Dynamic Voltage Restorer (DVR) – A Review

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Abstract

Power quality (PQ) is gaining a great deal of importance as more sensitive loads are introduced into the utility grid. The degradation of product quality, damage of equipment and temporary shutdowns are the general issues associated with PQ problems in industries. Any mal-operation or damage of the industrial sensitive loads results in monetary losses disproportionately higher than the severity of the PQ issues. The evolution of power electronics technology replaced the traditional power quality mitigation methods with the introduction of Custom Power System devices (CUPS). The major power electronic controller based CUPS are DSTATCOM, DVR and UPQC. DVR is a pertinent solution for the economic losses caused by the PQ issues in the industries. Among the CUPS, DVR is the most cost-effective one. In the published literature, only a few papers correspond to the review of DVR technology. In this paper, a systematic review of published literature is conducted and a description is given on the design, standards and challenges in the DVR technology. A detailed survey is conducted on the published

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literature to address the various aspects and issues in the DVR system. This paper arrangement gives the working principle, structure, various topologies, compensation techniques, voltage sag detection methods and control methods of the DVR under different sections. The section “Challenges faced by the DVR” included in the manuscript can be useful for the researchers beginning their work in the domain of DVR. The simulation results using the sim power system tool of MATLAB/Simulink software are provided for analysis and comparison.

Keywords: Voltage sag, DVR, Inverter, Compensation techniques, Voltage sag detection method, Control methods.

1 Introduction

Voltage sags, swells, flicker, voltage notch, harmonic distortions, transients and momentary interruptions are most common PQ problems affecting the industrial customers [1, 2]. Sensitive electronic equipment, critical and non-linear loads comprising of precision manufacturing processes are adversely affected by PQ problems and results in monetary losses, damaged equipments and product quality degradation etc [1].

Voltage sag is the reduction in rms value of the voltage from 0.9p.u to 0.1p.u for a short duration of 0.5 cycles to less than one minute, usually occurring due to faults in transmission and distribution lines and it is the most severe PQ problem [1]. Through temporary shutdowns, deteriorated products and damaged equipment, sags majorly affects the paper, semiconductor and chemical industries [3–6]. Fault conditions mostly single line to ground fault (SLGF), starting of large motor drives, energization of transformers, animal contact are some of the reasons for voltage sags [5, 7, 8]. Voltage sags are characterised by magnitude, duration and phase jump if any. The location of the fault from the sensitive load, associated impedances of the transformers, conductors and related equipment, voltage class of the feeder, speed of response of load protection switchgear are the factors determining the magnitude and duration of the sag experienced by the sensitive loads [1, 9].

To diminish the potential losses caused by the PQ problems, a new class of power electronic based voltage support solutions are offered by CUPS such as DSTATCOM, DVR, UPQC and they bring considerable and measurable improvement in the power quality [7, 10]. The inclusion of these compensating type CUPS in the power line is a prerequisite for profitable operations in the

Table 1 DVR merits and demerits

Sl. No	Merits	Demerits
1	Static series conditioning and compensation in the distribution power system level	Compensation is cost effective when the injection voltage capability is limited to a fraction of the rated supply voltage (usually 50%)
2	Very effective protection of critical loads than any shunt compensation devices	Protection becomes obsolete if the voltage to be injected is greater than its voltage rating
3	Low power rating than shunt connected compensators and UPS	Higher power rating (making voltage injection capability greater than 50%) makes DVR expensive
4	Efficiency, simpler control and ease of its implementation makes DVR a feasible solution	Unfeasible solution for power interruption problems
5	Less maintenance cost	Protection scheme is difficult and requires most investment.

critical industries. DVR provides an economically and technically optimized corrective measure in this field. Table 1 gives the merits and demerits of the DVR and finds it as a promising solution with cost benefit than any other CUPS [10–17]. The impact of DVR during voltage sag, harmonics and unbalance is studied in [18] which gives a better understanding about the mitigation property of the DVR.

Extensive research work is going on in the field of DVR technology. At present, the research in DVR system has arrived to a matured level. However, only few review papers are available in the published literature. A comprehensive review given by Mohammad Farhadi et.al incorporates the DVR topologies, control schemes and applications [19]. The major research contributions in DVR technology for a span of fifteen years since its first installation in 1996 is presented by El-Gammal et.al in the paper [20]. The perspective of the paper presented here is to include all the aspects such as fundamentals, principle, structure, topologies, compensation techniques, detection methods, control schemes and challenges in the DVR system. The simulation results included gives better understanding about the discussion made in the paper. The one of the aims of the paper is to mention about the design specifications and power quality standards associated with the DVR. The authors have incorporated the main challenges faced by the DVR system in general from the published literature. There is no review paper reported in the DVR comprising the challenges encountered by the DVR systems.

These issues can be addressed by the researchers as their research problems for bringing new advancements in this field.

2 Principle of Operation of DVR and Basic Elements

DVR is the most economical solution for mitigating upstream voltage disturbances in the distribution system [21]. DVR can be considered as a variable or controllable voltage source (V_{DVR}) connected in series between the point of common coupling (PCC) (V_S) and the load (V_L). DVR helps to regulate the load voltage profile by injecting appropriate voltage during the voltage quality events and allows control of real and reactive power exchange between the DVR and the distribution system [1, 4, 10, 13, 16, 22, 23]. The features such as sub-cycle protection, harmonic compensation and series conditioning adds more value to the DVR and increases the demand for it in the sectors with critical customer loads [1, 4, 10, 13]. Moreover, during severe sag conditions DVR avoids load tripping [24]. The low voltage ride through capability of the micro grid can be improved with the aid of DVR [25, 26].

The details of first installed DVR is given in Table 2 [13, 15, 27, 28].

Figure 1 shows the restoration of load voltage (three phase, 400V, 50 Hz) by the three phase inverter based DVR during a three phase balanced sag event of depth 0.3 p.u from t = 0.1s to t = 0.3s. As soon as the sag is detected, DVR shifts from standby mode to compensating/active mode. The inverter

Table 2 Details of first installed DVR

1	Manufacturer	Siemens Power Transmission and Distribution Company (formerly Westinghouse Electric Corporation)
2	Year of commissioning	1996
3	Type	Medium Voltage(MV)
4	Location	12.47kV distribution system in USA
5	Connected load	4 MVA
6	DVR Rating	2 MVA
7	On board energy storage	660kJ
8	Number of Voltage Source Inverters (VSI)	3
9	Number of injection transformers	3
10	Compensation technique	In-phase compensation

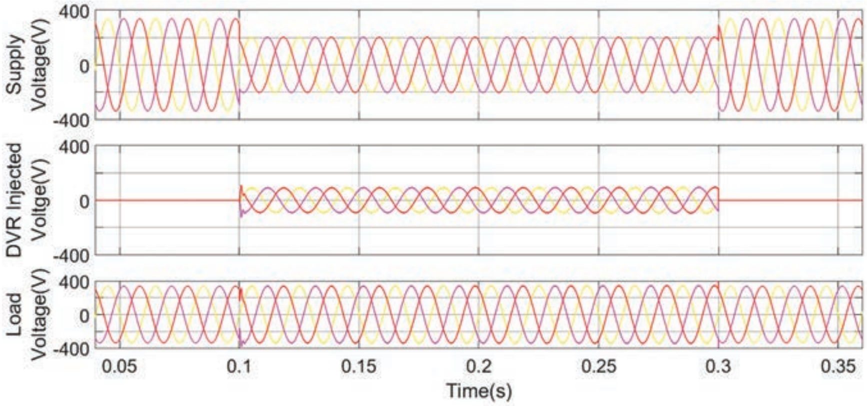


Figure 1 Compensation of load voltage by a three phase inverter based DVR.

switches are operated to inject appropriate voltages so that each phase voltage is restored both in magnitude and phase to presag values and thus the load profile is regulated.

The DVR supplies reactive power (Q_{DVR}) and/or active power (P_{DVR}) for the quick restoration of load voltage as shown in Figure 2. P_S and Q_S represent the real and reactive power of the supply, respectively. P_L and Q_L denote the real and reactive power associated with the load, respectively.

The ideal operation of the DVR aims for a strictly positive sequence composed load voltage and prevents the DVR from either supplying or absorbing any real power for voltage compensation [29].

Figure 3 gives the simplified model of the power circuit of the DVR. The simplified model concept of the DVR is based on an ideal voltage source

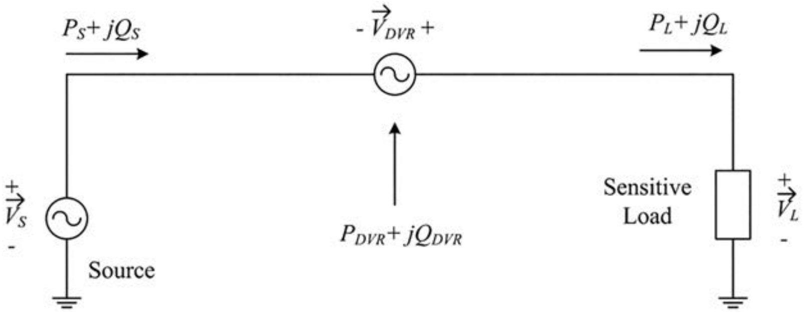


Figure 2 Schematic diagram of DVR.

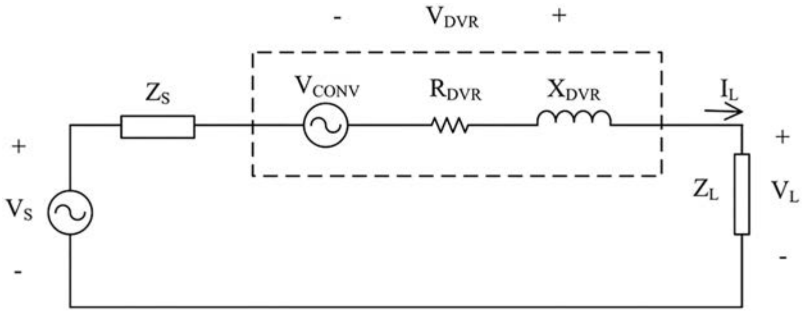


Figure 3 Simplified model of the DVR.

