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Enhancement of transient and steady state responses of voltage by using DVR

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Abstract: Voltage sag is one of the most important power quality problems challenging the utility industry voltage sags can be compensated for by voltage and power injection into the distribution system. Voltage sags are an important power quality problem and Dynamic Voltage Restorer is known as an effective device to mitigate voltage sags .The dynamic voltage restorer has become popular as a cost effective solution for the protection of sensitive loads from voltage sags. Simulations of the dynamic voltage restorer have been proposed at low voltage level; and give an opportunity to protect high power sensitive loads from voltage sags. This paper reports simulation test results obtained on a low voltage level using a dynamic voltage restorer. Dynamic voltage restorer was designed to protect a load from voltage sag. The proposed Dynamic Voltage Restorer obtains good transient and steady state responses.

Keywords: Voltage Stability, Transient, Voltage Sag, Simulation, DVR Etc

1. Introduction

Significant deviations from the nominal voltage are a problem for sensitive consumers in the grid system. Interruptions are generally considered to be the worst case with the load disconnected from the supply. The number of interruptions, though expensive, can be minimized with parallel feeders and are less likely to occur with the transition from over headlines to cables in the LV and MV distribution system.

Voltage sags are characterized by a reduction in voltage, but the load is still connected to the supply. Sags are in most cases considered less critical compared to interruptions, but they typically occur more frequently. Voltage sags have in several cases been reported as a threat to sensitive equipment and have resulted in shutdowns, loss of production and hence a major cost burden.

Sags are so far almost impossible to avoid, because of the finite clearing time of the faults causing the voltage sags and the wide propagation of sags from the Equipment can be made more tolerant of sags either via more intelligent control of the equipment or by storing more energy in equipment. Instead of modifying each component in for instance a factory to be very tolerant to voltage sags, a better solution might be to install one dynamic voltage restorer to mitigate voltage sags. A DVR can eliminate most sag and minimize the risk of load tripping at very deep sags.

The control of a DVR is not a 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 quality problems and the voltage sags with a phase jump and illustrates different control strategies for a DVR and some DVR limitations, which should be included in the control strategy. Two control methods are proposed with the ability to protect the load from a sudden phase shift caused by voltage sag with phase jump. Simulations and measurements illustrate how symmetrical voltage sags with phase jump successfully can be compensated.

Dynamic voltage restorer (DVR) was originally proposed to compensate voltage disturbances on distribution systems. The restoration is based on injecting ac voltages in series with the incoming three- phase net work, the purpose of which is to improve voltage quality by adjustment in voltage magnitude, wave –shape and phase shift. These are important voltage attributes as they can affect the performance of the load equipment. The ideal restoration is Compensation, which enables the voltage seen by the load to be unchanged in The face of upstream disturbances. Also, voltage restoration involves energy injection into the distribution systems and this determines the capacity of the energy storage device required in the restoration scheme.

If the voltage restoration is to be realized by in-phase voltage injection, minimum –magnitude injected voltage is achieved. However, in-phase injection does not take into consideration of minimizing the energy required to achieve voltage restoration. By employing reactive power to implement compensation, voltage injection with an appropriate phase advance with respect to source side voltage can reduce the consumption of energy, from the perspective of the DVR energy storage device. The increased reactive power is generated electronically from within the voltage source inverter (VSI). Thus the energy saving voltage restoration methods means that the capacity of the energy storage device can be reduced. In other words for a given DVR this has fixed energy storage capacity, Reduced energy injection means increased ride-through ability for the compensated load. Voltage injection with a phase advance, however, does require a larger injected voltage, and the resulting voltage shift can cause voltage waveform discontinuity, inaccurate voltage zero crossing, and load power swing.

Although the energy saving concept was mentioned, no systematic analysis was given to explore such possibility and the associated problems were not addressed. Balanced voltage sag is considered first. The voltage injection control strategy proposed is to achieve energy saving subject to voltage injection limit placed on the DVR. The results are then extended to include unbalanced voltage sags. Simulation results are given to show the efficacy of the proposed method.

