-phase. The approach that should use after the voltage sag cleared,

Table 5. Advantages and disadvantages of compensation methods.

Methods	Advantages	Disadvantages
Via Pre-Sag methods	Magnitude and phase jump mitigation Restore both Phase jump and voltage drop. Mitigate completely disturbance of voltages	Needs active power. Need for high Energy storage
Via In phase method	Low DC link Low harmonic distortion low injected voltage magnitude	Needs active power. Can't restore phase jump in variation
Energy Optimization method	Not required Active power during compensation Minimal Exchange active power b/w DVR and power grid	Almost high magnitude injected. High Dc link Voltage disturbance not completely mitigate
Hybrid Voltage method	At start, restore the phase jump and voltage drop Avoid transient current at load side in the start	Needs active power during compensation Can't restore the phase jump

on the other hand, has not been explored, and this might be a disadvantage of the hybrid compensating method [111].

To summarize the Comparison of compensation techniques Advantages and Disadvantages of different compensation techniques given in table 5.

8. Control algorithms

8.1. Voltage detection method

The ability to accurately identify and classify disturbances can aid in the implementation of appropriate countermeasures to maintain adequate power quality. The detection algorithms are utilized for accurate voltage fluctuations in the supply voltage prediction.

8.1.1. Fourier transform (FT)

The Fourier transform (FT) is done by decomposing the power system signal orthogonally. In most cases, a collection of trigonometrically orthogonal or exponentially orthogonal functions is used. It is feasible to determine the amplitude and each phase of frequency of the waveform supply by applying FT to each supply phase. Windowed fast FT utilized for practical digital implementation since it can simply be implemented in a real-time control system [112]. The disadvantage of FT is that it just takes one complete cycle to accurately determine the sag depth and phase. It is feasible to have real-time control [113].

- Both sag detection and harmonic computation are available using the discrete Fourier Transform (DFT). It is necessary to have a stationary input signal. An integer should be used for the number of samples each cycle. Massive computations are required, and detection is delayed [114].
- The FFT approach is quicker than the DFT method. Jumps in phase calculated. The length of the window determines the accuracy. It is necessary to have a stationary input signal. An integer should be used for the number of samples each cycle. Harmonic measurement is possible [115].

8.1.2. Phase locked loop technique

The PLL applied to each power supply's self-managing system and adjusts for rapid jumps in phase hops. This technique requires pre hang size and stage jump freezes. The PLL voltage has the same phase as the fine voltage. Some assumptions need to be postponed to half a circle. Execution logic control systems are becoming increasingly disadvantageous [116].

8.1.3. Strategy of wavelet

WT performs improved with continuous and fixed signs. It perceives change in the condition of the easily arranged rapidly. The wavelet assessment procedure plans a wavelet model breaking point. A drawback of this method is the requirement to select an appropriate mother wavelet for each application, as the choice of wavelet influences the related channel bank coefficients. This aspect can introduce complexity and inconvenience in terms of execution and practical implementation [117].

Depending on the type of event, the wavelet transform (WT) gives multiple 'signatures.' The disadvantages of this technique are that the signs returned might be tough to comprehend and quantify directly. To categorize and quantify the disruption, one more approach may be required [118].

8.1.4. Space vector' control

This technique provides information about mutual voltage size and angle shift. The three phase voltages va, vb, and vc are converted to two estimation voltages vd, vq, which may be turned into size and phase shift in this way. It's snappier anyhow, and it necessitates a tough regulator. This is a logically control structure that may be usefully recognized [119].

8.1.5. Root mean square (RMS) strategy

Voltage and current readings are often expressed as root mean square (rms) values. When Vrms initially falls below 0.9 p. u., the sag officially begins. Determine whether Vrms stay below 0.9 p. u. for at least half a cycle using the formula. The first point in this interval is then picked as the recovery time. This procedure is straightforward and quick. Memory isn't as important. There is a quarter-cycle minimum delay. It can't tell the difference between fundamental and harmonic frequencies. There are no phase jumps identified.

