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Overview of Dynamic Voltage Restorer (DVR) for Power Quality Improvement.

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Abstract-

Power quality is one of major concerns in the present era. It has become important, especially, with the introduction of sophisticated devices, whose performance is very sensitive to the quality of power supply. Power quality problem is an occurrence manifested as a nonstandard voltage, current or frequency that results in a failure of end use equipments. One of the major problems dealt here is the voltage sag. To solve this problem, custom power devices are used. One of those devices is the Dynamic Voltage Restorer (DVR), which is the most efficient and effective modern custom power device used in power distribution networks. Its appeal includes lower cost, smaller size, and its fast dynamic response to the disturbance. This paper introduces power quality problems and overview of Dynamic Voltage Restorer so that young electrical engineers come to know about such a modern custom power device for power quality improvement in future era.

Key words: power quality, voltage sags, Dynamic Voltage Restorer (DVR).

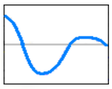
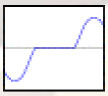
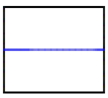
I. INTRODUCTION

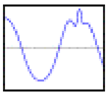
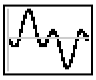
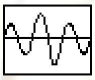
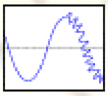
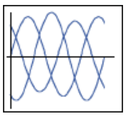
Power quality issues are of vital concern in most industries today, because of the increase in the number of loads sensitive to power disturbances. The power quality is an index to qualify of current and voltage available to industrial, commercial and household consumers of electricity. The problem regards both the utilities and customers. For the utilities, to provide adequate power quality is a moving objective because of changes in user equipment and requirements. For consumers, problems stemming from the sensitivity of electrical equipment to voltage quality have often very heavy consequences.

Power quality is a topic embracing a large field. On one side, several different events are involved in power quality: spikes or surges, sags, swells, outages, under and Overvoltage, harmonics, flicker, frequency deviations, electrical noise. Accordingly, different measurements and analysis tools are required to investigate such phenomena, and different remedial actions can be adopted to compensate them or to reduce their effects. On the other side, many electronic devices (such as computers, process controls, adjustable speed drives, solid-state-relays, optical devices, to name a few) are sensitive to a different extend to power quality. Since a certain event may be not serious problem for a given customer class, but it may represent a big problem for another class, it has doubtful practical sense to rank the above events in terms of importance without referring to a more specific context. As far as industrial and commercial customers are concerned, several recent studies agree on the statement that voltage sags must be regarded as one of the most important concerns in power quality. This statement is particularly true for industrial facilities, where even short duration voltage sags are often responsible for much more long-lasting production downtimes and consequent large lost revenue.

This study introduce various power quality problems and basic concept of DVR (Dynamic Voltage Restorer) This study deals with overview of a Dynamic Voltage Restore (DVR) for mitigation of voltage sags.

Table I –Most common Power Quality problems

1. Voltage sag (or dip) 	Description: A decrease of the normal voltage level between 10 and 90% of the nominal rms voltage at the power frequency, for durations of 0,5 cycle to 1 minute. Causes: Faults on the transmission or distribution network (most of the times on parallel feeders). Faults in consumer's installation. Connection of heavy loads and start-up of large motors.
2. Very short Interruptions 	Description: Total interruption of electrical supply for duration from few milliseconds to one or two seconds. Causes: Mainly due to the opening and automatic reclosure of protection devices to decommission a faulty section of the network. The main fault causes are insulation failure, lightning and insulator flashover.
3. Long interruptions 	Description: Total interruption of electrical supply for duration greater than 1 to 2 seconds Causes: Equipment failure in the power system network, storms and objects (trees, cars, etc) striking lines or poles, fire, human error, bad coordination or failure of protection devices. Consequences: Stoppage of all equipment.
4.	Description: Very fast variation of the voltage value for durations from a