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1.1. Literature Survey

Power quality has a significant influence on high–technology equipments related to communication, advanced control, automation, precise manufacturing technique and on-line service. For example, voltage sag can have a bad influence on the products of semiconductor fabrication with considerable financial losses; power quality problems include transients, sags, interruptions and other distortions to the sinusoidal waveform. One of the most important power quality issues is voltage sag that is a sudden short duration reduction in voltage magnitude between 10 and 90% completed to nominal voltage. Voltage sag is deemed as a momentary decrease in the RMS voltage, with duration ranging from half a cycle to up to one minute. Deep voltage sags, even of relatively short duration, can have significant costs because of the proliferation of voltage sensitive computer-based and variable speed drive loads. The fraction of load that is sensitive to low voltage is expected to grow rapidly in coming decades. Studies have shown that transmission faults, while relatively rare, can cause widespread sags that may constitute major process interruptions for very long distances from the faulted point.

Distribution faults are considerably more common but the resulting sags are more limited in geographic extent. The majority of voltage sags are within 40% of the nominal voltage. Therefore, by designing drives and other critical loads capable of riding through sags with magnitude of up to 40%, interruption of processes can be reduced significantly. The DVR can correct sags resulting from faults in either transmission or distribution system.

2. Introduction to Power Quality

The term “power quality” has barren used to describe the extent of variations of the voltages, current and frequency on the power systems. Most power apparatus made over a decade back could operate normally with relatively wide variations of three parameters. However, equipment added to power system in recent years generally is not tolerant to these variations for two main reasons. First one is the design tolerances have been going down in a competitive market and second one is the increasing use of sophisticated electronic controls. Hence, system disturbances, which were tolerated earlier, may now cause interruption to industrial power system with a resulting loss of production and this could be substantial with greater stress on productivity and quality now. Especially for a developing country like India, power quality is of prime importance considering the need for the energy conservation. It is a paradox that some of the energy conserving devices themselves is the reasons for some of the power quality problems.

2.1. Power Quality Problems

Power quality refers to ac power supply with rather perfect sine wave, constant magnitude and constant frequency.

The power quality problems originate primarily from industries; transmissions and distribution systems. The real power quality problems can be put under the following main categories:

- Voltage dips or sags
- Voltage swells
- Voltage fluctuations and flicker
- Interruptions
- Harmonics
- Unbalances
- Transients
- Commutation notches
- Electric noise

PQ variations fall into three categories: 1) transient disturbances: these include uni-polar transients, oscillatory transients, localized faults and other events typically lasting less than 10ms. These disturbances are expected to change shape as they propagate through the power system. Hence the recorder/monitor location, relative to the point of origin of disturbances is critical.2) momentary disturbances: these are voltage increases (swells) or voltage decreases (sags) lasting more than 10 ms, but less than 3 sec.3) steady state disturbances: these are voltage deviations lasting more than 3 sec.

With the revolution in technology, the trend in the industrial world is towards completely automated process control. Hence, PQ problem results in failure or mal-operation of electronic equipment, sensitive microprocessors personal computers and all electric gadgets. This has driven the utilities to concentrate their research efforts on improvement of power quality.

2.2. What is Power Quality

Maintaining the near sinusoidal waveform of power distribution bus voltage at rated voltage magnitudes and frequency termed as "power quality". There can be various definitions

(1) As meant by consumers: the relative absence of utility related voltage variations, particularly, the absence of outages, sags, surges and harmonics as measured at the point of service.

(2) As meant by manufactures: power quality means equipment compatibility at the supply of electrical power.

2.3. Aspects of Power Quality

2.3.1. Voltage Fluctuations and Flicker

These cause variations in the intensity of illumination. The frequency of variation is in the range of 10hz.The electric furnaces are the major source of voltage fluctuation that is caused by the rapid variation in the reactive power drawl. The adverse effects are irritation at home and offices, and interface with certain equipment.

2.3.2. Voltage DIP or SAG

A dip or sag in the voltage is referred to as a decrease in RMS voltage or current at the power frequency followed by a rapid return to the initial value. The voltage dips and sags are caused by lightning strikes, ground faults, energizing heavy loads, etc. The problems caused due to the voltage dips and sags include loss of conduction, loss of data and damage to the equipment, etc.

2.3.3. Voltage Swells

An increase in RMS voltage or current at the power frequency for duration from 0.5 cycles to 1 minute is known as voltage swell. The cause include drop of large loads and Unsymmetrical faults. The voltage swells may result in loss of production damage or loss of life of equipment, etc.