(V$_{conv}$) connected in series between the supply (V$_S$) and load (V$_L$) having impedances Z$_S$ and Z$_L$, respectively. The term R_{DVR} represents the losses in the DVR and X_{DVR} symbolizes the reactance of the injection transformer and the filters in the DVR. The value of X_{DVR} and R$_{DVR}$ are related to the voltage rating (V_{DVR}) and power rating (S_{DVR}) of the DVR as

$$X_{DVR} = \frac{V_{DVR}^2}{S_{DVR}} u_{DVR,X} \tag{1}$$

$$R_{DVR} = \frac{V_{DVR}^2}{S_{DVR}} u_{DVR,R} \tag{2}$$

$$Z_{DVR} = \frac{V_{DVR}^2}{S_{DVR}} u_{DVR,Z} \tag{3}$$

$$u_{DVR,Z} = u_{DVR,R} + j u_{DVR,X} \tag{4}$$

$u_{DVR,X}$, $u_{DVR,R}$ and $u_{DVR,Z}$ represents the p.u value of reactance (X), resistance (R) and impedance (Z) of the DVR, respectively.

The voltage handling capability (v_{DVR}) and current handling capability (i_{DVR}) of the DVR are expressed in percentage as

$$v_{DVR,\%} = \frac{V_{DVR}}{V_{s,rated}} 100\% \tag{5}$$

$$i_{DVR,\%} = \frac{I_{DVR}}{I_{L,rated}} 100\% \tag{6}$$

where I_{DVR} is the current rating of the DVR and the rated supply voltage and rated load current are represented by $V_{s,rated}$ and $I_{L,rated}$, respectively [17].

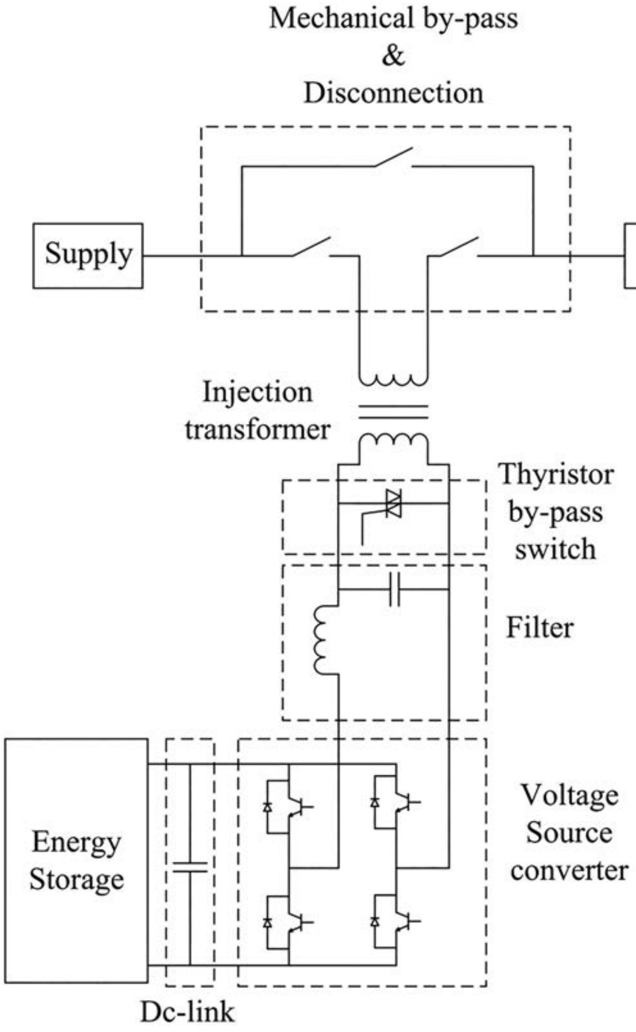


Figure 4 Power circuit of the DVR.

The basic elements of a DVR are *dc*-link and energy storage, converter, filter, injection transformer, bypass equipment and disconnection equipment as shown in Figure 4 [30]. Table 3 gives the description of each element.

Table 3 Basic elements of the DVR

Sl.No	Element	Description
1	Energy Storage [2, 3, 5, 16, 30–34]	1) Injects real power and provides dynamic nature to compensation. 2) Sources-battery, SMES (Superconducting magnetic energy storage), super capacitors, flywheel, and fuel cell. Hybrid energy storage systems are also used in DVR. 3) Selection depends on installed load MVA, load power factor, sag depth, frequency of sag occurrence and sag duration.
2	*Dc*-link capacitor [5]	1) Functions-a) supplies energy in the event of a sudden transient b) improves the quality of current from the energy storage c) maintains the *dc*-link voltage constant which improves the steady state operation of the DVR d) filters away some switching harmonics in injected voltage e) provides *dc* isolation.
3	Converter [2, 4, 16, 26, 30, 35–39]	1) Type-*dc*-*ac*/*ac*-*ac* converter. 2) Connection-series. 3) Selection depends on type of real power source. 4) Requirements-high efficiency, high reliability and inherent safety. 5) VSI are commonly chosen due to good output voltage characteristics with less current harmonics. 6) The most suitable inverter switch is Integrated Gate-Commutated Thyristor (IGCT). It is specifically deployed to diminish the conduction losses. The other merits of IGCT are a) low cost b) snubberless operation and c) high gate drive speed. 7) For real power absorption from utility, additional rectifier is required. 8) Bidirectional converters eliminate additional battery charging units. Rarely shunt connected converters are used [40].
4	Filter [8, 21, 40–42]	1) Two schemes-Inverter side filtering and Line side filtering (detailed description in Table 4). 2) Types-second order LC filters, RC and RCL filters. 3) Function-avoids the unwanted tripping of loads and the other problems by filtering the harmonics present in the injected voltage.

Table 3 Continued

5	Injection Transformer [2, 16, 30]	1) Connection-secondary winding in series with load and supply. 2) Type-Step up transformer. 3) Functions-a) galvanic isolation b) act as filter reactance in line side connected filters c) minimize energy storage capacity and inverter voltage rating 4) Rarely shunt connected transformers are used in low voltage applications for cost reduction.
6	Bypass Equipment/Crowbar circuit [2, 5, 43, 44]	1) Condition for operation-line current greater than inverter current rating during downstream fault or short circuit. 2) Connection-in parallel between inverter and series injection transformer 3) Functions-a) takes DVR system offline or online from the distribution feeder b) shields the DVR from heavy downstream fault currents. 4) Realised using thyristor switches due to their low conduction losses and high surge current capability.
7	Disconnection equipment	1) Functions-a) disconnects the DVR from the power line while in service b) provides provision to remove load from the utility.

Table 4 presents a detailed comparison of the filtering schemes employed in the DVR system [8, 41, 42].

3 Topologies of DVR

Economic design, quick response to the PQ problems and modularity are the main factors considered while proposing new topologies. The number of end users is a significant factor deciding the location of the DVR. The location of the DVR is suggested either at the MV distribution level or at the LV level.

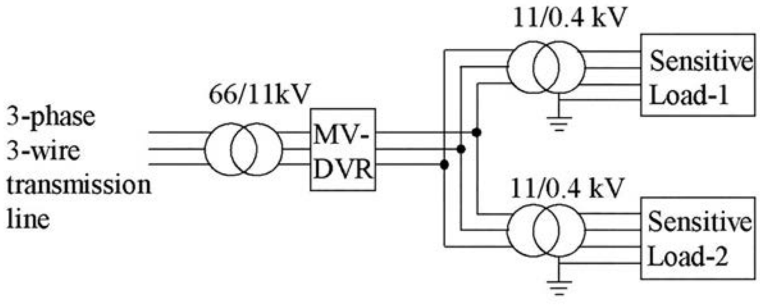
The MV three wire DVR systems centralize the custom power conditioning for multiple critical customers in a single grid and thereby reduce the cost per MVA [45]. The decentralised compensation by LV DVR targets mainly voltage dip sensitive loads. The LV four wire DVR systems compensate for positive, negative and zero sequence voltages wherein the MV DVR injects only positive and negative voltages [17]. Figure 5 shows the MV and LV DVRs, respectively.

Table 4 Comparison of inverter side connected and line side connected filter in the DVR

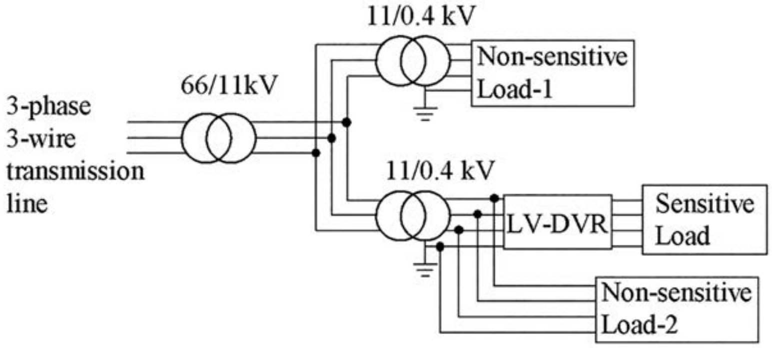
Sl.No	Inverter Side Connected Filter	Line Side Connected Filter
1	Filter components in the low voltage (LV) side of the series injection transformer	Filter components in the high voltage (HV) side of the series injection transformer
2	Closer to the harmonic source	Away from the harmonic source
3	Higher order harmonic currents filtered out from entering series transformer	Higher order harmonic currents present in the secondary of the series transformer
4	Voltage drop and phase shift in the fundamental component due to the presence of filter inductor	Leakage reactance of the transformer can be used as filter inductor
5	Filter capacitor rating depends on the highest possible inverter rms voltage that appear across the capacitor and the current through it	Filter capacitor rating depends on the highest possible injection rms voltage that appear across the capacitor and the current through it
6	The phase angle shift and amplitude difference in the fundamental voltage before and after filter causes errors in the control system of the DVR	Does not affect the control system of the DVR

The size and weight of the DVR decides platform/ground mounting of the system. The platform mounted DVR reported in [10] is having a compact mechanical design. The on-board energy storage acts as a stringent limitation to the platform mounting of DVRs [10]. Modular inverters and energy storage systems are the requirements for the overhead mounting of the DVR.