8.1.6. Kalman filtering method

The Kalman Filter approach used to provide the best assessment of amplitude, frequency, and the phases using voltage or current sample values. Furthermore, the KF can correctly measure the period of voltage sag/swell between the start and finish. In power systems, three KF utilized to automate the detection and analysis of voltage events [120]. Due to its significant vulnerability to high-frequency noise and other PQ disturbances in power supply, employing the WT's high frequency coefficient values for the assessment of real voltage events might result in a lot of errors, according to the Kalman filtering and WT findings [117, 121].

8.1.7. Numerical matrix method

In comparison to the other approaches, the numerical matrix method provides a number of benefits. The implementation and recovery times for system anomalies are quite quick. Additionally, it has low memory requirements and works well with real-time implementations. Applying this technique individually to each stage is possible. In addition, it can determine the sag's onset and termination times as well as its magnitude and phase shift. The voltage supply is sampled, and the resulting data is stored in a matrix, making up the foundation of the method's core functionality. Sag depth, phase leap, sag onset, and sag termination may all be detected quickly and reliably, and there is a wealth of ready-to-use information on disturbances [122].

8.1.8. Improved morphological filtering

The theoretical foundation of morphological filters is mathematical morphology, while the method itself encompasses many random theories and the integral geometry expertise. Perform the algebraic actions on signal with various features to accomplish the objective of filtering out the drawbacks such as harmonics and noise by selecting and creating structural elements. The morphological filter, in comparison to the typical low-pass filter, requires less computation and has a shorter latency, making it useful in engineering [123].

8.1.9. Period phase method

This technique rearranges the voltage phases to zero, when the waveform passes zero with an increasing edge, and it counts the voltage phase by accruing mode at every sample point. Using the method of detection which based on the specification above, the phases and magnitudes of voltage can be simply calculated, and the voltage sag can be precisely determined [124].

8.1.10. Missing voltage technique

The difference between the desired instantaneous voltage and the actual instantaneous voltage is referred to as the missing voltage. To maintain the amplitude and phase of the pre-sag condition, a phase-locked loop (PLL) is necessary. This approach is particularly well-suited for analyzing voltage sags rather than simply detecting their occurrence [125]. The reason for this is that the magnitude of the voltage sag remains unknown until after the disturbance event takes place. This approach enables swift detection of voltage sags. On the other hand, the RMS approach provides additional information regarding the timing of the sag's initiation and recovery in terms of the point-on-wave [126].

8.2. Reference generation

8.2.1. Park and clark transformation

This method's description is as follows: Synchronous rotating frame sag detection makes use of Clark's transformation and Park's transformation. As can be seen in figure 20, the Park's transformation, commonly known as the dq transform, is only applicable for computing balanced three-phase voltage sags [15]. One such modified method for calculating harmonics in imbalanced sag conditions is the multiple d-q transform [127].

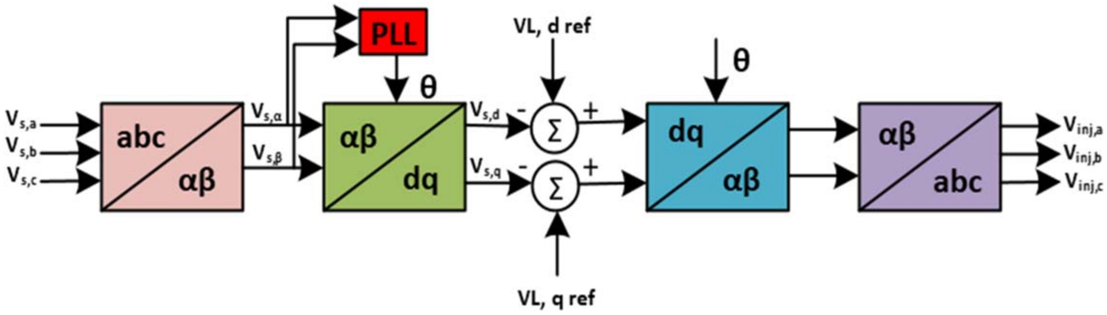


Figure 20. Park and clark transformation.

The computation of changes depending on the voltage compensation technique. The PLL locked to the voltage supply in the in-phase technique, allowing the system to adapt to the voltage supply. On the other hand, PLL is kept at the pre-sag value in order to change with the pre-sag supply voltage. The PLL and the equations of the EM compensation technique used to measure it [15, 128].

