International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 12, Issue 3 [March. 2023] PP: 26-34

An Overview of Dynamic Voltage Restorer for Power Quality Enhancement

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Abstract—*Controlled power quality is one of the important needs in any power driven industry for resources utilization. However severe problems in power quality have been found out such as voltage sag, voltage dips, swells, harmonics etc. Out of these sags and swells are predominantly recognized and have severe impact on the electrical devices and therefore those severities should be compensated in prior to ensure any mal-functions. To find such issues customizable power devices are to be used like unified power-quality conditioner (UPQC) and dynamic voltage restorer (DVR). The DVR is a one of such devices used for voltage sag and swell compensation with the control of both active and reactive power. A list of literatures reported in past years on different forms of DVR and different control techniques used in it. In this paper a detailed review on DVR has been presented with different circuit topologies and control techniques to settle these power quality issues. This review paper will help in better selection of control for better performance of DVR.*

Index Terms—*DVR, Power quality, Voltage sag, Compensation Technique.*

Date of Submission: 01-03-2023 Date of acceptance: 12-03-2023

I.INTRODUCTION

Power quality is most important in all the areas where electricity is part. Power quality can be influenced by important factor like quality service. Power quality issues were classified by five major events such as sags, swells, transients, interruptions and harmonics. These problems may cause degradation in services which can cost economic losses to both utility and consumers. Deregulating of power system has made power quality as considering parameter to achieve a higher price per kilowatt, to increase the revenue and share [1]. The power quality issues emanate from various events ranging from switching events at the end user facility or faults on transmission lines [2]. The more usage ofvoltage deviation sensitiveequipment has made industrial applications more susceptible to voltage sags and swells. Among these the sags is considered to be vital issue. Voltage sags can cause mal-functioning of equipment, resulting in loss of production. There are two general approaches to mitigate power quality disturbances. One is to ensure that the process equipment is less responsive to disturbances, allowing it to ride-through the disturbances. The other is customizable power device installation to reduce or neutralize the disturbances at the end user side[3]. The DVR is one of the most effective devices, which is used in distribution systems. The DVR is used to inject voltage in series with distribution feeder in order to compensate for voltage sag/swell [4-5]. To restore the load voltage, active and/or reactive power should be injected into the distribution feeder. This paper will give an idea on various power quality issues and to introduce DVR as customizable power device for mitigation of such issues [6].

II. POWER QUALITY

Any power problem manifested in voltage, current orfrequency deviations that result in failure or mal-operation of customer equipment[2].

a. Power quality issues

There are wide ranges of power quality issues; eachmay have a various causes, different effects and different solutions that can be used to improve the power quality and equipment performance. Table 1 show different power quality issues, its causes and effects[1-2], [4-6], [8-12].

POWER QUALITY ISSUES	CAUSES	EFFECTS
TRANSIENT: "Transient is a sudden, non power frequency change in steady state condition of voltage, current or both".	Lightning, Turning major equipment on or off, back to back capacitor energization.	Tripping, Processing error, Data loss, and Hardware reboot required, Component failure.
VOLTAGE SAG: "A sag is decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min".	Starting of large Motors, Energization of heavy loads, Incorrect VAR compensation. Faults on network.	Dim lights, Data error, Shrinking display screens, Equipment shutdown, Memory loss.
VOLTAGE SWELL: "A swell is an increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min".	Energizing a large capacitor bank, Switching off a large load, incorrect VAR compensation	Bright lights, Data error, Racing or blinking of digital clock.
VOLTAGE INTERRUPTION: "An interruption is when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 min".	Faults (Short circuit), Equipment failures, insulator failure, lightning, Control malfunctions.	Equipment trips off, Programming is lost, Computer shut down, Disk drive crashes.
HARMONICS: "Harmonics are integral multiples of some fundamental frequency that, when added together, results in a distorted waveform".	IT equipment, Fluorescent lighting and any non linear load such as variable frequency drives, Electro-Magnetic Interference from appliances, SMPS.	Line current increases, Higher losses Transformer and neutral conductor overheating, leading to reduced equipment life span, instruments malfunctioning.