2.3.4. Interruptions

An interruption is a type of short duration variations of voltage resulting in complete loss of voltage (<10%) on one or more phase conductors for a time period greater than one minute. The causes of interruptions are lightning. Wind, tree and animal contact, equipment failure, accidents involving power lines, generator failures, etc.

2.3.5. Harmonics

The Harmonics are caused by converters, rectifier loads, switched mode power supplies, etc. These harmonics distort the voltage and currents. The harmonics cause heating in machines, noise, mal-operation of control and protection equipment, etc.

2.3.6. Unbalances

The unbalances could be due to the differences in either amplitude or phase or both. The unbalance is caused due to the traction and other unbalanced loads. The ill effects of unbalance include generation of harmonics, when non-linear loads are supplied by unbalanced power supply, and damaging effect on machines due to the flow of negative sequence currents.

2.3.7. Transients

Lightning, power line feeder switching, capacitor bank switching and system faults Cause the transients. The transients may stress equipment insulation or even cause damage to Equipment.

2.3.8. Commutation Notches

Commutation notches are caused by converters, rectifiers, switched mode power supplies, etc. The commutation notches may stress insulation, because heating in machines, noise, and mal-operation of control and protection equipment.

2.3.9. Electric noise

The cause of electric noise in the supply voltage and currents include radar and radio Coupling, arcing utility equipment, industrial arc equipment, converters and switching circuits. It can cause interference with communication systems, damage to equipment, etc.

2.3.10. Geo Magnetic Disturbances

Results from low frequency magnetic fields, typically below 5 Hz, associated with solar flares. The slowly varying field induces low frequency current in long transmission lines. These currents when pass through transformer winding, saturate the magnetic core and the voltage waveforms at the transformer may be distorted.

2.4. Interest in Power Quality

The fact that power quality has become an issue recently does not mean that it was not important in the past. Utilities all over the world have for decades worked on the improvement of what is now known as power quality. And actually, even the term has been in use for a rather long time already. The oldest mentioning of the term "power quality" known to the author was in a paper published in 1968.The paper detailed a study by the U.S navy after specifications for the power required by electronic equipment. That paper gives a remarkably good overview of the power quality field, including the use of monitoring equipment and even the suggested use of a static transfer switch. Several publications appeared soon after, which used the term power quality in relation to airborne power systems. Already in 1970"high power quality" is being mentioned as one of the aims of industrial power system design, together with "safety"," reliable service" and "low initial and operating costs". At about the same time the term "voltage quality" was used in the Scandinavian Countries and in the Soviet Union, mainly with reference to slow variations in the voltage magnitude.

The recent increased interest in power quality can be explained in a number of ways. The main explanations given are summarized below. Of course it is hard to say which of these came first; some explanations for the interest in power quality given below will by others be classified as consequences of the increased interest in power quality.

2.5. Overview of Power Quality Phenomenon

We saw in the previous section that power quality is concerned with deviations of the voltage from its ideal waveform (voltage quality)and the deviations of the current from its ideal waveform(current quality).such a deviation is called a 'power quality phenomenon' or a 'power quality disturbance'.

Power quality phenomena can be divided into two types, which need to be treated in a different way.

- A characteristic of voltage or current (e.g., frequency or power factor) is never exactly equal to its nominal or desired value. The small deviations from the nominal or desired value are called "voltage variations" or "current variations". A property of any variation is that it has a value at any moment in time. e.g. The frequency is never exactly equal to 50hz or 60hz; the power factor is never exactly unity .Monitoring of a variation thus has to take place continuously.
- Occasionally the voltage or current deviates significantly from its nominal or ideal wave shape .These sudden deviations are called "events". Example are a sudden drop to zero of the voltage due to the operation of a circuit breaker (a voltage event) and a heavily distorted over current due to switching of a non_ loaded transformer (a current event).monitoring of events take place by using a triggering mechanism where recording of voltage and /or current starts the moment a threshold is exceeded.

The classification of a phenomenon in one of these two types is not unique .it may depend on the kind of the problem due to phenomenon.