The DVR topologies with energy storage presented in the literature are a) system 1-with constant *dc*-link voltage b) system 2-with a variable *dc*-link voltage. The system 1 DVR shown in Figure 6(a) offers a constant *dc*-link voltage throughout the operation whereas system 2 DVR shown in Figure 6(b) can be utilized only up to a certain *dc*-link voltage level. The system 2 topology of DVR is also called as capacitor supported or self-charging DVR. The stored energy in the *dc*-link capacitor is utilised during the compensation mode of the DVR. The capacitor is recharged during the stand-by mode of the DVR operation using the series converter or auxiliary converter. However, only limited energy can be stored in the capacitor and this restricts the variable dc-link DVR topology from compensating deep sags and high pf loads for long duration. On the contrary, the system 2 topology is economical over the system 1 topology. An extra energy converter present in the system 1 hikes the capital cost of the DVR. The DVR connected with energy storage occupies space and limits the modularity of the system [19, 21, 29, 46–49].



(a) DVR located at medium voltage distribution system

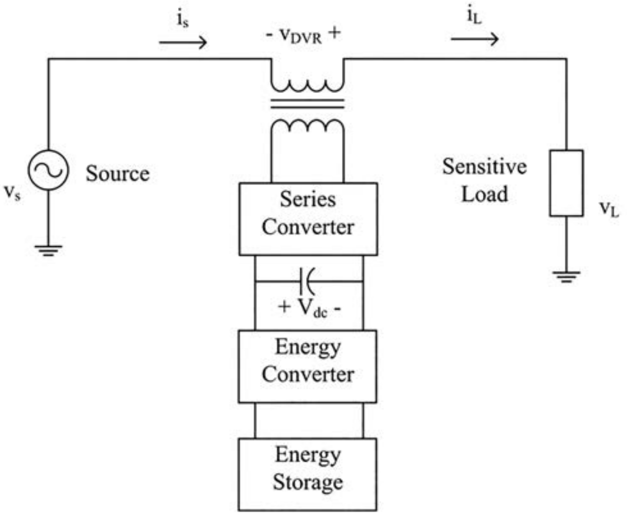


(b) DVR located at low voltage distribution system

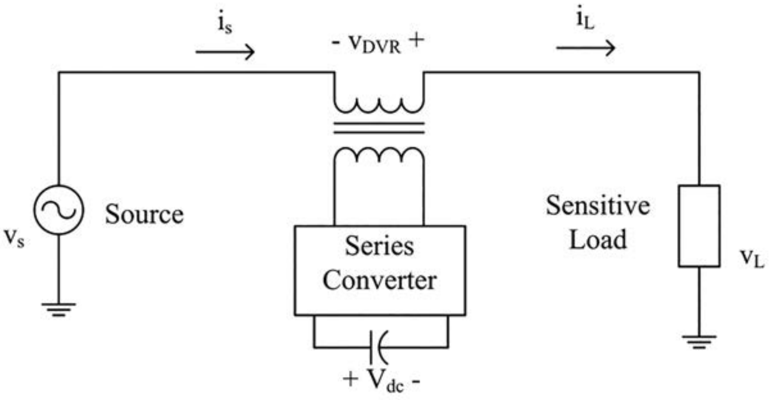
Figure 5 DVR topologies based on distribution line voltage levels.

The DVR topologies with no energy storage take advantage of the remaining utility power for compensation. The location of the passive converter – either on the supply side or the load side bifurcates the storageless DVR topology into supply side connected DVR and load side connected DVR as shown in Figures 7(a) and 7(b), respectively [50–54]. It is proved theoretically and experimentally that the load side connected shunt converter DVR is superior among all the topology classification based on energy storage [10, 21, 46, 49, 55, 56].

VSI is the sole supplier of reactive power in the DVR topology [2, 3, 6]. The different configuration of inverter circuits for DVR system is discussed in [57]. For three-phase applications, three level inverters or three phase inverters (Graetz bridge or split capacitor inverter topology) or four switching leg inverters are used [2, 58]. A three phase inverter based DVR compensating



(a) Constant dc- link DVR

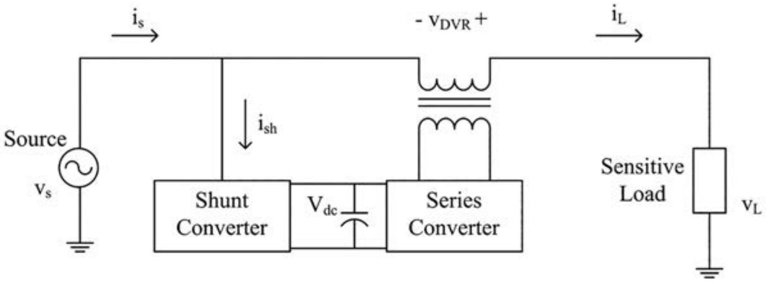


(b) Variable dc-link DVR

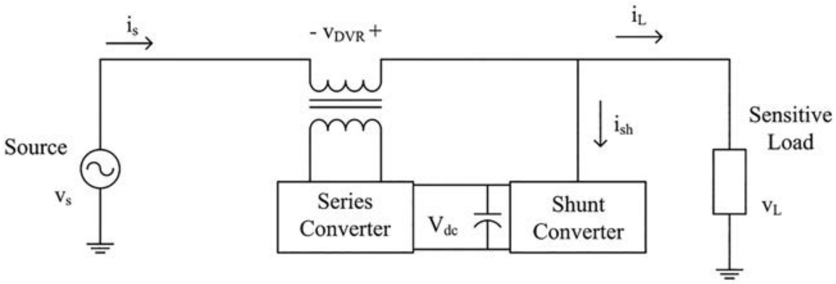
Figure 6 DVR topologies with energy storage.

phase ‘a’ voltage encountered with a sag event from t=0.15s to t=0.35s is simulated and its THD analysis and results are given in Figure 8. The THD of the voltage before and after compensation is obtained as 15.61% (supply voltage) and 0.56% (load voltage), respectively.

The supply side connected DVR topology employing half bridge inverter for single phase voltage compensation [16, 22] and for three-phase voltage



(a) Supply side connected DVR

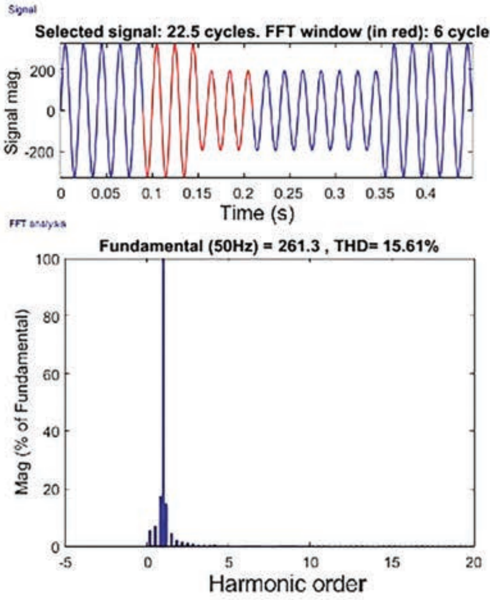


(b) Load side connected DVR

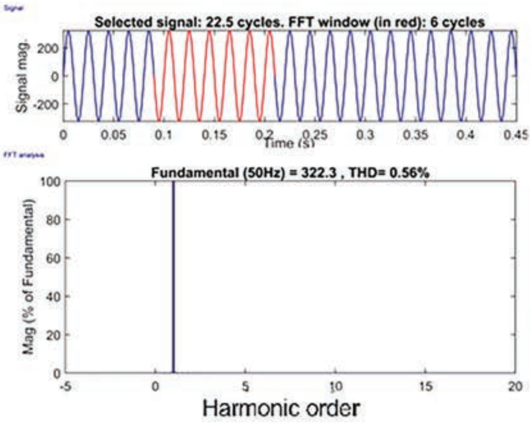
Figure 7 Storageless DVR topologies.

compensation [50, 59] with reduced switch count and cost is reported in literature. Among the two level and three level inverters, the latter is most frequently in use due to the advantages such as low device stress, low THD and low switching losses. The large voltage stress experienced in higher-level inverters opens a new problem statement, which needs further investigation [14].

The multilevel inverters are divided in to cascaded, quasi linear, binary and trinary inverters (all except cascaded is collectively called as hybrid inverters). Cascaded multilevel converter structures are regarded as the plausible solution for the MV and HV distribution system in [11, 14, 60–62]. The interline DVR employing two cascaded H bridge multilevel converter gives an improved THD result [60]. A cascaded H bridge multilevel inverter (11 level) which demands of having features such as low THD, low EMI, high power and voltage applications and elimination of *dc*-link voltage balancing is presented in [61]. Five and thirteen level multilevel inverter based DVRs are discussed in [62] and [14], respectively. The paper [14] proves that as



(a) Uncompensated system



(b) Compensated system by
three phase inverter based DVR

Figure 8 THD analysis of load voltage.

the levels goes up, cascade multilevel inverters offer less harmonics and less losses. The DVR supported with adjustable *dc*-link connected multilevel inverter suitable for both deep and shallow sag mitigation is presented in [63]. The low inverter losses and reduced harmonic content welcomes the open end winding transformer into the DVR topology [64]. A multilevel inverter based DVR coupled with cascaded open-end winding (OEW) transformer is reported in [65]. However, [2] rules out the need for multilevel structures in FACTS. Other inverters like the Z source inverters introduced in the design enhanced the capability and performance of the DVR [37, 66]. The DVR topology based on semi-Z-source inverter reported in [67] ensures same inverter output voltage range as the full-bridge inverter with reduced number of switches. The doubly grounded feature makes the semi-Z-source inverter suitable for Photovoltaic (PV) and fuel cell based DVR. Table 5 gives a basic comparison between the commonly used inverters in the DVR structure.