There are also extra reference generation approaches like Phase parameter method and Symmetric Component Estimation, which are discussed below.

8.2.2. Symmetrical component estimation

When the transient overvoltage occurs, the ultrahigh-voltage grid's three-phase voltage is asymmetrical. The decomposition of the asymmetrical three-phase voltage can be achieved by utilizing the superposition of symmetrical positive, negative, and zero-sequence components. This recommended approach is rooted in the concept of superposition, enabling the analysis and separation of different sequence components in the voltage [129].

The three-phase grid voltages during the formation of transient overvoltage are represented by va, vb, and vc. The amplitude value and phase position of the symmetrical zero-sequence component are denoted as V0 and 0, respectively. Similarly, the amplitude value and phase position of the symmetrical positive-sequence component are represented as V+ and +, respectively [129].

8.2.3. Phase parameter estimation method

A recursive adjustable window LES approach is presented as a better phasor estimation strategy for the DVR control system, allowing for fast, consistent phasor parameter estimation of currents and voltages with little computational overhead. According to the study's results, using this method improves the frequency responsiveness of the control scheme based on the specified data window LES digital filter while simultaneously reducing the computational burden on the hardware [130].

8.3. Switching strategy

8.3.1. Pulse width modulation (PWM)

PWM finds extensive application in various domains such as motor speed control, converters, and audio amplifiers. It is a voltage adjustment technique employed to regulate the voltage supplied to a motor. However, it is important to note that there is no universal PWM approach that can be universally applied to all applications due to their specific requirements and constraints [131]. Advancements in solid-state power electronics and microprocessors have led to the development of various pulse-width modulation (PWM) techniques for a wide range of industrial applications. The main objective of PWM is to control the output of the inverter while simultaneously reducing the harmonic content in the output voltage [132].

8.3.2. Sinusoidal pulse width modulation (SPWM)

When a pulse waveform with a variable width, obtained through the application of sinusoidal pulse width modulation (SPWM) technique, is passed through filtering, it results in the generation of a sinusoidal waveform [133]. Improve the filtered sinusoidal waveform by increasing the switching frequency and adjusting the reference or modulating voltage's amplitude and frequency. By maintaining varying widths for the pulses, unlike the uniform widths in multi pulse width modulation (MPWM), the utilization of sinusoidal pulse width modulation (SPWM) method effectively reduces both distortion factor (DF) and lower order harmonics (LOH) [62].

8.3.3. Third harmonic injection pulse width modulation (THIPWM)

Three phase systems do not have a third harmonic component, third harmonic injection PWM recommended in three phase systems. The THIPWM is superior when using a DC source. For three phase inverters, several modulations are employed, including space vector pulse width modulation (SVPWM) extending the linear modulation range by 15% more than SPWM. By infusing the tripled harmonics, the modulation range of THIPWM expanded [133].

8.3.4. Space vector pulse width modulation (SVPWM)

The space vector pulse width modulation (SVPWM) approach is another way to enhance the output voltage over that of the SPWM technique [119]. For variable-speed drives, this approach utilized. When compared to SPWM, this approach can boost the fundamental by 27.3 percent. The rotating synchronous reference frame used by SVPWM [134].

8.3.5. Fundamental frequency

Low switching losses, switching stress, and EMI are all advantages of fundamental frequency control modulation. The DVR uses one cycle control, which is superior to SPWM in terms of stable and dynamic state functioning. When employed in a practical DVR application, the ease of installation with simple procedures is the highlight of one cycle control [63].

8.3.6. Selected harmonic elimination (SHE-PWM)

One of the main ideas behind SHE-PWM is using the Fourier series of the PWM waveform to represent the signal. For ease of computing the Fourier coefficients, it is conventional to assume that the waveform is QW symmetric [112, 113]. When compared to other PWM techniques, SHE-PWM stands out due to its high quality output voltage, low switching frequency ratio over fundamental frequency, reduced filtering needs, minimal switching losses, and elimination of low-order harmonics, among other benefits [135].

