DYNAMIC VOLTAGE RESTORER (DVR) FOR THE IMPROVEMENT OF POWER QUALITY: A TECHNICAL REVIEW

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Abstract

The issue of power quality is one of the most priority concerns in power system operation, in order to have an optimum utilization of the resources. Most of the power quality problems are encountered due to non-linear loads within the utilities and consumers jurisdictions. Power quality problems exist such as swells, sags, harmonic distortions, frequency variations etc. Among of these problems, the most frequent or predominantly and severe impact on electrical equipment and devices are sags and swells. To mitigate these power quality problems, customs devices are normally used such as Unified Power- Quality Conditioner (UPQC), distribution STATCOM (DSTATCOM) devices, and dynamic Voltage Restorer (DVR). In this work, DVR is considered to be the device used to mitigate voltage sags and swells with advantage of active/reactive power control. In this paper, also a comprehensive literature review on different configurations and control strategies of DVR are presented. This review paper, gives better control strategy and optimization in selecting DVR among custom devices for enhancing good simulation model.

KEYWORDS:
Power Quality, mitigation, Sags, Swells and Literature review.

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Introduction

The issue of power quality is very important in all modern environments where electricity is Involved. Power quality can be essentially influenced by important factor like quality service. Power quality problems were categorized by five major events; 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 electric power system market has made power quality a factor of consideration to achieve a higher price per kilowatt, to increase the revenue and share of the market (IEEE Standard. 1995). The power quality problems emanate from various events ranging from switching events at the end user facility or faults on transmission lines (Roger et al, 2012). The extensive use of equipment sensitive to voltage deviation has made industrial applications more susceptible to voltage sags and swells. Among these the sags and swells appeared as a top issue (Venmathi and Ramesh, 2012). Voltage sags can cause improper functioning and eventual tripping of industrial equipment, resulting in loss of production and hence profit (Benachaiba and Ferdi, 2009), (Omar and Rahim 2008). There are two general approaches to mitigate power quality disturbances. One approach is to ensure that the process equipment is less responsive to disturbances, allowing it to ride-through the disturbances (Bollenl, 2000). The other approach is to install a custom power device to suppress or neutralize the disturbances at the customer end. The DVR is one of most effective dynamic and efficient custom power device, which is used in power distribution systems (Hingorari, 1995). The DVR is a power electronic device used to inject voltage in series with distribution feeder in order to compensate for voltage sag/swell. To restore the load voltage, active and/or reactive power should be injected into the distribution feeder (Pakharia and Gupta, 2012).. This paper provides an insight on various power quality problems and introduce custom power device DVR for mitigation of such problems.

Power Quality Problem?

Any power problem manifested in voltage, current or frequency deviations that result in failure or Mal-operation of customer equipment is known as power quality problem. (Roger et al, 2012).

Causes and Effects of Power Quality

The subject of power quality is one of cause and effect. Power quality is the cause, and the ability of the electrical equipment to function in the power quality environment is the effect. The ability of the equipment to perform in the installed environment is an indicator of its immunity. Figures 1. And 2. Show power quality and equipment immunity in two forms. If the equipment immunity contour is within the power quality boundary, as shown in Figure 1. then problems can be expected. If the equipment immunity contour is outside the power quality boundary, then the equipment should function satisfactorily. The objective of any power quality study or solution is to ensure that the immunity contour is outside the boundaries of the power quality contour. Two methods for solving a power quality problem are to either make the power quality contour smaller so that it falls within the immunity contour or make the immunity contour larger than the power quality contour.

In many cases, the power quality and immunity contours are not two-dimensional and may be more accurately represented three-dimensionally. While the ultimate goal is to fit the power quality mass inside the immunity mass, the process is complicated because, in some instances, the various power quality factors making up the mass are interdependent. Changing the limits of one power quality factor can result in another factor falling outside the boundaries of the immunity mass. This concept is fundamental to solving power quality problems. In many cases, solving a problem involves applying multiple solutions, each of which by itself may not be the cure. A two-dimensional immunity graph that applies to an electric motor as the sensitivity of the equipment increases, so does the complexity of the immunity contour.