2.5.1. Voltage and Current Variations

- Voltage magnitude variation
- Voltage frequency variation
- Current magnitude variation
- Current phase variation
- Voltage and current unbalance
- Voltage fluctuation
- Harmonic voltage distortion
- Harmonic current distortion
- Inter harmonic voltage and current components
- Periodic voltage notching
- Mains signaling voltage
  - ➢ Ripple control signals
  - ➢ Power line carrier signals
  - ➢ Mains marking signals
- High frequency voltage noise

2.5.2. Events

Events are phenomenon which only happen every once in a while. An interruption of the supply voltage is the best known example. They are

- interruptions
- under voltages
- voltage magnitude steps
- over voltages
- fast voltage events
- phase angle jumps and three phase unbalance

2.5.2.1. Interruptions

A voltage interruption / supply interruption / interruption is a condition in which the voltage at the supply terminals is close to zero. Close to zero is defined as lower than 1% of the declared voltage. Interruptions can also be subdivided based on their duration, thus based on the way of restoring the supply.

- Automatic switching
- Manual switching
- Repair or replacement of the faulted component

2.5.2.2. Under Voltages

Under voltages of various duration are known under different names. Short-duration under voltages are called "voltage sags" or "voltage sags" or "voltage dips". Long duration under voltage is normally simply referred to as "under voltage".

Voltage sag is a reduction in the supply voltage magnitude followed by a voltage recovery after a short period of time. When a voltage magnitude reduction of finite duration can be called a voltage sag or voltage dip. According to IEC, a supply voltage dip is a sudden reduction in the supply voltage to a value between 90% and 1% of the declared voltage, followed by a recovery between 10ms and 1 min later.

2.5.2.3. Voltage Magnitude Steps

Load switching, transformer tap changers, and switching actions in the system can lead to a sudden change in the voltage magnitude. Such a voltage magnitude step is called a "rapid voltage change" or "voltage change".

2.5.2.4. Over Voltages

Just like with under voltage, over voltage events are given different names based on their duration. Over voltages of very short duration, and high magnitude, are called “transient over- voltages”, “voltage spikes”, or sometimes “voltage surges”. The letter term is rather confusing as it sometimes used to refer over voltages with duration between about 1 cycle and 1 min. The latter event is more correctly called voltage swell or “temporary power frequency over voltages”. Longer duration over voltages is simply referred to as “over voltages”. Long and short over voltages originates from, among others, lightning strokes, switching operations, sudden load reduction, single-phase short circuits and nonlinearities.

A resonance between the nonlinear magnetizing reactance of a transformer and a capacitance can lead to a large over voltage of long duration. This phenomenon is called Ferro resonance, and it can lead to serious damage to power system equipment.

2.5.2.5. Fast Voltage Events

Voltage events with a very short duration typically one cycle system frequency or less referred to as “transients” /transient voltages / voltage transients/wave shape faults. The term transient is not fully correct, as it should only be used for the transition between two steady states. Events due to switching actions could under that definition be called transients. Events due to lightning strikes could not be called transients. Even very short duration voltage sags (due to fuse clearing) are referred to as voltage transients, or also “notches”. Fast voltage events can be divided into impulsive transients (mainly due to lightning) and oscillatory transients (mainly due to switching actions).

2.5.2.6. Phase Angle Jumps and Three Phase Unbalance

We will see that voltage sag is often associated with a phase angle jump and some three phase unbalance. An interesting thought is whether or not a jump in phase angle without drop in voltage magnitude should be called voltage sag. Such an event could occur when one of two parallel feeders is taken out of operation.

3. Voltage Sags- Characterization

3.1. Introduction

Voltage sags are short duration reductions in RMS voltage, caused by short circuits, overloads and starting of large motors. The interest in voltage sags is mainly due to the problems they cause on several types of equipment adjustable-speed drives, process-control equipment and computers are notorious for their sensitivity. Some pieces of equipment trip when the RMS voltage drops below 90% for longer than one or two cycles.

3.1.2. Voltage Sag Magnitude

3.1.2.1. Monitoring

The magnitude of voltage sag can be determined in a number of ways. Most existing monitors obtain the sag magnitude from the RMS voltages. But this situation might well change in the future. There are several magnitude of the fundamental (power frequency) component of the voltage and the peak voltage over each cycle or half cycle. As long as the voltage is sinusoidal, it does not matter whether RMS voltage, fundamental voltage, or peak voltage is used to obtain the sag magnitude. But especially during voltage sag this is often not the case.

RMS VOLTAGE:

As voltage sags are initially recorded as sampled points in time, the RMS voltage will have to be calculated from the sampled time-domain voltages. This is done by using the following equation:

$$V_{rms} = \sqrt{1/N\sum_{i=1}^{N}(v_i)2} \qquad (3.1)$$

Where N is the number of samples per cycle and v1 are the sampled voltages in time domain.