9. Control scheme of DVR

The primary control function is to keep the voltage magnitude constant. The inverter is a critical component of the DVR, and its control technique has a direct impact on the DVR's performance. The inverter control technique includes two forms of control which are linear and non-linear control.

9.1. Linear control

This control approach is said to be a popular DVR strategy. Feed forward control, ramp control, composite control, feedback control, state feedback controller, synchronous PI regulator predictive control, feedback linearization, and dead-beat controller are some of the linear controls utilized in DVR.

9.1.1. Feed-forward control

These controllers are a major choice for the Dynamic Voltage Restorer, considering its straightforwardness and speed. This control method does not detect the load voltage rather it figures the injection voltage based on the distinction among the pre and during sags voltages. The disadvantage is the high reliable state error [19, 80].

9.1.2. Feedback control

State space-based feedback control techniques can be employed to configure closed-loop poles, resulting in faster time response [15]. Compared to the feedforward method, this approach excels in terms of accuracy in power quality mitigation. However, it is a more advanced technique that introduces a delay in providing the appropriate control response [134].

9.1.3. Composite control

The Composite Control Strategy combines feed-forward and feedback controllers to enhance system performance, stability, dynamic response rate, and flexibility. By utilizing this approach, the feed-forward control provides the source voltage, the feedback control manages the load side voltage, and the combined power of both controllers is utilized. Implementing a double-loop feedback control within the composite control further improves performance, stability, dynamic response rate, and reduces compensation time [136].

9.1.4. Ramp control

To operate the DVR's inverter switches, the ramp controller compares a triangular carrier to the voltage error signal. The ramp controller's goal is to make sure that the switching frequency matches that of the carrier. When compared to the hysteresis voltage control approach, ramp-based control achieves a constant switching frequency, and this constant switching frequency has been lowered by integrating a ramp controller with a hysteresis band [137].

9.1.5. Predictive control

Predictive control methods, including deadbeat control and model predictive control, find diverse applications in three-phase inverters with LC filters. Among these methods, deadbeat control is extensively employed for voltage regulation due to its rapid dynamic response and straightforward approach [138].

Deadbeat control is a potential regulating strategy because it assures that state variable mistakes are reduced in a small number of time steps and that discrete time systems respond quickly. As a result, many strategies have been devised utilizing the deadbeat control method, i.e., a method with a computational delay for quick system response, but it lacks the potential to handle dynamic response of other variables. A strategy for multi-loop response employing conventional state feedback linearization has developed for voltage and current management of the system [139].

With the synchronous dq frame, a deadbeat control mechanism for a three-phase inverter is presented, and the SVPWM methodology is applied on it. A disturbance observer used to construct a deadbeat control system. With a one-step forward predictor, for sensitivity reduction and voltage control [140].

9.1.6. PI control

Under system disruptions, the control technique's importance is to restrict constant voltage magnitude to the point where a sensitive load is attached. No reactive power measurements are required since the control system just examines the root mean square (RMS) voltages at the load terminals. The VSC switching method is based on a sinusoidal PWM mechanism, which implies that it is simple and responsive. PWM approaches give a more versatile alternative to Fundamental Frequency Switching (FFS) systems since bespoke power is a relatively low-power need. In PI control, high switching frequency is very beneficial for the efficiency of converters without causing significant losses of switching [141].

9.2. Non-linear control

Non-linear controller is more suitable than the linear controller. Artificial Neural Network Control (ANN), Fuzzy Controller, hysteresis control, sliding mode control, H infinity, repeated control, PR Control, and hard switching control are only a few of the non-linear controllers presented in the literature.

9.2.1. Artificial neural network control (ANN)

The ANN has adaptable and conscience capabilities, which improves precision through interpolation. To increase power quality and eliminate harmonic distortions in sensitive loads, the ANN controller is employed in the design and modelling of DVR [142]. In the event of a disruption, DVR is used to enhance the real power of the inverter. The DVR may be utilized as a voltage sag restorer and voltage distortion compensator with ANN to reduce harmonics and voltage sag/swell caused by zero sequence components when attached between the power source and the booster transformer [143].