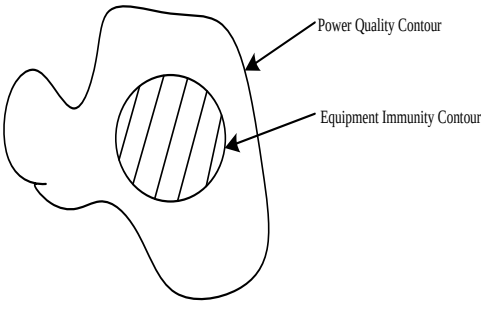


Fig. 1. Criteria for equipment susceptibility

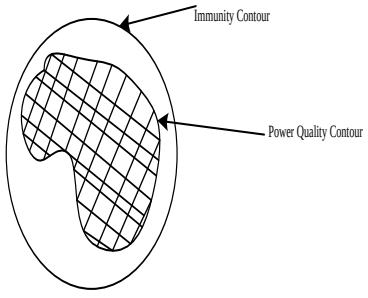


Fig. 2. Criteria for equipment susceptibility

Power Quality Improvement Alternative

There are varieties 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) (Stones and Collinson et al, 2001).. 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 (Benachaiba and Ferdi, 2009), (Ghosh and Ledwich 2002), (Pal et al, 2008), (Chang et al, 2000).

Dynamic Voltage Restorer

Among the several types of power quality problems, (sags, swells and harmonics) Dynamic Voltage Restorer is recognized as the most effective and efficient modern custom power device used in power distribution networks. (Benachaiba and Ferdi, 2009). A Dynamic Voltage Restorer (DVR) is a solid state inverter based on injection of voltage in series with a power distributed system. The DC side of DVR is connected to an energy source or an energy storage device, while its AC side is connected to the distribution feeder by a three-phase interfacing injection transformer.

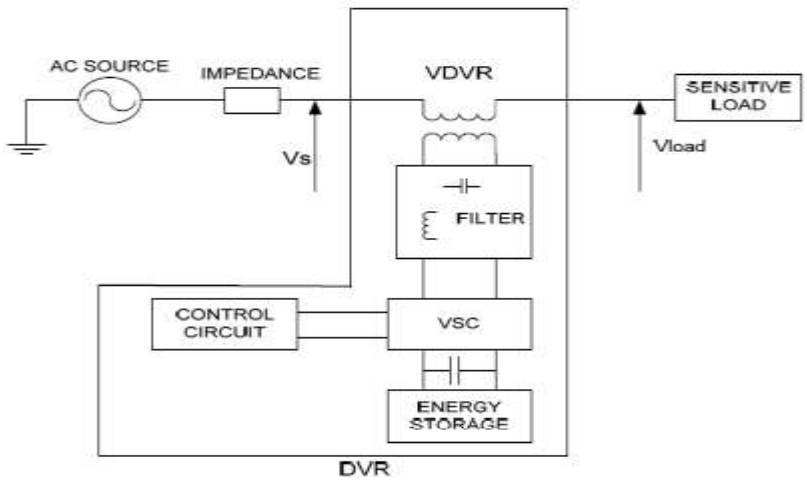


Fig 3. Conventional Circuit Configuration of DVR (Bollen,2003).

Basic Principle of DVR Operation

A DVR is a solid state power electronics switching device consisting of either GTO, MOSFET or IGBT, a capacitor depository as a power storage device and inoculation transformer. (Ahn et al, 2003).. It is connected in series between a distribution and a load.

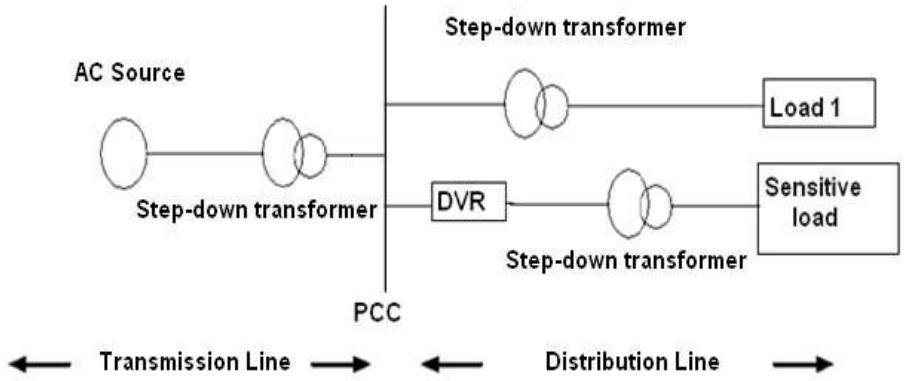


Fig 4 Location of Dynamic Voltage Restorer (Reid, 2009).

The DVR is capable to generate or absorb reactive power but the active power injection of the device must be provided by an external energy storage system. The response time of DVR is very short and is limited by the power electronics devices.

A DC to AC inverter regulates this voltage by sinusoidal PWM technique. Although normal operating condition, the DVR inject only a small voltage to compensate for the voltage drop of the injection transformer and device losses. However, when voltage sag occurs in the distribution system the DVR control system calculates and synthesizes the voltage required to preserved output voltage to the load by injecting a controlled voltage with a certain magnitude and phase angle into the dissertation system to the critical load. (Tiwari and Gupta, 2010).