Fundamental voltage component:

The advantage of using the fundamental component of the voltage is that the phase-angle jump can be determined in the same way. The fundamental voltage component as a function of time may be calculated as

$$V_{fund}(t) = \frac{2}{T}\int_{t-T}^{t} v(\tau)e^{j\omega_0\tau}d\tau \qquad (3.2)$$

Where ω_0= 2Π/T and T one cycle of the fundamental frequency. Note that this results in a complex voltage as a function of time. The absolute value of this complex voltage is the voltage magnitude as a function of time; its argument can be used to obtain the phase angle jump. In a similar way we can obtain magnitude and phase angle of a harmonic voltage component as function of time. This so-called “time-frequency analysis” is a well-developed area within digital signal processing with a large application potential in power engineering.

Peak Voltage:

The peak voltage as a function of time can be obtained by using the following expression.

$$V_{peak} = \max |v(t-\tau)| \qquad 0< \quad <<T \qquad (3.3)$$

Where V (t) the sampled voltage waveform and T an integer multiple of one half cycle.

One cycle voltage sag: the voltage is low in one phase for about one cycle and recovers rather fast after that. The other phases show some transient phenomenon, but no clear sag or swell.

Obtaining one sag magnitude:

Until now, we have calculated the sag or as the fundamental voltage component obtained over a certain window. There are various ways of obtaining one value for the sag magnitude as a function of time. Most monitors take the lowest value. Thinking about equipment sensitivity, this corresponds to the assumption that the equipment trips instantaneously constant RMS value during the deep part of the sags, using the lowest value appears an acceptable assumption.

3.2. Theoretical Calculations

To quantify sag magnitude in radial systems, the voltage divider model shown in fig.1 can be used. This might appear a rather simplified model, especially for transmission systems.

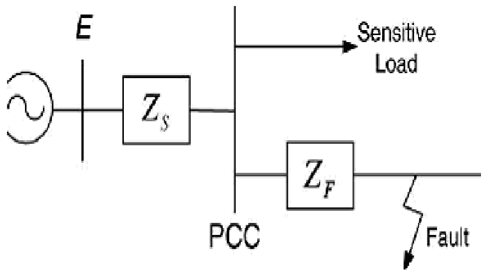

Fig. 1. *Voltage divider for voltage sag*

In fig.1 we see two impedances: Z_s is the source impedance at the point-of-common coupling; and Z_f is the impedance between the point-of-common coupling and the fault. The point-of-common coupling is the point from which both the fault and the load are fed. In other words: it is the place where the load current branches off from the fault current. We will often abbreviate "point-of-common coupling" as PCC. In the voltage at the PCC and thus the voltage at the equipment terminals, can be found form

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \tag{3.4}$$

In the remainder of this chapter, we will assume that the pre-event voltage is exactly 1pu, thus E=1. This results in the following expression for the sag magnitude.

$$V_{sag} = \frac{Z_F}{Z_F + Z_S} E \tag{3.5}$$

Any fault impedance should be included in the feeder impedance Z_f. We see from that the sag becomes deeper for faults electrically closer to the customer (when Z_F becomes smaller), and for systems with a smaller fault level (when Z_S becomes larger)

Note that a single phase model has been used here, whereas in reality the system is three phase. That means that this equation strictly speaking only holds for three phase faults.

Above equation can be used to calculate the sag magnitude as a function of the distance to the fault. Therefore we have to write Z_f=z x∈, where z the impedance of the feeder per unit length and ∈ the distance between the fault and the PCC, leading to

$$V_{sag} = \frac{z\varepsilon}{Z_S + z\varepsilon} \tag{3.6}$$

Influence of cross section: overhead lines of different cross section have different impedance, and lines and cables also have different impedance. It is thus to be expected that the cross section of the line or cable influences the sag magnitude as well.

Faults behind transformers:

The impedance between the fault and the PCC not only consists of lines or cables but also of power transformers. As transformers have rather large impedance, among other to limit the fault level on the low voltage side, the presence of transformer between the fault and the PCC will lead to relatively shallow sags.