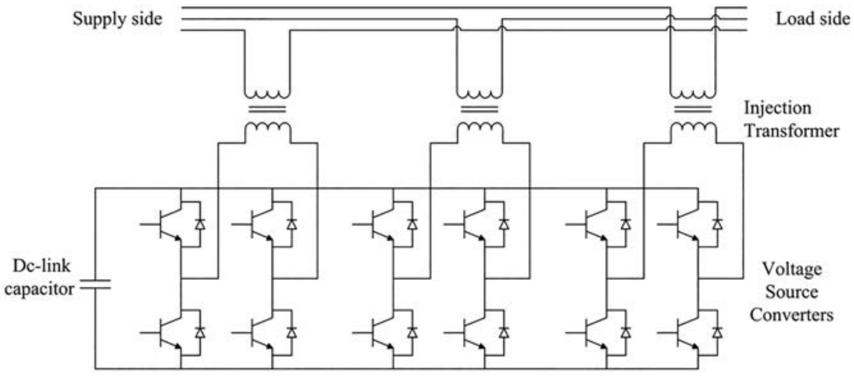
Table 5 Comparison between the inverters used in the DVR structure

Sl. No	Inverter	Merits	Demerits
1	Half bridge inverter [16, 22, 48, 58]	Reduced switch count and low cost	Harmonic content present in the voltage is high
2	Full bridge or H bridge inverter [11, 45]	Used in high voltage distribution system Independent single phase connection available	Harmonic content is high
3	Three phase inverter [2, 5, 16, 57]	Lower cost and simpler control	Presence of differential and common mode EMI
4	Four switching leg inverter [2, 57]	No *dc*-link capacitor balancing problem	Presence of differential and common mode EMI
5	Multilevel inverter [61, 62]	Low switching frequency, low device stress and low THD	Complex structure after level 5
6	Cascaded multilevel inverter [14, 60]	Medium and high voltage applications, simpler filter design, low harmonics and less losses	Complex control and structure

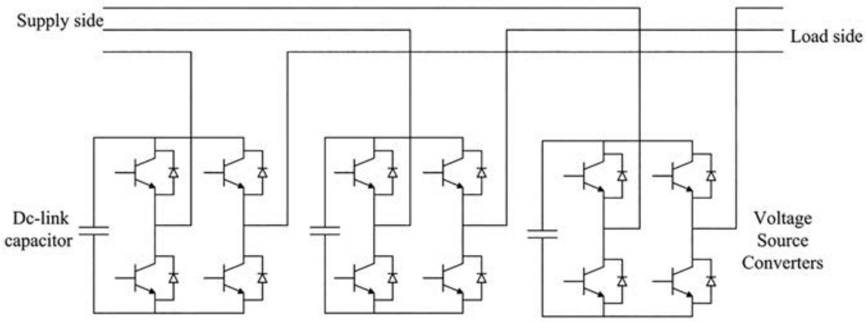
The *ac-ac* converters augmented the growth of *ac*-link approach in the DVR technology. It opened a new range of storageless DVR systems as the compensation in one particular phase is carried out by taking power from the remaining two phases. The lower cost, compactness and low semiconductor switch rating compared to the *dc*-link supported DVR makes this classification of the DVR a promising one. The *ac-ac* converter based DVR presented in [68] performs the load compensation with only two switches. The DVR can utilise low voltage rating switches for dealing with high voltage by employing *ac-ac* converter in its circuitry [69]. This topology implemented with IGBT switches eliminates the need for auxiliary force commutation circuit which are required with high voltage thyristor switches. The buck-boost *ac-ac* converter based transformer-less DVR discussed in [70] helped in eliminating the huge dc-link capacitor and injection transformer, thereby reducing the weight and volume of the DVR. An energy storage-less topology of DVR explained in [71] utilizes inter-phase direct *ac-ac* converter as the missing voltage synthesizer. The characteristics of the quasi-Z-source *ac-ac* converter such as continuous input current and common ground sharing between input and output contributes in proposing a DVR topology based on the same *ac-ac* converter [72]. The simple control is the merit that makes the cascaded multilevel direct PWM *ac-ac* converters suitable for DVR application [73]. For optimisation of cost and size, the switching cell concept is extended in to the DVR architecture based on multilevel direct *ac-ac* converter [73]. The storageless interphase *ac-ac* topology is a major development in the DVR technology as it reduces the cost of the sag mitigation system [74]. The *ac-ac* conversion by matrix converter (MC) replaced the *ac-dc-ac* interface and increased the reliability and power density of the DVR circuits [48, 75]. The absence of electrolytic capacitor in MC makes it a recommended sag mitigation device [76].

The incorporation of high-frequency transformer is a breakthrough approach in the *ac-ac* converter based DVR topology [77, 78]. The high-frequency link provided by the power electronic transformer in the cyclo-converter based series compensators overcomes the limitations in capability, size and cost of its line-frequency transformer-based counterparts while sustaining all the benefits of the latter [79, 80].

Regardless of line-frequency and high-frequency transformer based DVR, the economical design considerations paved the way to the development of transformerless DVR with relevant advantages such as negligible losses, modular design, dynamic restoration, good voltage regulation and power quality enhancement capabilities [15]. In literature [50], the authors give description about single phase transformerless supply side connected DVR



(a) Transformer connected DVR



(b) Transformerless DVR

Figure 9 DVR topologies based on isolation.

with half wave diode bridge rectifier (topology I) and full wave diode bridge rectifier (topology II) for providing *dc*-link voltage. The transformerless multilevel DVR topology for high voltage application is presented in [62]. With multilevel inverters, one can go for transformerless DVR topology up to 10 kV level [61]. The DVR topologies with and without isolation are shown in Figures 9(a) and 9(b), respectively.

The independent *dc*-links in conjunction with each inverter to avoid phase-to-phase short circuit scenario and cascaded switches/inverter connections (type 1 and type 2 transformerless DVR, respectively) to bring the voltage boost function are the modifications introduced in the transformerless DVR compared to the conventional DVR scheme. The shortcoming of conduction overlapping of the switches is addressed by introducing separate *dc*-links for each inverter in the transformerless DVR [81]. The same ride through capability of transformerless DVR for both balanced and unbalanced sag conditions increased the momentum to collaborate the same with storage-less topologies [82]. The transformerless DVR topology, converters with reduced switch count and supply side or load side connected DVRs are the available possibilities for cost reduction in the DVR systems [50]. Table 6 summarises the capabilities and restrictions of the different DVR topologies [19, 44, 45, 49].

Table 6 Capabilities and restrictions of different DVR topologies

Sl.No	Topology	Capabilities/Merits	Restrictions/Demerits
1	MV Level DVR	Protect the critical industrial and commercial customers. Suitable for medium voltage electrical distribution network applications.	Requires inverter switches with high voltage blocking property
2	LV level DVR	Suitable for low voltage electrical distribution system.	Specific design requirement for each sensitive load in a system
3	DVR with energy storage	Improved performance due to stored internal energy. Less strain on the grid. Complexity of control is less	Expensive. As the stored energy decays, the compensation capability decreases
4	DVR without energy storage	Economical. Compact and modular design as there is no internal energy storage. More suitable for strong electrical grids	Comparatively more strain on the grid Complicated control
5	Transformerless DVR	Reduction in cost, size and weight. No transformer saturation and inrush current problems	Not suitable for high voltage application.

(*Continued*)

Table 6 Continued

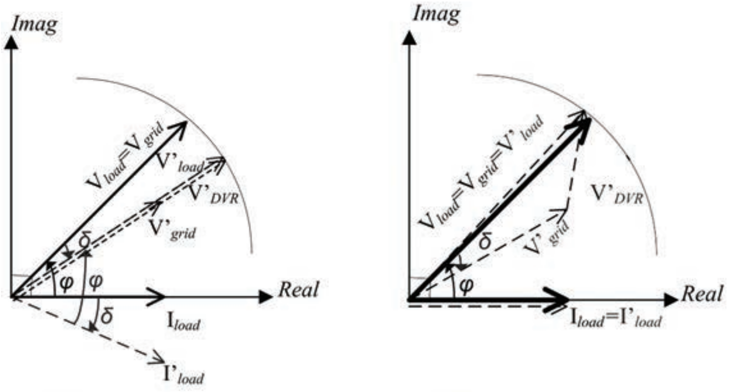
6	DVR with injection transformer	According to the transformer turns ratio, proportional reduction in inverter voltage rating. Suitable for high voltage application. Compact design possible using high frequency transformer	Difficult to protect the transformer from downstream fault current. Transformer with high current tolerance required as it experience high current until the protection switch gear operates. Issues related to transformer saturation and inrush current. DVR with high frequency transformer may require *ac-dc-ac* conversion stages. Efficiency is less.
7	Multilevel inverter based DVR	Reliable operation. Improved power quality. Low switching stress on each switch	Excess number of clamping diodes, capacitors and energy sources are required depending on the type of multilevel inverter. Voltage unbalance problem. More number of switches, bulky and packaging constraints.