b. Power Quality Improvement Alternative

There are variety of custom power devices available each with its own benefits and boundaries: Active Power Filters (APF), Battery Energy Storage Systems (BESS), Distribution Series Capacitors (DSC), Solid-State Transfer Switches (SSTS), Surge Arresters (SA), Super conducting Magnetic Energy Systems (SMES), Uninterruptible Power Supply (UPS), Static Electronic Tap Changers (SETC), Solid State Fault Current Limiter (SSFCL), Static VAR Compensator (SVC) and Thyristor Switched Capacitors (TSC), unified power-quality conditioner (UPQC), Distribution-STATCOM (DSTATCOM) and dynamic voltage restorer (DVR).

DVR is considered as an effective and efficient custom power device for mitigating the impact of voltage disturbances on sensitive load. In addition DVR also has functions such as reactive power compensation and harmonic compensation[4] [13-15].

c. Merit of DVR over other Custom Power Devices

- The SVC pre-dates the DVR, but the DVR is still favored because the SVC has no capability to control the active power flow.
- The DVR is small in size and price is less compared to DSTATCOM and other custom power devices.
- The DVR has more energy capacity compared to the UPS and SMES. DVR has many advantages over UPS, like less cost, higher capacity, low losses, injects only the missing part of the supply voltage and less maintenance.
- Economic comparisons of SSTS and DVR has been investigated and it reveals that SSTS provides better solution in terms of expected savings, cost of solution per KVA, annual operating cost and a higher

benefit/cost ratio if, a secondary undisturbed or independent feeder is present otherwise DVR is considered to be the most cost effective solution, because SSTS does not regulate voltage neither generate/absorb reactive powers. Its only purpose is to deactivate a faulty feeder in favor of a healthy one[16-22].

III. DYNAMIC VOLTAGE RESTORER (DVR)

The DVR (Dynamic Voltage Restorer) is a series connected solid state device that injects additional voltage into the system in order to regulate the load side voltage to the desired magnitude and waveform even when the source voltage is unbalanced or distorted as shown in figure 1[23-24].. This process involves injection of active/reactive power from DVR to distribution feeder [25]..

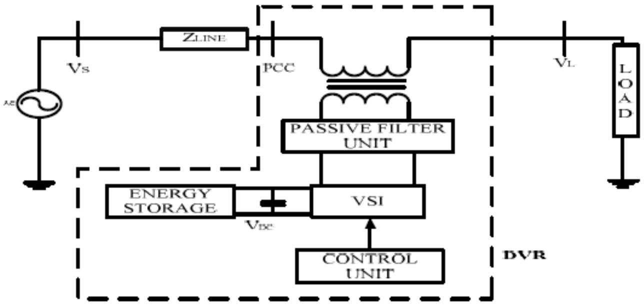


Figure 1 Basic structure of DVR

The general configuration of the DVR consists of power circuit and control circuit. Equivalent circuit as shown in Figure 2 and equation is as under:

$$V_{DVR} = V_L + Z_{TH} I_L + V_{TH}$$

Where V_L is desired load voltage magnitude, Z_{TH} is load impedance, I_L is load current and V_{TH} is system voltage(during faulty condition)

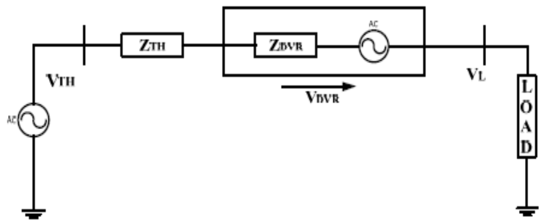


Figure 2 Equivalent circuit

The load current I_L is given by

$$I_L = \frac{P_L + jQ_L}{V_L}$$

When V_L is considered as a reference equation can be written as

$$V_{DVR} \angle\alpha = V_L \angle 0 + Z_{TH} I_L \angle(\beta - \theta) + V_{TH} \angle\delta$$