Voltage spike 	several microseconds to few milliseconds. These variations may reach thousands of volts, even in low voltage. Causes: Lightning, switching of lines or power factor correction capacitors, disconnection of heavy loads.
5. Harmonic distortion 	Description: Voltage or current waveforms assume non-sinusoidal shape. The waveform corresponds to the sum of different sine-waves with different magnitude and phase, having frequencies that are multiples of power-system frequency. Causes: *Classic sources*: electric machines working above the knee of the magnetization curve (magnetic saturation), arc furnaces, welding machines, rectifiers, and DC brush motors. *Modern sources*: all non-linear loads, such as power electronics equipment including ASDs, switched mode power supplies, data processing equipment, high efficiency lighting.
6. Voltage fluctuation 	Description: Oscillation of voltage value, amplitude modulated by a signal with frequency of 0 to 30 Hz. Causes: Arc furnaces, frequent start/stop of electric motors (for instance elevators), oscillating loads. Consequences: Most consequences are common to Undervoltage. The most perceptible consequence is the Flickering of lighting and screens, giving the impression of unsteadiness of visual perception.
7. Noise 	Description: Superimposing of high frequency signals on the waveform of the power-system frequency. Causes: Electromagnetic interferences provoked by Hertzian waves such as microwaves, television diffusion, and radiation due to welding machines, arc furnaces, and electronic equipment. Improper grounding may also be a cause.
8. Voltage Unbalance 	Description: A voltage variation in a three-phase system in which the three voltage magnitudes or the phase angle differences between them are not equal. Causes: Large single-phase loads (induction furnaces, traction loads), incorrect distribution of all single phase loads by the three Phases of the system (this may be also due to a fault).

II. VOLTAGE SAG.

IEEE Standard 1100-1992 (IEEE Emerald Book) defines sag as "an rms reduction in the AC voltage, at the power frequency, for durations from a half-cycle to a few seconds". Note: The IEC terminology for sag is dip. They may be accompanied with phase jumps. If the voltage is reduced to zero, the disturbance is said to be a momentary outage or micro interruption. The most obvious way to characterize voltage sag is in terms of the reduced voltage rms, duration and probably accompanied phase jump.

Voltage dips (sags) are generally caused by faults occurring in the customers' installations on in the public distribution system. They are unpredictable, largely random events. The annular frequency varies greatly depending on the type of the supply systems and on the point of observation. Moreover, the distribution over the year can be very irregular.

Voltage sags are often generated by starting of large loads, such as motors, transformer energizing, equipment faults, transmission and distribution system faults. Faults on the distribution and transmission systems can be caused by numerous sources such as lightning strikes, conductors blowing together in a storm, contact with objects (e.g. tree branches, animals, etc.) or vandalism. Most of these faults (70-80%) are temporary in nature; they are self-clearing within a few milliseconds. The fault that does not clear will cause a protective device/s (e.g. fuse, circuit breaker, or recloser) to operate to interrupt current to that part of the system in the affected area.

There are several solutions currently available that
will provide ride-through capability to critical loads under
voltage sag condition.

1) Uninterruptible Power Supplies (UPS's)
2) Ferroresonant, Constant Voltage Transformers (CVT's)
3) Magnetic Synthesizers
4) Superconducting Storage Devices
5) Dynamic Voltage Restorer (DVR)

III. DVR BASICS

Developed in the early 1990's, a Dynamic Voltage Restorer, with its excellent dynamic capabilities, when installed between the supply and a critical load feeder, can compensate for voltage sags, restoring line voltage to its nominal value within a few milliseconds and hence avoiding any power disruption to that load.

A power electronic converter based series compensator that can protect critical loads from all supply side disturbances other than outages is called a dynamic voltage restorer. The restorer is capable of generating or absorbing independently controllable real and reactive power at its AC output terminal. This device employs solid-state power electronic switches in a pulse-width modulated (PWM) inverter structure. It injects a set of three-phase AC output voltages in series and synchronism with the distribution feeder voltages. The amplitude and phase angle of the injected voltages are variable thereby allowing control of the real and reactive power exchange between the device and the

distribution system. The DC input terminal of the restorer is connected to an energy source or an energy storage device of
appropriate capacity. The reactive power exchanged between the restorer and the distribution system is internally generated by the restorer without AC passive reactive components. The real power exchanged at the restorer output AC terminals is provided by the restorer input DC terminal from an external energy source or energy storage system.