4 Compensation Techniques in the DVR

The way in which the compensation is carried out to maintain the load voltage constant depends on the type of load – whether it is magnitude sensitive, phase sensitive or both. The analysis and study of load reaction to magnitude variation, phase disturbance or both is required and compensation method is selected according to whichever disturbance reflects as more severe and critical on the load. Different voltage injection schemes are described in this section.

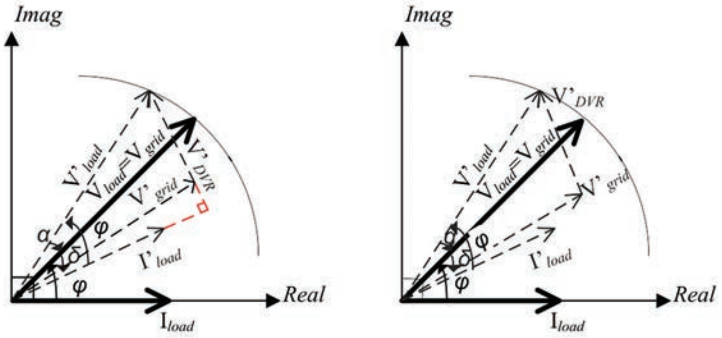
4.1 In-phase Voltage Compensation Method

The in-phase voltage compensation method is the most suitable compensation technique for magnitude sensitive loads. Irrespective of the prefault conditions, it restores the load voltage by injecting missing voltage in phase with the supply voltage [12, 47, 52] and hence known as voltage amplitude optimized control. The corresponding phasor diagram is shown in Figure 10(a). V_{grid}, V_{load} and I_{load} represents the grid voltage, load voltage and load current, respectively and the same quantities after sag is given by V'_{grid}, V'_{load} and I'_{load}.



(a) Phasor diagram of in-phase compensation

(b) Phasor diagram of presag compensation



(c) Phasor diagram of energy minimised compensation for balanced sag

(d) Phasor diagram of energy minimised compensation for unbalanced sag

Figure 10 Different compensation techniques.

V'_{DVR} – the injected voltage by the DVR.
φ – phase angle between load voltage and load current
δ – angle corresponding to the phase jump of the grid voltage during sag condition.
k – phase *a*, *b* or *c* of the supply voltage.

The in-phase compensation furnish maximum voltage boost with minimum injected voltage. However, the energy injected by the DVR in this method is non-minimum. The injected voltage V'_{DVR} is given by the Equation (7).

$$V'_{DVR,k} = \sqrt{2}\left|V_{load} - V'_{grid,k}\right| \tag{7}$$

Since the injected voltage is in phase with the supply voltage, there is a need of energy storage for active power compensation. This method fails to address the phase jumps. The in-phase compensation involves both real and reactive power in load voltage restoration.

4.2 Presag Compensation Method

For compensating both magnitude and phase jumps, presag compensation method or voltage quality optimized technique is employed. The voltages of complementary nature in magnitude, wave shape and harmonics are injected by the DVR to compensate the difference between the prefault and fault voltage [24, 40, 83]. The load voltage post and prior to the fault matches in both magnitude and phase. This method is well suited for both balanced and unbalanced sags with or without phase jumps. The DVR employing this technique of compensation ensures large voltage injection capability. The distortions appearing in the load side are low in this compensation [84]. There is requirement of large energy storage source in this compensation strategy for supplying the active power along with reactive power injected by the inverter. The phasor diagram of presag compensation is given in Figure 10(b). The magnitude and the phase angle of the injected voltage are given by the Equations (8) and (9), respectively.

$$V'_{DVR,k} = \sqrt{2}\sqrt{(V_{load})^2 + (V'_{grid,k})^2 - 2V_{load}V'_{grid,k}\cos(\delta_k)} \tag{8}$$

$$\angle V'_{DVR,k} = arctan\left(\frac{V_{load}\sin(\varphi) - V'_{grid,k}\sin(\varphi - \delta_k)}{V_{load}\cos(\varphi) \; - V'_{grid,k}\cos(\varphi - \; \delta_k}\right) \tag{9}$$

4.3 Energy Minimized Compensation Method

The type of voltage disturbance and the type of compensation method decides the amount of real and reactive power required by the DVR for compensating a particular disturbance. The reactive compensation technique proposed by Gyugyi [85] is the fundamental concept of the DVR voltage restoration.

Zero active power compensation is achieved by injecting the voltage in quadrature with the load current [86]. This is called as energy minimized compensation. The capacity of energy storage is reduced and this reduction is inversely proportional to the sag depth. This method is not applicable for sag mitigation of sensitive loads with high power factor [16, 22].

The pure reactive compensation significantly increases the compensating device rating and restricts the range of compensation [57]. The another method termed as energy optimised method or phase advance method discussed in the literature minimizes the real power consumption by injecting voltages at a phase angle shift of α between the injected voltage and the load current. The phasor diagram of energy minimized compensation for balanced and unbalanced sag conditions is given in Figures 10(c) and 10(d), respectively. The magnitude and phase angle of the injected voltage for balanced and unbalanced voltage under this compensation technique is given by Equations (10), (11), (12) and (13), respectively.

For balanced sag

$$V'_{DVR} = \sqrt{2}\sqrt{(V_{load})^2 + (V'_{grid})^2 - 2V_{load}V'_{grid}\cos(\delta+\alpha)} \tag{10}$$

$$< V^{'}_{DVR} = arctan\left(\frac{V_{load}\ \sin(\varphi+\alpha) - V'_{grid}\ \sin(\varphi-\delta)}{V_{load}\ \cos(\varphi+\alpha) - V'_{grid}\ \cos(\varphi-\delta)}\right) \tag{11}$$

For unbalanced sag

$$V'_{DVR,k} = \sqrt{2}\sqrt{(V_{load})^2 + (V'_{grid,k})^2 - 2V_{load}V'_{grid,k}\cos(\delta_k+\alpha)} \tag{12}$$

$$\angle V'_{DVR,k} = arctan\left(\frac{V_{load}\ \sin(\varphi+\alpha) - V'_{grid,k}\ \sin(\varphi-\delta_k)}{V_{load}\ \cos(\varphi+\alpha) - V'_{grid,k}\ \cos(\varphi-\delta_k)}\right) \tag{13}$$

4.4 Hybrid Compensation Method

The advantages of presag and in-phase compensation methods are blended to produce a hybrid voltage compensation method. Without compromising the operation range, this method avoids large *dc*-link capacitor and over modulation [84]. The three compensation methods- reactive power control, minimum energy injection and maximum voltage injection are combined together to form another hybrid compensation technique in [87]. The proposed compensation method in [88] initially restores the load voltage through presag compensation and takes a transition to minimum active power injection method. A novel compensation technique called as elliptical compensation presented in [89] controls the magnitude and phase of the injected voltage in such a way that the DVR accomplish low voltage ride through capability. For optimal utilization of DVR, a compensation technique based on voltage elliptical parameters is developed [90]. The elliptical restoration technique reported is applicable to all voltage quality problems. There is a scope of vast research in the compensation methods- either by merging the conventional methods or by proposing novel techniques which improves the performance of the DVR.

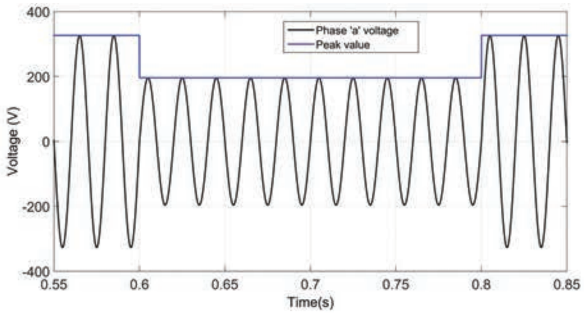
5 Control Techniques of the DVR

The basic functions of the control system of a DVR are a) voltage sag detection b) voltage reference generation c) converter control and d) protection of the system [45]. The performance of control algorithm will be completely affected by the quality and accuracy of the detection methods. The detection algorithms such as Discrete Fourier Transform (DFT) algorithm, Fast Fourier Transform (FFT) algorithm, Kalman filtering (KF) are used for the accurate prediction of voltage disturbances in the supply voltage [6, 83, 91]. The KF is an optimum state estimation technique for detecting balanced and unbalanced sags [91–93].

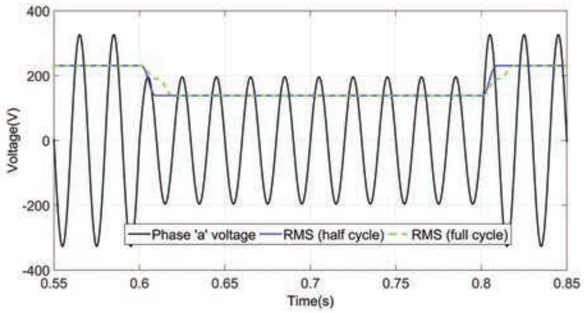
In traditional detection techniques such as RMS detection method or peak detection method, the variation in the RMS or peak voltage is monitored closely to detect the sag events. Figures 11(a) and 11(b) shows the variation in the peak and RMS values of phase ‘a’ voltage, respectively, during a SLGF event with sag depth of 40% occurring from t=0.6s to t=0.8s in a three phase, 400V, 50 Hz supply. The half cycle RMS and full cycle RMS values are marked in blue and green (dashed line), respectively in Figure 11(b).

A flag signal is generated corresponding to any variation in the RMS or peak value of the utility voltage from the set reference and this indicates the sag event as shown in Figure 11(c). Table 7 gives a comparison between the detection time, sag duration and difference from the actual sag duration of 10 cycles for the same SLGF simulated in MATLAB/SIMULINK software using peak and RMS detection methods.