Where α is angle of V_{DVR} , β is angle of Z_{TH} ,δ is angle of V_{TH} and θ is load power angle

$$\theta = \tan^{-1}\frac{Q_L}{P_L}$$

The complex power injection of the DVR can be written as

$$S_{DVR} = V_{DVR}\, I_L{}^*$$

IV. LOCATION OF DVR

The objective is only to protect one consumer or a group of consumers with value added power. Applying a DVR in the Medium Voltage (MV) or Low Voltage (LV) distribution system would often be feasible. A key difference between an MV connection and an LV connection is the generation of zero sequence voltages and the flow of zero sequence currents.

Fig.1 represents the four-wire LV distribution system as shown in figure 4, the DVR must secure low impedance for zero sequence currents and the zero sequence must either flow in the power converter or in a delta winding of the injection transformer, and the impedance introduced due to the placing of the DVR seen at the LV side is comparatively high [26-27]..

Fig.2 indicates the three-wire MV distribution system, in most countries makes the use of simple DVR topology and therefore relatively easy control possible since there is no zero-sequence component. The DVR requires high isolation level for the injection transformers, and the short circuit level is also high in MV level[26-27].

Fig.3 represents the implementation at LV level, the MV implementation of DVR could achieve reduced costs per megavolt ampere .

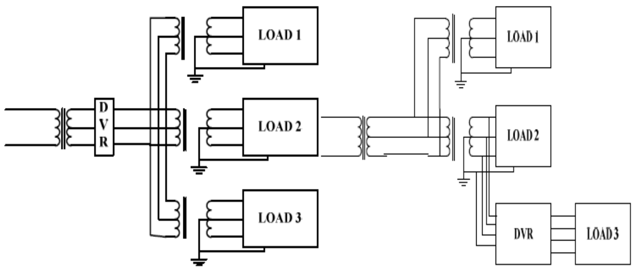


Figure 3 DVR located at the MV system

Figure 4 DVR located at the LV system

V. POWER CIRCUIT

In basic DVR topology, power circuit of DVR consists of an injection/booster transformer, a harmonic filter, an energy storage device, a voltage source inverter and a bypass switch.[26-27].

a.Injection / Booster transformer

The basic function of the injection transformer is to connect the DVR to the distribution network via the HV-windings and couples the injected compensating voltage generated by Voltage SourceInverter (VSI) to the incoming supply voltage after the detection of any voltage disturbance by the control circuit. The injection transformer increases the voltage supplied by the filtered VSI output to the desired level, in addition it serves the purpose of isolating the DVR circuit from the distribution network. For single phase DVR one single-phase transformer is connected and for a three phase DVR, three single-phase transformers or a single three phase transformer can be connected either in delta/open or star/open configuration. The winding configuration of the injection transformer is very important and it mainly depends on the upstream distribution transformer.

If delta-star transformer is used in distribution feeder, zero-sequence voltages will not circulate through the transformer when earth faults occur on the higher voltage level. Therefore, restoration of positive sequence and compensation of negative voltage are necessary [29]. Hence, a delta-open injection transformer can be used. The delta/open winding as shown in figure 5 maximizes the utilization of DC link voltage [30].

If an earthed star-star distribution circuit transformer is used, zero sequence voltages have to be compensated . For this case, a star-open injection transformer as shown in figure6 is used with injection of zero sequence voltages from the DVR [31].

The transformer ratio can be sized to have maximum utilization of the converter. The rating of the injection transformer is an key factor when deciding the DVR performance, since it limits the maximum compensation capability of the DVR, if the transformer is under rated the injected voltage may saturate the transformer and result in improper operation of the DVR, this problem can be solved by over rated transformer, however this increases the overall size and price of the DVR [33].