Fault levels:

Often the source impedance at a certain bus is not immediately available, but instead the fault levels. One can of course translate the fault level into source impedance and use to calculate the sag magnitude. But one may calculate the sag magnitude directly if the fault levels at the PCC and at the fault position are known. Let S_{flt} be fault level at the fault position and S_{pc} at the point-of-common coupling. For a rated voltage V_n the relations between fault level and source impedance are as follows:

$$S_{FLT} = \frac{V^2{}_n}{Z_S + Z_F} \tag{3.7}$$

$$S_{pcc} = \frac{V^2{}_n}{Z_S} \tag{3.8}$$

With the voltage at the PCC can be written as

$$V_{sag} = 1 - \frac{S_{FLT}}{S_{PCC}} \tag{3.9}$$

We use to calculate the magnitude of sags behind transformers.

Critical Distance

Equations give the voltage magnitude as a function of the distance to the fault. From this equation we can obtain the distance at which a fault will lead to sag of a certain magnitude. If we assume equal X/R ratio of source and feeder, we obtain

$$\text{E critical} = \frac{Zs}{Z} \times \frac{V}{1-V} \tag{3.10}$$

We refer to this distance as the critical distance for a voltage V. supposes that a piece of equipment trips when the voltage drops below a certain level the critical voltage). The definition of critical distance is such that each fault within the critical distance will cause the equipment to trip.

If we assume further that the number of fault is proportional to the line length within the critical distance, we would except that the number of sags below a level V is proportional to V/ (1-V) another assumption is needed to be infinitely long without branching off. Of course this is not the case in reality. Still this equation has been compared with a number of large power quality surveys.

4.1. Introduction to DVR

Dynamic voltage restorer is a series connected device for mitigating voltage sag and swell. The first DVR was installed by the then Westinghouse in 1996. Since, then a lot of installations have taken place worldwide along with wide spread research in different aspects of DVR and control philosophies.

To improve power quality a custom power device Dynamic Voltage Restorer (DVR) can be used to eliminate voltage sags and swells. DVR is an inverter based voltage sag compensator. DVR protects the precision manufacturing processes and sophisticate sensitive electronic equipments from the voltage fluctuations and power outages. DVR offers sub cycle protection, restores the quality of electric power delivered to the sensitive load. The DVR regulates voltage within acceptable tolerances and meet the critical sensitive power quality needs. The DVR has been developed by Westinghouse for advance distribution. DVR injects a set of three single-phase voltages of an appropriate magnitude and duration in series with the supply voltage in synchronism via booster transformer to restore the power quality.

The injection voltages are of controllable amplitude and phase angle. The reactive power exchange between the DVR and distribution system without capacitors or inductors. The DVR is a series conditioner based on a pulse width modulated voltage source inverter, which is generating or absorbing real or reactive power independently. The ideal restoration is compensation which enables the voltage seen by the load to be unchanged in the face of upstream disturbances. The DVR injects the independent voltages to restore the line voltage to sensitive loads from sags caused by unsymmetrical line-to-ground, line-to-line, double-line-to-ground and symmetrical three phase faults. The output voltage waveform of DVR is highly regulated and clean. The DVR provides harmonic compensation and mitigates voltage transients.

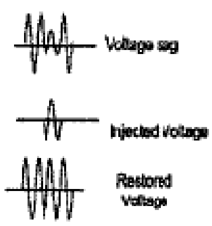

Fig. 2. *Voltage sag, DVR voltage, final load voltage*

4.2. Operating Principle of DVR

The DVR is designed to inject the missing voltage into the distribution line. Its basic idea is to dynamically inject a voltage u_c (t) as shown in Figure. The upper part of Figure shows a simplified single-phase equivalent circuit of a distribution feeder with a DVR, where the supply voltage u_s (t), the DVR-injection voltage $u_c(t)$ and the load voltage $u_L(t)$ are in series. So, the DVR is considered to be an external voltage source where the amplitude, the frequency and the phase shift of *u,(f)* can be controlled. The purpose is to maintain the amplitude of the load voltage fixed and prevent phase jumps.