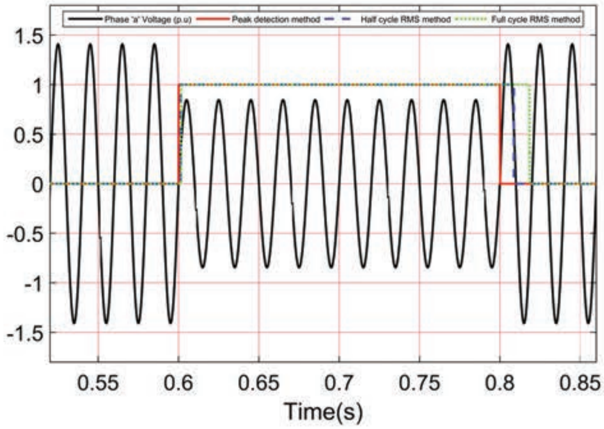
The conventional detection methods such as RMS detection method, peak voltage detection method and waveform envelope method are overruled by advanced detection methods [94–98]. A new detection method for single phase power systems is proposed by clubbing together the RMS detection method and instantaneous detection method [46]. The sliding mode control is incorporated in to the same combination of detection methods for an improved result [99]. The Discrete Wavelet Transform (DWT) detection method locates the sag start/stop points by examining the wavelet transform co-efficient. The only drawback is that one need to select the appropriate kennel function for accurate detection [95, 96]. The authors discuss the



(a) Peak detection method



(b) RMS detection method



(c) Detection flag for Peak detection method, Half cycle RMS method and Full cycle RMS method

Figure 11 Sag detection techniques.

Table 7 Simulation result

Sl.No	Detection Technique	Detection Time (ms)	Sag Duration (Cycles)	Difference from the Actual Sag Duration (ms)
1	Peak detection method	0.05	9.995	0.10
2	Half cycle RMS method	1.30	10.365	7.30
3	Full cycle RMS method	1.60	10.835	16.70

currently available methods to detect the sag and introduced the numerical matrix sag detection method [100]. The accuracy of this method increases with decreasing the sampling period and by taking into account more number of dominant harmonics. The neural network architecture is adopted for pattern recognition and is used along with fuzzy controller for power disturbance detection [101]. A robust detection method with least estimation error when compared to KF and FFT algorithms gives excellent results during frequency varying conditions and sags with and without phase jumps [102]. The two-point approach based period phase method of voltage sag/swell magnitude and phase jump detection introduced in [96] is easy to realize and is popularly used among three phase and single phase power lines. The missing voltage method compares the instantaneous voltage of the actual supply with the instantaneous voltage of the desired supply and gives the missing voltage that the DVR needs to inject. In Figure 12, the missing voltage is represented in blue dashed line for a sag depth of 40% from t=0.6s to t=0.8s. The detection of the PQ events using the missing voltage technique is improved with dead band and hysteresis band controllers [103, 104].

The Synchronous Rotating Frame (SRF) detection of sag/swell uses Clark's transformation and Park's transformation [68, 75, 100, 105–107]. The Park's transformation or *d-q* transform is suitable only for estimating balanced three phase sags. The multiple *d-q* transform is a modified method that is applicable to harmonics and unbalanced sag conditions [108]. The introduction of separate modules for extraction of positive and negative sequence components from the fundamental and harmonic waves ameliorated the multiple *d-q* transform [109]. For single phase and three phase system, an Improved SRF (ISRF) capable of detecting balanced and unbalanced sags is introduced in [110]. Table 8 summarises the available sag detection methods.

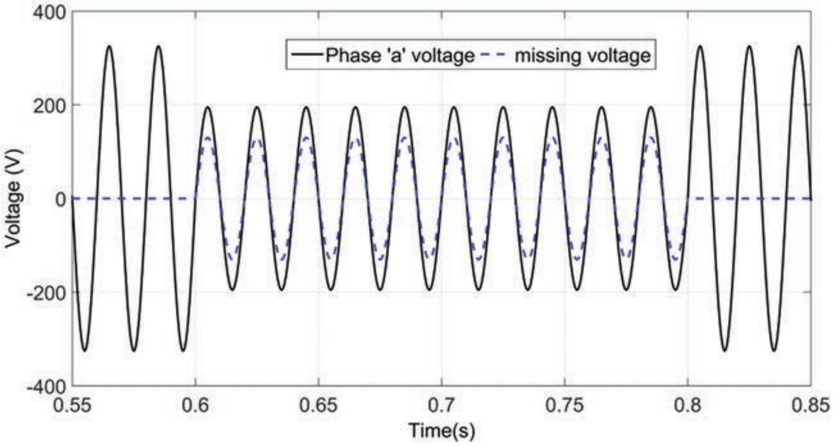


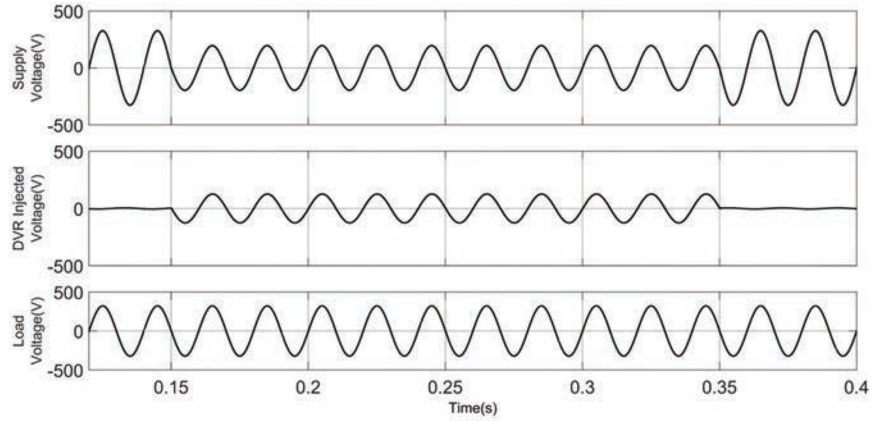
Figure 12 Missing voltage method.

The fast and accurate detection of voltage disturbance accelerates the generation of appropriate control signal. The phase angle and frequency are the two parameters which plays important role in the performance of the DVR controller. The variants of phase locked loops (PLL) such as hardware PLL, vector product PLL and software PLL (SPLL) are used to grab this information and detect the disturbances in the utility [111]. A sine wave in phase with the utility is generated using PLL and is compared with the utility or the load terminal voltage to find out the occurrence of disturbances [16, 112]. The reference signal is generated from either the supply side or load side and is called as feed forward control or feedback control, respectively [2, 3, 5, 6, 31]. The compensation of a single phase power system during a fault condition from t=0.15s to t=0.35s is simulated in MATLAB/SIMULINK software by using full bridge inverter connected constant *dc*-link type DVR topology and the results are given in Figure 13.

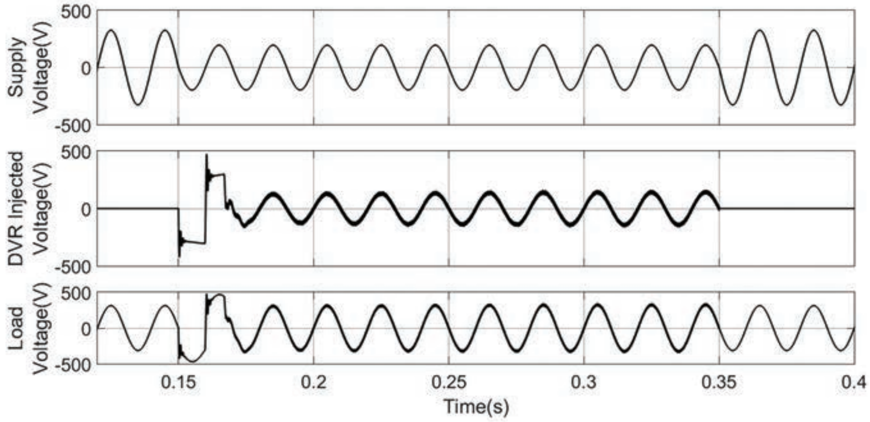
A quick restoration of the load voltage is seen in Figure 13(a) as it corresponds to the feed forward controlled DVR system. Robustness and simplicity are the key advantages of the feedforward voltage control in the DVR system [17]. However, there is no mechanism in the feed-forward control strategy to take the system output as a variable and to adjust the system performance to acquire the desired output. The feedback control takes into consideration the system output and guarantees a better performance compared to the feed-forward control scheme. The commonly used PI controller is employed for achieving the feedback control and the waveforms are given

Table 8 Summary of available sag detection methods

Sl.No	Detection Technique	Remarks
1	Root Mean Square (RMS) method [45, 92, 95, 97]	Simple and fast. Less memory required. A minimum delay of quarter cycle is present. Fails to distinguish between fundamental frequency and harmonic components. Phase jumps are not detected.
2	Peak value method [96, 102]	Noise signals are not considered. Delay of a quarter cycle is present to detect the sag event.
3	Wavelet method [93, 94]	Both time and frequency information about the signal are available. Selection of appropriate wavelet prototype is important.
4	Kalman Filtering (KF) method [6, 89–91]	Optimum estimation of sag possible. It exhibits high performance under linear systems. For non-linear power systems, improved KF algorithm is needed. With non-recursive algorithms, better filtering of higher frequency noises achieved compared to Fourier techniques.
5	Discrete Fourier Transform (DFT) method [82, 89]	Both sag detection and harmonic calculation possible. Stationary input signal is required. Number of samples per cycle should be an integer. Massive computations involved and there is delay in detection.
6	Fast Fourier Transform (FFT) method [89]	Faster than DFT method. Phase jumps are determined. Accuracy depends on window length. Stationary input signal is required. Number of samples per cycle should be an integer. Suitable for harmonic measurement.
7	Numerical Matrix method [98]	Consistent and fast detection of sag depth, phase jump, start and stop of the sag. Ready to use information about the disturbances are obtained.
8	Period Phase method [94]	Variation in the rms value of the voltage, phase jump, beginning and end of the sag are detected. Quick response. Applicable to both three phase and single phase power systems.
9	Missing Voltage method [101, 102]	Fast detection. Information about the point-on-wave of initiation and recovery of the sag are clearer than RMS method.
10	Synchronously Rotating Frame (SRF) method [67, 74, 98, 103–105]	Detection possible in very short time. Mostly applicable for three phase system. Not much recommended for single phase power system. Unsuitable for unbalanced sag detection.