The DVR functions by injecting three single phase AC voltages in series with the three phase incoming network voltages during a dip, compensating the difference between faulty and nominal voltages. All three phases of the injected voltages are of controllable amplitude and phase. Voltage source inverter fed from the DC link supply the required active and reactive power.

In August 1996, Westinghouse Electric Corporation installed world's first DVR in Duke Power Company's 2.7kV substation in Anderson, South Carolina. This was installed to provide protection to an automated rug manufacturing plant. For a total load of 3.5MVA at a power factor of 0.8, a 2MVA DVR, with 660kJ of energy storage was installed and put into service on September 4, 1996. The next commissioning of a restorer was done by Westinghouse in February 1997 in
Powercor's 22kV distribution system at Stanhope, Victoria, Australia to protect a diary milk processing plant. The total load was approximately 5.25MVA and a 2MVA DVR was installed. The saving that results from the installation of this
Installation is estimated at over $100,000 per year. In the next phase of development, Westinghouse (now taken over by Siemens) installed world's first platform mounted DVR to protect Northern Lights Community College and several other smaller loads in Dawson Creek, British Colombia, Canada. ABB installed and commissioned the world's biggest dynamic voltage restorer in August 2000, in Israel. The two systems (each 22.5MVA) protect the production facility of a microprocessor manufacturer located in a desert environment.

3.1 *Propitious Choice of DVR*

There are numerous reasons why DVR is preferred over other devices:

1) Although, SVC predominates the DVR but the latter is still
preferred because the SVC has no ability to control active power flow.
2) DVR is less expensive compared to the UPS.
3) UPS also needs high level of maintenance because it has problem of battery leak and have to be replace as often as five years.
4) DVR has a relatively higher energy capacity and costs less compared to SMES device.
5) DVR is smaller in size and costs less compared to DSTATCOM
6) DVR is power efficient device compared to the UPS.

3.2 *Basic Configuration of DVR*

Power circuit and the control circuit are the 2 main parts of the DVR. There are various critical parameters of control signals such as magnitude, phase shift, frequency etc. which are injected by DVR.

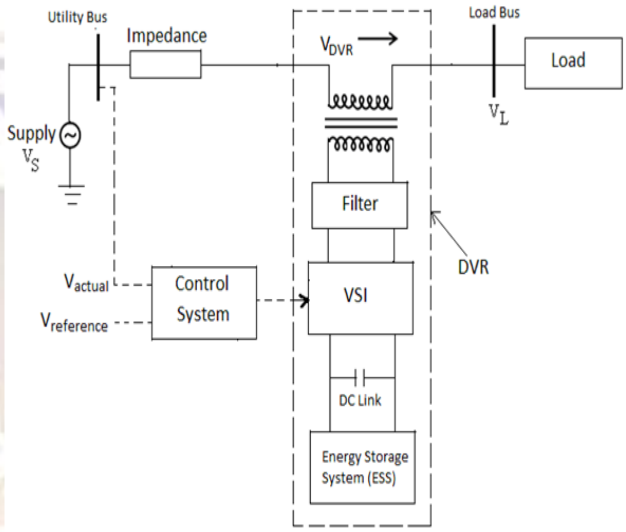


Fig.1 Basic Configuration of DVR

These parameters are derived by the control circuit. This injected voltage is generated by the switches in the power circuit based on the control signals. Furthermore the basic structure of DVR is described by the power circuit and is discussed in this section. The 5 main important parts of power circuit, their function and requirements are discussed ahead.

3.3 DVR Components

A typical DVR consist of the following major components.