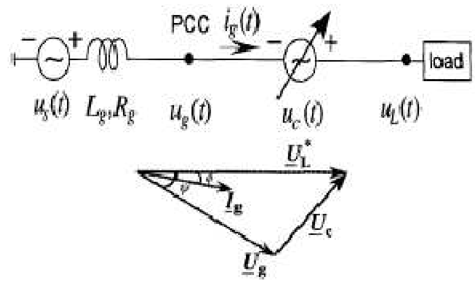

Fig. 3. *DVR operational principal: up) simplified equivalent circuit, down) Phasor diagram.*

A phasor diagram for a voltage dip with a phase-jump case is shown in Figure (down). From Figure, the load voltage is deduced:

$$u_L\ (t) = u_s(t) + u_c(t)$$

If the supply voltage u_s (t) has dropped due to a voltage dip or increased due to a voltage swells, the DVR compensating voltage u_c (t) should be controlled so that the load voltage remains the same as during no-disturbance conditions. Thus, the instantaneous amplitude of u_c (t) is controlled such as to eliminate any detrimental effects of a system fault to the load voltage as long as the disturbance does not cause the circuit breaker to open.

4.3. Block Diagram of DVR

A schematic diagram of the DVR incorporated into a distribution network is shown in Fig. V_s are the source voltage, V_1 is the incoming supply voltage before compensation, V_2 is the load voltage after compensation, V_{DVR} is the series injected voltage of the DVR, and I is the line current.

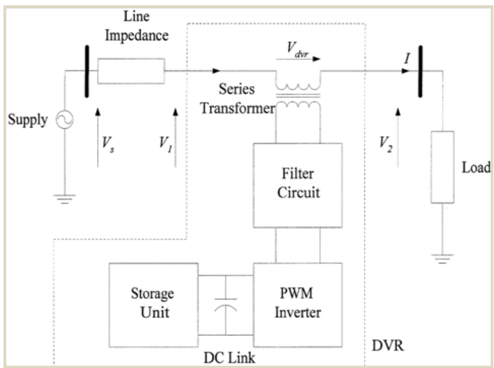

Fig. 4. *Typical schematic of a power distribution system compensated by a DVR.*

The restorer typically consists of an injection transformer, the secondary winding of which is connected in series with the distribution line, a voltage-sourced PWM Inverter Bridge is connected to the primary of the injection transformer (actually three single phase transformers) and an energy storage device is connected at the dc-link of the inverter bridge. The primary winding (connected in series with the line) of the transformer must be designed to carry the full line current. During the transient period at the occurrence of voltage sag, DVR booster transformer can experience a flux linkage that is up to twice its normal steady state value. In order to overcome the transformer from saturating a rating of flux i.e. twice that of steady state limit is used. An alternative method is to limit the flux linkage during the transient switch-on period, thus preventing saturation. The primary voltage rating of the transformer is the maximum voltage the DVR can inject into the line. The DVR rating (per phase), is the maximum injection voltage times the primary current. The bridges are independently controllable to allow each phase to be compensated separately. The inverter bridge output is filtered in order to mitigate the switching frequency harmonics generated in the inverter. The series injected voltage of the DVR V_{DVR} is synthesized by modulating pulse widths of the inverter-bridge switches. While online, the DVR can get heated-up due to switching and conduction losses in semiconductor switches. Therefore, it is necessary to provide proper means of heat sinking in order to operate the DVR safely and to increase the life-span of semiconductor switches.

The injection of an appropriate V_{DVR} in the face of an up-stream voltage disturbance requires a certain amount of real and reactive power supply from the DVR. The reactive power requirement is generated by the inverter. To inject the active power, energy storage is needed to increase the ride through capability of DVR. Ride through capability is the time that DVR can restore or sustain the output voltage to 100% of DVR rating. The available energy storage devices are batteries, capacitor banks, super capacitors, superconducting magnetic energy storage (SMES), flywheels, and he1 cells. The required active power can also be obtained from the grid through an AC/DC rectifier. In this case, a capacitor should be used to link the AC/DC rectifier with the converter. The capacitor size depends on the required active power to be injected and the voltage drop at its terminal during the discharge period.

The capacitor size is characterized as a time constant T, defined as the ratio between the stored energy at rated dc voltage and the rated apparent power of the converter as:

$$T = \frac{1}{2}\frac{CU^2{}_{dcN}}{S_N}$$

Where U_{dcN} is the nominal dc-converter voltage and S_N is its rated apparent power. The capacitor cost is approximately proportional to the square of its terminal voltage.

Another source of stored energy is batteries. They are much cheaper than capacitors per KJ. As the internal impedance of batteries is rather high, the amount of power that can be extracted from them is small, so that the cost per kW is still rather high. Batteries are more suitable for minute-scale events like interruptions. The disadvantage of using batteries is the required maintenance and their adverse environmental effects.