(a) feed forward control



(b) feedback control

Figure 13 Voltage compensation by full bridge inverter based DVR.

in Figure 13(b). Table 9 gives the differences between feed forward and feedback control.

With the advent of software technology, SPLL is the new trend in the detection methods and its performance under different disturbance conditions is discussed in the literature [58, 111, 113]. A detection method based on SPLL and least square filters (LES) significantly improved the dynamic performance of the DVR [114]. In literature [115], a fundamental amplitude detection

Table 9 Comparison of feed forward and feedback control

Sl. No	Feed Forward Control	Feedback Control
1	Simple control	Complex compared to feed forward control
2	Stability of control system is achieved.	Less stable. Less steady state error.
3	Fast dynamic response	Slow response due to the time delay introduced by the controller

method without PLL and look up table is explained. The absence of filters and less computation time has made it popular in both single phase and three phase systems.

The inverter is the inevitable element in the DVR structure and its control is duly important. The inverter control, modulation scheme and generation of switching pulses for the DVR inverter are intertwined. The control strategy of the DVR inverter is mainly classified to linear (ramp comparison current regulator, synchronous PI regulator, state feedback controller, predictive and dead beat controller etc.) and non-linear (hard switching control, neural network, fuzzy logic etc).

The ease of implementation is a factor concerning the selection of control technique in the DVR. An array of controllers employed in the inverter control scheme such as PI controller, hysteresis voltage controller, dead beat controller, multi loop control, state feedback controller, fuzzy logic controller, current instantaneous feedback controller, neural controller and adaptive controller are discussed in the literature [30, 37, 47, 48, 52, 61, 83, 87, 116–119]. The open loop control and linear quadratic regulator based control for four leg VSC is presented in literature [120, 121]. In the DVR system, a state feedback controller and repetitive controller are implemented together to improve its performance [122]. The double band hysteresis control devised for the DVR can eliminate the chattering in the inverters [123]. The simulation results of a PV based DVR with hysteresis based control strategy is given in paper [124].

The predictive voltage controller proposes a new method of non-linear control unit [113]. The inverter control strategies with active and passive damping of LC oscillations due to filter components are required in the DVR systems. The active damping of the output filter gives reduction in frequency response of the filter. The control with passive damping of the output filter requires additional information about the filter inductor current and the load current [50]. The resonant damping method of the LC filter oscillations is proposed in [125]. The genetic algorithm optimized PI controllers are used in the PEMFC supported DVR for compensation [105, 126]. An indirect fuzzy controller which is tuned dynamically for a PV based DVR system is presented in [127]. An emotional controller similar to human brain mitigates the voltage sag condition and improves the THD of the load voltage [128]. The constant switching frequency band controller reported in [129] acquire the benefits such as excellent dynamic response, robustness, zero magnitude/ phase errors and ease of implementation. A DVR implemented with time-varying and constant switching frequency based sliding mode control is described in [59]. The use of adaptive reaching law in the sliding mode control of DVR gives negligible chattering and reduces the time to reach the sliding regime [130]. The passivity based control scheme in DVR gained recognition because of its simple tuning, no overshoot settling and fast response [131].

The inclusion of both feedback and feed forward path in the control loop is called as two degree of freedom (2 DOF) control. The cascaded HVDVR employed this scheme with posicast and P+resonant compensators and ensured the fast dynamic tracking of disturbances with improved reliability and damping of transients [62]. The DVR compensation utilising the 2 DOF resonant control scheme is described in [132]. The DVR voltage regulation accomplished using embedded two step posicast controller and multiloop P+resonant and H infinity controllers are reported in the literature [125, 133]. The multiloop state feedback based direct flux linkage control strategy reported in [134] takes the challenge of eliminating the transformer saturation.

During the upstream disturbances, the DVR preserves the load profile with the series injection of the required compensation voltage by the appropriate control of the inverter. The proper operation of the DVR inverter depends on the DVR reference voltage generation and modulation technique. Once the reference voltage is generated, the inverter switches are modulated to obtain the desired voltage [19]. The Sinusoidal Pulse Width Modulation (SPWM) is the most commonly used modulation scheme in the multilevel inverter based DVR control [135]. Microprocessor and DSP based Space Vector PWM (SVPWM) is common in the DVR circuits. A control scheme analogous to that of a three phase single pole double throw vector-switching converter is used in [68]. Other PWM techniques such as power frequency modulation, three dimensional SVPWM, phase shifted PWM, carrier based sub oscillation PWM, hysteresis current PWM are detailed in the literature [2, 8, 14, 58, 60–62, 136]. The quasi square modulation and high frequency PWM with higher and lower value of *dc*-links are considered for multilevel inverters [62]. Fundamental frequency control modulation explained in [63] have the merits of low switching losses, low switching stress and EMI. The one cycle control which exhibits better steady and dynamic state operation compared to SPWM is employed in the DVR [137]. The ease of implementation with uncomplicated steps is the highlight of one cycle control when used in practical DVR application.

High performance, improved robustness, good steady and transient characteristics are the desirable features of the DVR control [133]. Extensive research can be performed in this area to develop a DVR control with all these attributes.

The controlled rectifiers are an advanced alternative for supplying the *dc* power from the other healthy phases of the supply to the inverter in a particular phase [121]. The load-side connected DVR with a high frequency isolated *dc-dc* converter integrates the advantages of high frequency transformer and shunt connected converter based DVR [138]. The controlled rectifier connected to supply-side or load-side of the DVR indulges in bringing significant savings in the cost by reducing the energy storage capacity. Wang Jing et al. presented a detailed discussion of various rectifier control strategies in [139] and opened the possibility of rectifier connected DVR topologies.

The series connection of the inverters makes the protection of the DVR complicated when compared to the shunt connected inverters. The traditional protection scheme of the DVR consists of varistors and other protection devices in parallel with the secondary of the transformer. Iurie et al. proposed a new scheme of protection without additional switchgears [140]. The integrated control or protection method and high impedance active filter based protection are also presented in the literature [141].

6 Design Specifications of the DVR

The general requirements of the DVR are quick and proper response to faults, insensitivity to supply harmonics and blocking capability of supply harmonics [57]. However, designing the DVR to accomplish the general requirements faces two main constraints in terms of injected active power and injected voltage [142]. The optimum design of DVR is of size 2.0 p.u for protecting all the sensitive loads from any expected disturbances, however it breaks the economics of designing a cost-effective DVR [32].

The voltage rating of the DVR depends on the maximum injection voltage and the nominal line voltage. In most of the DVR design, the maximum sag depth is considered to be 50% of the utility voltage. The maximum compensation time is also interrelated to the energy available in the DVR circuit. The energy storage elements such as battery, SMES, fuel cell etc are the sources of real energy in the DVR. One of the cost raising factors of the DVR is the expensive *dc*-link energy storage devices. The selection of energy storage capacity depends on the compensation scheme. The capacity of energy storage determines the ride through capability of both isolated and non-isolated DVRs. As the *dc*-link voltage decreases with voltage compensation during PQ events, modulation index is continuously varied to maintain the load profile constant. Since the THD of the load side goes up with over modulation, usual practice is to limit the modulation index to 1 [9, 11, 84].

The compactness and the cost of the DVR are closely related to the rating of the inverter. The main constraints while choosing the inverter type is the range of output voltage, harmonic content in the output, the switch count and the complexity of the control method. The current rating of the DVR is the same as the load current rating. The factors concerning the voltage rating of the DVR are the maximum injection voltage of the DVR and the turns ratio of the injection transformer. Generally, the inverter selection should satisfy the voltage and current rating of the DVR.

The power semiconductor switches present in the inverter makes the DVR non-linear in nature [6]. The commonly used inverter switches are IGBT, cryoMOSFET, GTO and IGCT. While IGBTs find small and medium power DVR applications, cryoMOSFET's are recommended due to their low on-state resistance, zero on-state threshold voltage (reducing conduction loss), high current carrying capability and fast switching speed [11, 31]. The high surge current capability of IGCT helps to remove the bypass switch from the DVR topology [43]. The conduction losses during the stand-by mode is also minimized by IGCTs [31, 35, 36] and it offers 30% less losses compared to GTO [28]. Taking in to consideration these attributes, IGCTs are the good choice of solid state switches for the DVR inverter applications [31].

High switching frequency is an economical consideration in the design of DVR [3]. The switching frequency in a low range of 3–5 kHz reported in the literature fails to address the transient spikes and oscillations in the utility voltage [43]. The recommended practices in the modulation scheme of the inverter are a) the frequency modulation index m_f should be an odd number to reduce the harmonics in the output voltage of the VSI and b) the amplitude modulation index m_a should be equal to or less than 1 [84]. If the supply and load are ungrounded, the injection of zero sequence component of load voltage is not required. The inverter rating is reduced due to the elimination of zero sequence component of load voltage and results in cost reduction [143].

The placement of the LC filter circuits on the inverter side or the line side of the injection transformer classifies the filtering scheme of the DVR. The information about the harmonic content of the voltage waveform during disturbances can be taken as a design consideration for setting the cut-off frequency of the output filter and the switching frequency of the converter [50]. The switching frequency should be large enough to get pure sinusoidal waveform and it helps to reduce the size of the filter components [3]. The resonant frequency, the filter capacitor value and the order of harmonics determines the value of filter inductor. The leakage reactance of the transformer secondary can add to the filter inductance in line side filter. In line side filtering, the critical frequency should be chosen in such a way that it is much greater than two times the fundamental frequency of the utility voltage and far less than the frequency to be filtered. The ideal selection is that filter reactance is reduced as possible and filter capacitance is increased to make the inverter rating high [14, 50].