3.3.1 Voltage Source Inverter/s (VSI)
3.3.2 Injection Transformer/s
3.3.3 Harmonic Filter
3.3.4 Energy Storage Unit
3.3.5 Control and Protection System

3.3.1 Voltage Source Inverter

Generally Pulse-Width Modulated Voltage Source Inverter (PWMVSI) is used. In the previous section we saw that an energy storage device generates a DC voltage. To convert this DC voltage into an AC voltage a Voltage Source Inverter is used. In order to boost the magnitude of voltage during sag, in DVR power circuit a step up voltage injection transformer is used. Thus a VSI with a low voltage rating is sufficient.

3.3.2 Voltage Injection Transformers

The injected voltages are introduced into the distribution system through an injection transformer connected in series with the distribution feeder. The primary side of the injection transformer is connected in series to the distribution line, while the secondary side is connected to the DVR power circuit. Now 3 single phase transformers or 1 three phase transformer can be used for 3 phase DVR whereas 1 single phase transformer can be used for 1 phase DVR. The type of connection used for 3 phase DVR if 3 single phase transformers are used is called "Delta-Delta" type connection. If a winding is missing on primary and secondary side then such a connection is called "Open-Delta" connection which is as widely used in DVR systems. In order to carefully select a suitable injection transformer the following issues should carefully be addressed.

1) The MVA rating
2) The primary winding voltage and current ratings
3) The turn-ratio which, in turn, determines the secondary 4) Winding voltage and current rating
5) The short-circuit impedance

3.3.3 *Harmonic Filters*

To convert the PWM inverted pulse waveform into a sinusoidal waveform, low pass passive filters are used. In order to achieve this it is necessary to eliminate the higher order harmonic components during DC to AC conversion in Voltage Source Inverter which will also distort the compensated output voltage. These filters which play a vital role can be placed either on high voltage side i.e. load side or on low voltage side i.e. inverter side of the injection transformers. We can avoid higher order harmonics from passing through the voltage transformer by placing the filters in the inverter side. Thus it also reduces the stress on the injection transformer. One of the problems which arise when placing the filter in the inverter side is that there might be a phase shift and voltage drop in the inverted output. So this could be resolved by placing the filter in the load side. But this would allow higher order harmonic currents to penetrate to the secondary side of the transformer, so transformer with higher rating is essential.

3.3.4 *Energy Storage Unit*

Various devices such as Flywheels, Lead acid batteries, Superconducting Magnetic energy storage (SMES) and Super-Capacitors can be used as energy storage devices. The main function of these energy storage units is to provide the desired real power during voltage sag. The amount of active power generated by the energy storage device is a key factor, as it decides the compensation ability of DVR. Among all others, lead batteries are popular because of their high response during charging and discharging. But the discharge rate is dependent on the chemical reaction rate of the battery so that the available energy inside the battery is determined by its discharge rate.

3.3.5 *Protection and Short Circuit Operation of DVR*

The protection and short circuit operation of DVR is implemented by properly switching the semiconductors of the VSIs. By this way additional thyristors needed during short circuit operation are eliminated. Since DVR is rated to compensate for 50% voltage sags, the current rating of the semiconductor switches must be enough to handle full load current which makes them suitable for continuous operation during non-sag condition.

3.4 Location of DVR

The intention is only to protect one consumer or a group of consumers with value added power. Applying a DVR in the medium or low voltage distribution system would often be possible and a radial grid structure is the only type of system Considered here. In Europe three wire systems are common in the medium voltage systems and four wires in low voltage systems. In both systems the main purpose is to inject synchronous voltages during symmetrical faults and in some cases inject an inverse voltage component during non-symmetrical faults

A main difference between a Low Voltage (LV) connection and a Medium Voltage (MV) connection is the flow of zero sequence currents and the generation of zero sequence voltages. In the four-wire system, 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.