9.2.2. Fuzzy logic control

A set of linguistic principles governs fundamental control action in FLC. The system determines these rules. FLC does not require quantitative modelling of the system since numerical variables translated into verbal variables [144]. This controller is implemented into DVR and is developed from fuzzy set theory. This controller's benefit is its ability to eliminate PWM error and transient overshoot.

9.2.3. Sliding mode control

Among nonlinear control methods, the sliding mode controller gave the better and robust performance as compared to the other linear and non -linear controller in the shape of robustness, insensitivity, system parameter, simplicity, mathematical modeling and for system stability [145].

In power electronics circuits, regardless of its robustness, ideally SMC activates at an infinite frequency due to signum function utilized in sliding 'manifold' as well as delay and inadequacy activated in the switching devices [146]. But in this controller chattering effect produced by the switching and this effect, causes the heating loss, temperature loss and law control accuracy. For avoiding the Chattering effect, many algorithms can be used such as Super twisting [147], Real Twisting [148], Neural Network [142], Sub-Optimal [149], Smooth Super twisting [150] and Integral [151].

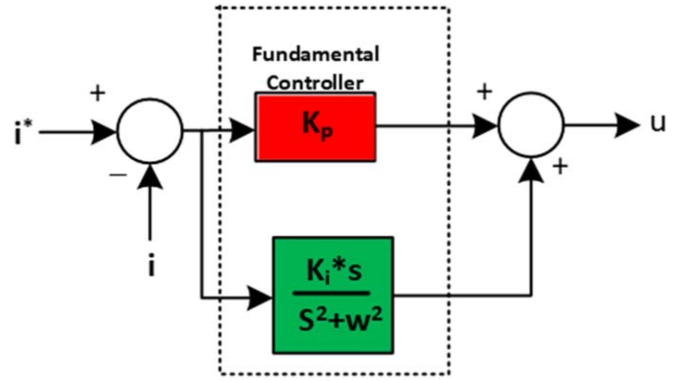


Figure 21. PR controller.

9.2.4. Proportional resonant control (PR)

The proportional-resonant (PR) control technique operates without the need for dq component identification in voltage and current control loops. Instead, it directly utilizes AC signals. However, prior to implementation, the PR approach requires calibration to compensate for the fundamental component and specific harmonics [152]. In this circumstance, the controller's ability to safeguard the load from additional disruptions is limited. Covering additional frequencies complicates the control mechanism. PR controllers used to reduce individual harmonics and decrease the steady-state error associated with the system [153]. Figure 21 depicts the PR controller's block diagram.

9.2.5. Hysteresis control

Hysteresis control is used to regulate the switching instants of VSI switches. It is a pulse width modulation approach. The hysteresis controller's input is confine within a predefined hysteresis band (h), which is accomplished by alternating the VSI states (+Vdc/−Vdc). The reference load voltages (vLaref, vLbref, vLcref) and PCC voltages (vsa, vsb, vsc) as written in equation (7) are used to provide reference signals for the hysteresis controller [154].

$$\begin{bmatrix} (V_{inje})_a^{refe} \\ (V_{inje})_b^{refe} \\ (V_{inje})_c^{refe} \end{bmatrix} = \begin{bmatrix} V_{La}^{refe} \\ V_{Lb}^{refe} \\ V_{Lb}^{refe} \end{bmatrix} - \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{7}$$

9.2.6. Repetitive control

Repetitive control is derived from the internal model concept, which eliminates periodic inaccuracy in dynamic systems. Figure 6 depicts the repeating controller's block diagram. The notion of iterative learning control underpins repetitive feedback controllers (RC) (ILC). Repetitive controllers are appropriate for utility converters with periodic reference signals and/or disturbances [155]. The utilization of a repetitive controller (RC) in a grid-connected single-phase H-bridge inverter enables precise tracking of the desired current reference while effectively compensating for variations in grid voltage and load current, resulting in excellent correction of load reactive power and current harmonics. A mixture and a stationary-frame repeated control technique are developed to address the harmonic problem that occurs in utility grids [156].