The location of the filter makes impact on the rating of the series injection transformer. The secondary of the injection transformer carries the same current as the load. Consequently, the full load current decides the current rating of the injection transformer. The effect of higher order harmonics should be considered while designing current carrying capability of the injection transformer. The inverter side connected filter removes the higher order harmonics from the VSI output and leaves less impact on the injection transformer. In line filtering, higher order harmonics from the inverter penetrate through the transformer and the effect cannot be neglected. The type of the filtering scheme used in the DVR decides whether to consider only the fundamental or both the fundamental and harmonics in the current while designing the primary side current rating of the injection transformer. The voltage rating and the turns ratio of the transformer depends on the output voltage range of the VSI and the expected injection level into the power system. Apart from the aforementioned specifications of the transformer, a safety margin is included in both the voltage and current rating. The flux rating of the series injection transformer is selected twice as that of the steady state value at maximum injected voltage to avoid the saturation problem [11].

The choice of injection transformer depends on the type of connection of distribution feeder step down transformer. There is no need to consider the zero sequence component compensation if the step down transformer in the distribution feeder is of delta – star connection and results in cost reduction [2, 4, 5].

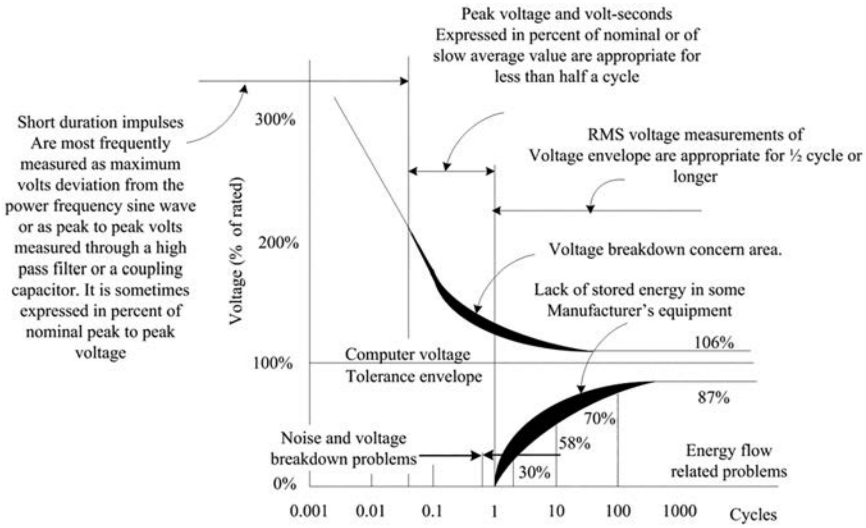


Figure 14 CBEMA curve.

7 Power Quality Standards Related to the DVR

The ride through capability of the sag compensators are devised by certain industrial standards such as IEEE 519-1992, IEEE 1159-1995, ITI (CBEMA) curve (shown in Figure 14), SEMI-F47, IEC 61000-4-11 and IEC 61000-4-34 [43, 104]. The measure of power quality in MV and LV distribution system under normal operating conditions is given by the standards IEC (1000-2-2/4) and EN 50160 [13]. The indices such as THD, Detroit Edison Sag Score (SS), Voltage Sag Lost Energy Index (VSLEI) and Phase unbalance rate (PVUR) measure the quality of the system after compensation [144].

8 Challenges Faced by the DVR

The sag depth and the sag duration determine the capacity of the energy storage. If the sag persists for long time, the capacity of the energy storage decreases and will affect the compensation property of the DVR. The significance of type of the load connected and nature of the sag is more on the energy storage. If the load is of poor power factor, compensation can be carried out with smaller energy storage and with less real power, thus extending the DVR operating range. The thyristor switched inductors are intentionally paralleled with the load for reducing the power factor for this compensation advantage [145]. A new DVR concept is proposed which can improve the displacement factor of the load under normal condition [146].

The load-side connected DVR continues to work irrespective of the long or short duration of the voltage sag whereas supply-side connected DVR fails if sag persists for longer duration. The load-side connected DVR takes command over supply-side connected DVR because of zero voltage drop across the shunt converter [53]. The active converters used as shunt converters prevent the dc-link voltage rise during swell events. The research scope is open in investigating the advantage of using dual converters for discharging the capacitor that is overcharged during voltage swells [121].

The *ac*-link approach in the DVR system lacks the ride through capability because of no energy storage. The energy extraction from other healthy phases for compensation of voltage in the faulty phase results in drawing additional current from the mains same as in supply connected DVR [68]. This can be taken up as a problem to be addressed in the DVR studies.

The efficiency of the DVR circuit is limited by the losses in the VSI, filter and the transformer. There is a trade-off between multilevel inverters and inverters with reduced switch count as the former partially or completely eliminates the need for filters and the latter gives less switching losses. The buck nature of the VSI output voltage demands a boost converter between the energy storage and the inverter and thus raises the issues of additional switch count, control and complexity [37, 147].

The proper heat sinking of the inverter switches is essential for the durable working of the DVR [37]. The *dc*-link capacitor balancing problem, the differential and common mode electromagnetic interference in the inverters are the other technical issues that need to be addressed with great relevance [58].

The transient spikes and the oscillations in the utility voltage lead to the mis-triggering of inverter switches and mal-operation of the DVR [43]. The non-linear characteristic of the inverter switch makes the inverter output distorted and causes the presence of harmonics in the output. The basic filtering schemes of either inverter side filtering or line side filtering is used to improve the quality of the DVR output. Due to the change in DVR reference, LC oscillations are experienced during the beginning and end of the sag events. The attenuation of these LC oscillations present due to the filter components is an important task in the DVR technology. The active or passive damping techniques are essential in the DVR systems to attenuate the LC oscillations [125]. While designing, measures should be taken to minimize the effect of filter components on the inverter rating and DVR. The voltage drop in the passive filtering components is also a drawback.

The injection transformers with low impedance are to be chosen in order to minimize the transformer voltage drop. The distorted compensation voltage, untimely triggering of the over current protection system due to inrush currents and the need for complex control are some problems related with the injection transformer. A proper control scheme should be designed for regulating the magnetic flux linkage in the injection transformer [134]. The transient period problem at the beginning of any power quality disturbance doubles the flux rating of the transformer and increases the total cost of the DVR. One of the solutions to mitigate this problem is by commencing the voltage injection at either voltage maxima or minima [15]. However, this affects the ride through time of the DVR. In that case, transformerless topology is the suggested solution to deprive the transient switch on problems seen by the conventional DVR transformers. The replacement of the copper and iron in the transformer with silicon operating at high frequency is one technical development reported in the DVR literature related to the series injection transformer [11, 148]. Flux unbalance in the series injection transformer of the DVR is another matter of concern. The prevention of flux unbalance in the single three limb injection transformer can depreciate the capital cost of the DVR and the service and maintenance of only one transformer is required in this case. The introduction of high frequency transformers in to the DVR topology is a feasible solution to make DVR more compact [78–80].

Even though a trade off between the cost and performance characteristics exists; the losses, the glitches and the inaccuracy related to the working of the DVR should be addressed properly in the DVR design. The compensation techniques should be chosen with great care after understanding the sensitivity of the connected load in the power line to the disturbances. The response given by each compensation method varies for deep and shallow sags, respectively. Firstly, the compensation method is chosen as the real power injection, injected voltage, transformer rating and inverter rating are dependent on the method. Once the restoration method is fixed, the design and selection of the DVR elements follows.

The reliability of the DVR is determined by analysing how fast the DVR moves from stand-by mode to active mode [4]. The false triggering and abnormal conditions due to heavy downstream loads and fault currents are unadvisable in the DVR system. The disturbance filters make the DVR immune to false switching caused by transient voltage spikes [43]. The forced commutation of the bypass thyristor switches improves the dynamic operation of the DVR [50]. The proper protection mechanism and smooth change-over from stand-by mode to active mode and vice versa are anticipated in a DVR operation and is a subject of intense study in the DVR domain.

The feed forward control strategy exhibits system stability compared to the feedback control of the DVR. The inadequate stability margin and the voltage oscillations caused by low output voltage damping adversely affects the sensitive load. The voltage oscillations are also accompanied by current surges in the *dc*-link capacitor. The voltage drop in the series injection transformer and the filter also prevents the exact compensation of the load voltage profile [149]. These factors make the feedback control scheme a better choice. Several improved control strategies are reported in the literature as presented in Section 5.

9 Conclusions

A detailed review of the DVR has been addressed in this paper for gaining a clear understanding about the DVR and its operation. The simulation results are included to validate the findings and the performance of the DVR operation. The fundamentals of the DVR, its principle and basic elements along with the major classifications of the DVR, different inverter configurations and filtering schemes are described in detail.

A comprehensive discussion is made on the DVR topologies, compensation technique, sag detection method and feedback/feed forward control. From the classical sag detection methods –a) the peak voltage sag detection b) half cycle rms sag detection and c) full cycle rms sag detection methods are compared and results are validated using MATLAB/SIMULINK software. The feedback method and feed forward methods are discussed in detail and simulation results are also provided. The design specifications for a cost-effective DVR and the performance indices and standards for custom power conditioning are discussed in Sections 6 and 7, respectively. This paper tends to provide details on the challenges faced by the DVR. The challenges faced by the DVR and some of its solutions from the published literature are also discussed. The shortcomings reported in Section 8 can be investigated by the researchers for proposing novel DVRs with the best performance in all aspects. This paper intends to provide the prospective researchers and engineers with an insight into the DVR discipline and inculcates the awareness and need of designing a better DVR system.

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