Basic Configuration of DVR

The general arrangement of the DVR is composition of injection/Booster transformer, Harmonic filter, storage Devices, voltage source converter (VSC) DC charging circuit, control and protection system(Chung et al, 2007).

Voltage Injection Methods of DVR

There are four method of DVR voltage injection.

i. Pre-sag/dip compensation method (PDC)

ii. In-phase compensation method (IPC)

iii. In-phase Advanced compensation method (IPAC)
iv. Voltage Tolerance method with Energy injection

Working of Dynamic Voltage Restorer

The working of dynamic voltage restorer it does not depends on fault type and any event that happened in the system. There are three different modes i.e protection mode, standby mode and Boost mode of operation of dynamic voltage Restorer.

1. Protection mode: if the current present on the load side exceeds a reasonable value because of short circuit on the burden and huge inrush current, the DVR could be separated from the system by utilizing the bypass switches and supplying a different path for current(El-mofty and Youssef, 2011).
2. Standby mode (voltage injected by DVR is zero): In this mode of operation there is no switch of semi-conductors occurs and through the converter the injection transformers low voltage winding is shorted i.e in this mode voltage injected by DVR is zero or inject small voltage to compensate voltage drop on transformer radiance or losses.
3. Injection/Boost mode: DVR injects a missing voltage through the injection transformer due to the recognition of a trouble in the input voltage

Compensation Strategies

There are three strategies used in sag compensation

(i) Pre-sag compensation: The DVR compensate the missing voltage between before and after sag voltages to the system, the DVR must injects for both magnitude and phase, it is the best explanation for getting the same load voltage as the pre-fault voltage and is best suited for susceptible loads.

$$V_{dvr} = V_{prefault} - V_{sag} \quad (1)$$

(ii) In- phase compensation method: In this strategy, the DVR is planned to balance the voltage magnitude just. The compensation voltage is in phase with input voltage. In this strategy the steady magnitude of load side voltage is satisfied.

(iii) Minimum energy injection: In this strategy, the load can ignore a little dip in voltage and a little jump in phase angle. In this case, the load

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operation characteristics are not disturbed. By injecting a little energy, control of phase and magnitude is done

Advantages of DVR

- It has capacity to manage the active power flow
- It has less cost compared with other
- It requires less maintenance
- It has high energy capacity
- DVR is more minor in size and expenses less compared with the DSTATCOM
- DVR comprises voltage dip, voltage swells
- DVR can use for factor correction
- DVR can eliminates Harmonics

Mathematical Modeling of DVR

The electrical circuit model to indicate voltage injection by a DVR system is shown in Fig-3

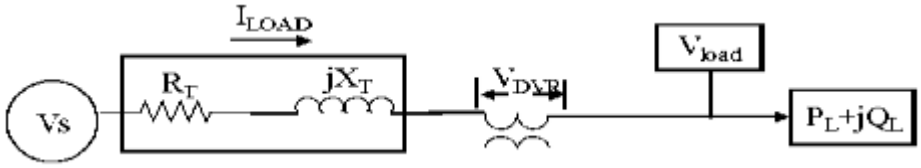


Fig. 5 Electrical Circuit Model for DVR Voltage Injection

The equation for the injected voltage of DVR can be written as

$$V_{DVR} + V_{sf} = V_{load} + Z_T I_{load} \quad (2)$$

$$V_{DVR} = V_{load} + Z_T I_{load} - V_{sf} \quad (3)$$

Where

$$Z_T = R_T + j_{XT} \quad (4)$$

Where, V_{DVR} is voltage supply by the DVR, V_{Load} is the desired load voltage magnitude, Z_T is the load impedance, I_{Load} is the load current, $V_{sf}$is the system voltage during fault condition.

Calculation for the load side current could be done as

$$V_{load} I_{load} = P_L + j_{QL} \quad (5)$$

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$$I_{Load} = \left[\frac{\left(P_L + j^* Q_L\right)}{V_{Load}} \right] \quad (6)$$

Where load voltage consider as a reference, P_L is load active power, and Q_L is load reactive power.

Then DVR voltage can be written as

$$V_{DVR} < \alpha = V_L < 0^0 + Z_I I_{Load} < \left(\beta - \theta\right) - V_{sf} < \delta \quad (7)$$

Where α, β and δ are the angles of V_{DVR}, Z_T, and V_{sf} respectively.

$$\theta = \tan^{-1}\left(\frac{\theta_L}{P_L}\right) \quad (8)$$

Where Θ is load power factor angle.