9.2.7. H-Infinity control

A current controller has been introduced, comprising an internal model and a stabilizing compensator, which is designed based on H-infinity control principles. Even when the grid disrupted, the H-infinity repeating current controller injects balanced current into the grid. In comparison to the traditional PI, PR, and DB controllers, the performance of the H - repetitive controller appears to be extremely good [157]. Even though the loads are nonlinear/unbalanced, the output current THD level is under the specified limit, and this holds true during grid-voltage disturbances as well [158].

10. Discussion

Review on the state of the art of Dynamic Voltage Restorers (DVRs) has delved into various dimensions, including topologies, operational modes, compensation methods, and control algorithms. In this paper, the aim is to synthesize the insights gained from the reviewed literature and highlight key findings, emerging trends, and potential avenues for future research.

The surveyed literature showcases a diverse range of DVR topologies, each tailored to address specific power quality challenges. From series and shunt configurations to hybrid approaches, researchers have explored innovative designs to enhance the effectiveness of DVRs. The discussion around these topologies has unveiled a nuanced understanding of their advantages, limitations, and applications in different scenarios.

Understanding the operational modes of DVRs is crucial for their successful deployment in power systems. The literature reveals a consensus on the primary modes—voltage sag and swell compensation. However, emerging discussions explore the integration of DVRs for harmonics mitigation, unbalance correction, and even power factor improvement. Exploring these extended operational modes opens up new possibilities for the versatile application of DVRs in diverse power quality scenarios.

The compensatory mechanisms employed by DVRs have undergone rigorous investigation in the literature. From voltage injection to energy storage systems, researchers have explored various compensation methods. The discussion has centered around the efficacy of these methods in mitigating power quality issues and the trade-offs involved in their implementation, providing valuable insights for practitioners and policymakers.

Advancements in control algorithms play a pivotal role in enhancing the performance of DVRs. The literature review has highlighted the shift from conventional to advanced control strategies, such as model predictive control, fuzzy logic, and artificial intelligence-based techniques. The discussion around these control algorithms emphasizes the need for real-time adaptability, accuracy, and robustness to effectively address dynamic power quality disturbances.

While the review has provided a comprehensive overview of the existing literature, a critical analysis of commonalities and differences among the studies is essential. Future research directions should focus on synthesizing findings, identifying gaps in knowledge, and proposing avenues for further exploration. The integration of comparative analyses and meta-analyses could contribute to a more cohesive understanding of DVRs' capabilities and limitations.

11. Conclusion

Dynamic voltage restorers (DVRs) are devices that are used to improve the power quality of an electrical distribution system by correcting voltage sags or dips that occur on the power line. DVRs are commonly connected in parallel with the load and have the capability to inject a voltage with the appropriate magnitude and phase angle to mitigate voltage sags. This ensures a consistent voltage supply to the load, which is crucial for ensuring the reliable operation of sensitive electronic equipment. DVRs find applications across various sectors, including industrial plants, commercial buildings, and electrical utilities. They can help to reduce the impact of voltage sags on sensitive electronic equipment, which can reduce downtime and improve the reliability of the electrical distribution system. There are several different types of DVRs, including series- and shunt-connected DVRs. Series-connected DVRs are connected in series with the load, while shunt-connected DVRs are connected in parallel with the load. Both types of DVRs are able to inject a compensating voltage to correct for voltage sags, but they differ in how they are connected to the load and in their operating principles. In summary, dynamic voltage restorers are useful devices that are used to improve the power quality of electrical distribution systems and to protect sensitive electronic equipment from voltage fluctuations. They are widely used in a variety of applications, and their effectiveness in improving power quality has been demonstrated through numerous studies and real-world deployments.

Our review on the state of the art of Dynamic Voltage Restorers (DVRs) aspires to provide a comprehensive understanding of various aspects; however, certain limitations inherent in the scope and methodology of this review warrant acknowledgment. Firstly, the scope of the literature examined is confined to the existing body of knowledge up to the knowledge cutoff date, which may restrict the inclusion of recent developments or studies. Additionally, regional variations in research focus and application scenarios may not be fully represented, potentially impacting the generalizability of our findings. In focusing predominantly on engineering and technical aspects, our review may fall short in incorporating interdisciplinary perspectives, such as economic or social considerations. This limitation may impede a holistic understanding of the real-world implications of DVR implementation.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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