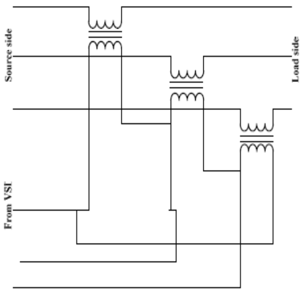


Figure 5 Delta open configuration

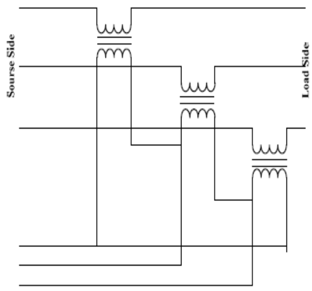


Figure 6 Star open Configuration

b. DC-link and Energy Storage Devices

The DC-link and energy storage device provides the real power requirement of DVR during compensation. The required energy can be taken from an auxiliary supply (topologies with energy storage) or grid itself (topologies with no energy storage) for compensation of load voltage during sag.

- The auxiliary supply system is used to raise the performance when the grid of DVR is weak. In this type, constant DC link voltage or variable DC link voltage topologies are used.
- Flywheels, batteries, superconducting magnetic energy storage (SMES) and super capacitors can be used in auxiliary supply system.
- In grid connected topology if grid is strong, the remaining voltage on supply side or load side is used to supply required power to the DVR, in this method AC/DC/AC converter is used.

If the topologies are compared by using some criterions like cost, system and control complexity, drawback and performance, they can be sequenced as[34-37]:

1- Load Side Connected Converter
2- Constant DC Link Voltage
3- Variable DC Link Voltage
4- Supply Side Connected Converter

c.Voltage Source Inverter (VSI)

VSI is a power electronics device consists of à storage devices, which can generate a sinusoidal voltage at any required frequency, magnitude and phase angle. The basic function of the VSI is to convert the dc voltage supplied by the energy storage device/dc-link into an ac voltage. The VSI used in the DVR can be two-level or multilevel.

- The two-level PWM inverter is the leading type of inverter used in DVR because implementation of the PWM in two-level inverter is simple and its cost is cheaper than multilevel inverter[28].
- The multilevel inverter has good harmonic characteristics and can operate in higher voltage levels. The most popular multilevel VSI topology is cascaded H-bridge (CHB) VSI. Apart from the CHB topologies, other multilevel inverters such as the neutral point clamped (NPC) multilevel inverter, and the flying capacitor multilevel inverter have also been used in the DVR structure[38-42]..
- In the DVR power circuit step up voltage injection transformer is used therefore a VSI with a low voltage rating is adequate[41].

d. Harmonic filter

The main purpose of the harmonic filter is to maintain the harmonics content generated by the VSI to the permissible level. The filter is placed to damp the switching harmonics generated by the PWM control of VSI. If the modulation index is set below one, the switching harmonics are normally centered around the switching frequency and multiples of the switching frequency . These filters can be inserted either in low voltage (inverter) side or in the high voltage (load) side of the injection transformer .

- The higher order harmonics are prevented from penetrating into transformer if filter is placed at inverter side, in this manner it reduce the voltage stress on the transformer. But there can be a phase shift and voltage drop in the output, which can disrupt the control strategy[45-46].

- By placing the filter at the load side phase shift cannot be take place but harmonics can penetrate into the high voltage side of the transformer, a higher rating transformer is required[47].

On the other hand the leakage reactance of the transformer can be used as a part of the filter, which will be supportive in tuning the filter.The DVR is a series connected device and one of the drawbacks with series connected devices is the difficulties to protect the device during short circuits and avoid interference with the existing protection equipment. During overload, faults and at time of maintenance an alternative path for the load current has to be ensured. Generally a crowbar by-pass switch is used which bypasses the inverter circuit[28].