The obvious electrical power inoculation from DVR is given with

$$S = V_{DVR} * I_L \quad (9)$$

Comparison between DVR and Others

i. DVR has ability to control active power flow when compare with SVC
ii. DVR is less costly and requires low maintenance as compared to UPS
iii. DVR has higher energy capacity and lower cost as compared to SME
iv. DVR is smaller in size and cost less when compared to the DSTATCOM

DVR can control Harmonics, power factor correction when compared to others.

Type of Control Strategies of DVR

There are many techniques to implement and control operation of the DVR for power quality improvement in the distribution system. Most of the identified DVR systems are equipped with a control system that is configured to mitigate voltage sags/swells. Other DVR application includes harmonic control, power flow control, reactive power compensation as well as limited responses to power quality problems. The main aim of this control scheme is to maintain constant voltage magnitude at the point where a sensitive load is connected under system disturbances (Nielsen et al, 2004). The control system only measures the r.m.s. voltage at the load point i.e., no reactive power measurements are required. The control of DVR is very important and involves detection of voltage sags by the required algorithms which can work in real time. Inverter is an important

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component of DVR in which the performance of the DVR is directly affected to the control strategy of the inverter. The inverter has two types of control namely:

a. Linear control
b. Non-linear control

Linear Control

A common method of DVR control is the linear and the ones commonly employed are feed forward control, feedback control and composite control.

a. Feed forward control is a simple method of DVR. The feed forward control technique does not sense the load voltage and it calculates the injected voltage based on the difference between the pre-sag and during sag voltages.

b. The feedback control strategy measures the load and the difference between the voltage reference of the load and actual load voltages, and the injected voltage required.

The feedback control methods based on the state space systems, which can be set up closed-loop poles in order to make faster time response.

c. Composite **control strategy** is a control method with grid voltage feed forward and load side voltage feedback. It has the strengths of feed forward and feedback control strategy, so it can improve voltage compensations effect.

If the feedback control in the composite control is designed to double-loop, it can improve system stability, system performance and the adaptability of dynamic load. The combination with feed forward control can improve the system dynamic response rate, shortening the time of compensation significantly.

Non-linear Control

The use of semi-conductor switches in the VSI, made DVR to be categorized as non-linear device. If the system became unstable, the model developed does not efficiently control target so all linear control methods cannot work properly due to their limitation, hence the need for non-linear control, examples of these are:

a. **Artificial Neural Network (ANN) Control**
   Artificial Neural Network (ANN) is one of the non-linear methods of control which is equipped with adaptive and self-organized capacity. ANN control can monitor the non-linear relationship based on input and output without detail mathematical model. Normally ANN control can be classified into feed forward neural networks feedback neural, local approximation neural networks and fuzzy net.

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b. Fuzzy Control

Injection of voltage based on Fuzzy Logic (FL) of the DVR differed from the previous methods by accommodating expert knowledge in controller design. It is derived from fuzzy set theory. FL controllers are an attractive choice when precise mathematical formulations are not possible. The advantages of this controller are capability to reduce the error and transient over shoot of pulse modulation (PWM).

c. Space Vector PWM (SVPWM) Control

Space vector pulse width modulation control strategy used in AC motor variable speed drives was initiated by Japanese scholars in 1980s. The main idea is to get qussi-circular rotating magnetic field instead of the original SPWM by adopting a voltage inverter space vector of the switch. In doing so, better performance of the exchange is gained in low switching frequency conductions. Apart from these controls, there is also available control for single phase sag detection methods used in DVR.

Advantages of DVR over other Custom Power Devices (Almeida et al, 2003), (Mohammed et al, 2013) (Anmol and Nijhawan, 2011), (Omar et al, 2011), (Hazarika et al, 2013), (Azim and Hoque, 2011), (Priyanka and Vijayakumar, 2011).

- 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.

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Conclusion

This paper gives description of Dynamic Voltage restorer (DVR) for the mitigation of voltage sags and swells for power quality improvement at the point of common coupling. In this work, DVR is considered to be the device used to mitigate voltage sags and swells with advantage of active/reactive power control. However, a comprehensive literature review on different configurations and control strategies of DVR are presented. This review paper, gives room in selecting a better control strategy and power circuit for optimum performance of DVR for a precise simulation model.

Recommendations

Technical review of Dynamic Voltage Restorer was explored for improvement of power quality in distribution system. The paper also gives better selection of DVR for compensation of voltage Sags and Swells for better power quality mitigation. Also, DVR is one of the famous techniques for immediate reduction of total harmonic distortion (THD) at the point of common coupling. So, in view of the above, DVR is one of the most viable solution in mitigating voltage sags and swells in distribution systems.

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