3.5 Basic DVR Operating Principles

The DVR functions by injecting three single phase AC voltages in series with the three phase incoming network voltages during sag, compensating for the difference between faulty and nominal voltages. All three phases of the injected voltages are of controllable amplitude and phase. Three pulse-width modulated (PWM) voltage source inverters (VSI) fed from a DC link supply the active and reactive power.

During undisturbed power supply condition, the DVR operates in a low loss standby mode. In the normal operation mode (no sag) the low voltage side of the booster transformer is shorted either by solid state bypass switch or by switching one of the inverter legs and it functions as a short-circuited current transformer. Since no VSI switching takes place, the DVR produces conduction losses only. These losses should be kept as low as possible so as not to cause steady state power loss.

Harmonics produced by the operation of VSI must be reduced to an acceptable limit defined by proper filtering scheme. Modulation scheme used on the VSI switches has also impact on the harmonics produced.

The required energy during sags has to be supplied by an energy source. The necessary amount of energy that must be delivered by the energy source depends on load MVA requirement, control strategy applied, deepest sag to be protected.

Under normal conditions, the short circuit impedance of the injection transformer determines the voltage drop across the DVR. This impedance must be low and has an impact on the fault current through the VSI on secondary side caused by a short-circuit at load side. The filter design is also affected by
the impedance of the injection transformer.

In case of fault or over current exceeding the rating of DVR on the load side, solid state bypass switches or electromechanical bypass switches must be added as a measure to protect DVR from getting damaged.

As an overview the following main design criteria influence the rating and the performance of the DVR:
1) Maximum MVA-load and power factor,
2) Maximum 1 phase and 3 phase voltage sags to be compensated,
3) Maximum duration of 3 phase voltage sag,
4) Maximum allowed voltage drop across DVR under steady-state conditions,
5) Short circuit impedance of the injection transformers,
6) Short circuit impedance and connection of step down transformers at the input and output sides of the DVR as well as the short circuit power.

3.6 Control of DVR

The control of a DVR is not straight forward because of the requirements of fast response, large variation in the type of sags to be compensated and variation in the type of connected load. The DVR must also be able to distinguish between background power problems and the voltage sags to be compensated. Sags are often nonsymmetrical and accompanied by a phase jump.

The possibility of compensation of voltage sags can be limited by a number of factors including finite DVR power rating, different load conditions, background power quality problems and different type of sags. If the DVR should be a successful device, the control may be able to handle most sags and the performance must be maximized according to the equipment inserted. Otherwise, the DVR may not be able to avoid load tripping and even cause additional disturbance to load.

A control strategy for voltage sags with phase jump should be included, to be able to compensate this particular type of sag. The control strategy can depend on the type of the load connected. Some loads are very sensitive to phase jump and the load should be protected from them. Other types of loads are more tolerant to phase jump and the main task is to maintain the nominal voltage on all three phases. Three basic control strategies for a DVR can be stated as:

Method 1: Pre-sag compensation; the supply voltage is continuously monitored and the load voltage is compensated to the pre-sag condition. The method gives nearly undisturbed load voltage, but can often exhaust the rating of the DVR.

Method 2: In-phase compensation; the generated DVR voltage is always in phase with the measured supply voltage regardless of the load current and presage voltage.

Method 3: Energy optimal compensation; to fully utilize the energy storage, information about the load current is used to minimize the depletion of the energy storage.

IV. CONCLUSIONS

With the development of more complicated process control equipment in the industry, more sensitive devices to the changes on the incoming supply voltage takes place on the market. This increase the severity of the power quality problems caused by non-ideal bus voltages. These non-idealities can be under-voltage, over-voltage, harmonics, shortages or sags. Although it does not seem so severe, every year large cost of lost production is paid by different manufacturers in the industry due to voltage sag, short periods of under-voltage, up to a few hundreds of milliseconds.

This paper introduces detailed overview of Dynamic Voltage Restorer so that young electrical engineers come to know about such a modern custom power device for power quality improvement in future era.

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