VI. MODES OF OPERATION OF DVR

a. Protection mode

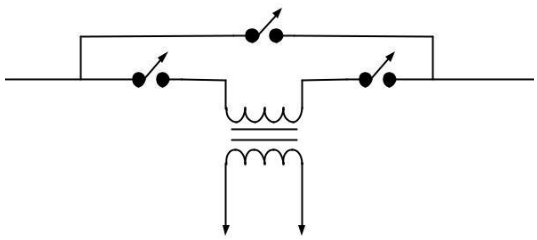
During fault, the DVR is protected from the high current in the load side due to short circuit on the load or large inrush currents the DVR will be isolated from the system by using bypass switches (S2 and S3 will open) and providing an alternative path for current (S1 will be closed) as shown[22].

b. Standby mode ($V_{DVR} = 0$)

During normal operation, the DVR may either go into short circuit operation which is called standby mode or inject small voltage to compensate the voltage drops on transformer reactance or losses. Generally standby mode is preferred [22], [48].

c. Injection/boost mode ($V_{DVR}>0$)

As soon as sag is detected the DVR goes into injection mode. AC voltage is injected in series with required magnitude, phase and wave shape for compensation [22].



VI. VOLTAGE INJECTION/COMPENSATION TECHNIQUES OF DVR

d. Pre-sag compensation method

In this method DVR keeps load voltage phasor unchanged in relation to that before the disturbance. This compensation strategy is recommended for the non linear load; i.e. sensitive to phase angle jump. It restores both the voltage sag and the phase jump. It avoids any circulating or transient current at load side. It needs active power during compensation [49-53].

e. In-phase compensation method

In this method DVR injects its voltage in phase with supply voltage. This compensation strategy is recommended for the linear load, where voltage magnitude is only required for compensation. Therefore amount of the injected voltage is minimal due to which the voltage rating of the dc link is minimal. It needs active power during compensation. It can’t restore the phase jump[49-53].

f. In-phase advanced/Energy optimization compensation method

In this method injected voltage advances the voltage, so the injected voltage phasor and line current are perpendicular. In case of pre-sag and In-phase the DVR is required to insert real power into the faulty line during the compensation period, the capacity of the energy storage device can become a limiting factor in the compensation. The real power is stored in the DC link and this is one of the most expensive parts of DVR. The basic idea of energy optimization method is to make the injected real power component zero by having the injection voltage phasor perpendicular to the load current phasor. In this method value of load current and voltage are fixed in the system so we can alter only the phase of sag voltage. It uses only reactive power during compensation, reactive power is generated electronically from within the voltage source inverter (VSI), hence higher rating of VSI required. Unfortunately, all the sags cannot be mitigated without real power; as a consequence this method is only suitable for a limited range of sags.

VIII. CONTROL CIRCUIT

In DVR the control circuit is used to derive the parameters such as magnitude, frequency, phase shift etc. Control of compensating device is implemented in 3 steps, detection of voltage sag/swell occasion in the system, comparison with reference value and generation of gate pulses to the VSI to generate the DVR output voltages which will compensate the voltage sag/swell.

a.Sag/Swell Detection Techniques

The accurate detection and classification of disturbances can help in taking effective countermeasure(s) to maintain adequate power quality. To detect the voltage sag, the starting point and the ending point of sag, depth of sag and phase shift, information are required. There are some detection techniques which are summarized below.

b.Fourier Transform (FT) method

To achieve the FT we use the orthogonal decomposition of power system signal. When we apply the FT to each supply phase, it is possible to get the magnitude and phase of each
of the frequency components of the supply waveform. The demerit of FT is that it takes one complete cycle to give the accurate information about the sag depth and its phase. The realization in real time control is possible[59-61], [65-66].

c.Phase Locked Loop (PLL) method

PLL is applied to each supply phase independently and is tuned to respond to phase jumps in the supply quickly. In this method it is required to freeze the pre-sag magnitude and phase. The PLL generates the voltage in same phase with the supply voltage. It takes time delay up to half cycle. The implementation in real time control system is more difficult[59-61].

d.Peak value detection method

Peak detection method is the very simplest method to observe the crest of the supply voltage. In this we find the point where the gradient of supply voltage phases is zero, and then we compare the supply value at that instant with a reference value and sense the sag. A controller could be set to distinguish if there is a deviation greater than a specified value. This method provides the information of sag depth, start and end time, although to extract phase shift information is difficult since a reference waveform is required. The drawback of this method is that it can take up to half a cycle for the sag depth information to become available[59-61].

e.Root mean square (RMS) method

It detects the start and end points of sag/swell. RMS value detection is an accurate way to detect the voltage sag or interruption, but it does not give phase angle shift information. It takes more time to calculate the RMS value [62-65].

f.Space Vector control

This method gives the both voltage magnitude and angle shift information. Three phase voltages V_a, V_b, V_c are transformed into a two dimension voltage V_d, V_q which in turn can be transformed into magnitude and phase angle. It is faster but requires complex controller. This can be easily realized in real time control system.[59-61], [65-66].

g.Wavelet Transform (WT) method

WT performs better with non-periodic and non-stationary signals. It detects change in the state of the supply phases quickly. In wavelet analysis procedure we design a wavelet prototype function, or the mother wavelet. The disadvantage of this method is selection of appropriate mother wavelet for each application, since the related filter bank coefficients are dependent on selected mother wavelet. There is also a delay associated with many mother wavelets as data either side of a time instant may be required in the convolution process. The implementation in real time control is difficult[59-61]

h.Control Strategies

The inverter control strategy includes of two types of control linear and non linear.

i.Linear Controller

The linear controllers used in DVR are feed forward, feedback and composite control. The comparison among these controllers is tabulated in Table 3.

j.Feed forward

The feed forward controller is the prime option for the DVR, because of its ease and fastness. The feed forward control technique does not sense the load voltage rather it calculates the injected voltage on the basis of the difference between the pre-sag and during-sag voltages. The drawback of this controller is the high steady state error [69-70].

k.Feed back

The feedback controller measures the load voltage and the difference between the voltage reference of the load and actual load voltage is injected. The feedback controller has the benefit of exact response, but it is complex and time-delayed[69-70].

l.Non –Linear Controller

The DVR is a non-linear device due to the power semiconductor switches in the inverter circuit. It appears that the nonlinear controller is more appropriate than the linear type since the DVR is actually a non-linear system.

m.Fuzzy Logic (FL)

FL controllers are an attractive alternative when precise mathematical formulations are not feasible. When it is used, the tracking error and transient overshoots of PWM can be significantly reduced. However, the properties of the FL controller are very susceptible to any change of fuzzy sets shapes and overlapping. Consequently, the designing and performance strongly depends on the knowledge and expertise of the designer [10-13].

n.Artificial Neural Network (ANN)

The ANN has adaptive and self-organizing capacity that gives improved precision by interpolation. It can institute the nonlinear relationship based on input and output, without the mathematical model [19].

o.Space Vector Pulse Width Modulation (SVPWM)

In SVPWM we adopt a voltage inverter space vector of the switch to get quasi-circular rotating magnetic field as an alternative of the original Sinusoidal PWM, so that improved performance of the switch over is achieved in low switching frequency conditions. The SVPWM method is an advanced, computation-intensive PWM method and probably the best among all the PWM techniques. SVPWM is used because of its easier realization and better dc bus utilization.

IX.CONCLUSION

In this paper a brief literature review is done on DVR configurations and its control strategies. By selecting any one of them we can provide solution to various power quality problems like voltage harmonics, voltage sag/swell compensation. To improve the performance of DVR, efforts needs to be made on energy savings, reduced parts and losses, minimum power injection, reduced rating, and selective harmonics mitigation.

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