The flywheel has been used for a long time, as cheap short-term energy storage, particularly in machine applications. As the energy stored by the flywheel is directly proportional to the square of the operational speed, the higher speed and composite flywheel can provide a ride-through capability for voltage dips and momentary interruptions.

In SMES, the electricity is stored by circulating a current in a superconducting coil. Because no conversion of energy to other forms is involved (like the flywheel), the round-trip efficiency can be rather high. Choosing the suitable energy storage for DVR applications depends on the expected total cost and the designed rated power.

Startup:

At the moment, capacitors are the most commonly used energy storage for the DVR because they provide a fast discharging response and have no moving parts. To startup the DVR with a capacitor bank as energy storage, the capacitor bank should be charged to the rated dc voltage. Charging of the capacitor bank can be realized by exploiting a separate energy supply such as an electric generator operated by a diesel engine. This solution is considered a good solution for the DVR in the respect of being always ready and not affected by grid disturbances, but it would be very expensive and slow in response. Two other techniques can be implemented to charge the dc capacitor bank. One of them is based on using a shunt diode rectifier, which is placed either on the load side or the grid side. The other exploits the VSC of the DVR to charge its capacitor bank with a proper control algorithm. After charging the dc capacitor bank, the DVR is transferred to the idle state where the dc voltage is blocked by the valves of the VSC and the bypass switch. When a voltage dip is detected in the grid, the bypass switch is turned off and the DVR transfers to the compensating state.

4.4. Topologies of DVR

Different types of topologies for DVR are discussed in the literature, which are classified according to

4.4.1. Location of a DVR

a) DVR-medium voltage three wire system

b) DVR-low voltage four wire system

In both systems the main purpose is to inject a synchronous voltage during faults. The difference between a Low voltage connection and a Medium voltage connection is the flow of zero sequence currents and the generation of zero sequence voltages.

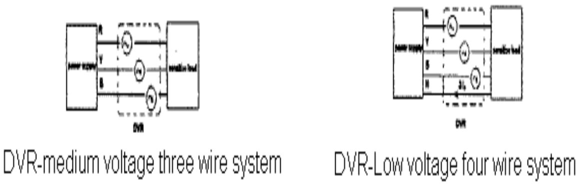

Fig. 5. *DVR with & low voltage*

4.4.2. Converter Type

Voltage sourced converters compensate for the missing voltage requires a boost inductance (L) and a line filter to damp the generated switching harmonics. Choosing a more complicated converter topology can help achieve low DVR impedance, low current ripple and low switching frequency, but the penalty is higher complexity.

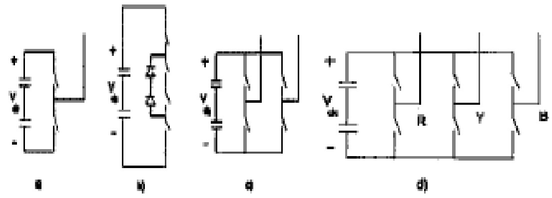

Fig. 6. *Different types of series converters for a DVR*

a) Two level (half bridge)
b) Three level (half bridge)
c) Three level (full bridge)
d) Series converter DVR with single 3-phase inverter block

4.4.3. Energy Source

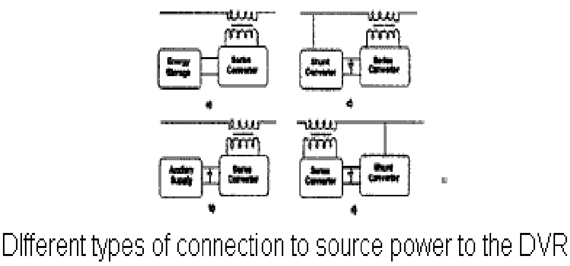

Fig. 7 *different types of connection*

a) Energy storage
b) Auxiliary supply
c) Front connected shunt converter
d) Back connected shunt converter

DVR needs the active power to restore the voltage waveform, which can be supplied from a Energy storage or auxiliary supply or from line connected shunt converter. The different topologies are illustrated in above figure.

4.4.4. Transformerless DVR

For the transformer less DVR scheme, the largest injection voltage is determined solely by DC- link voltage. Two topologies for transformer less DVR are shown below.

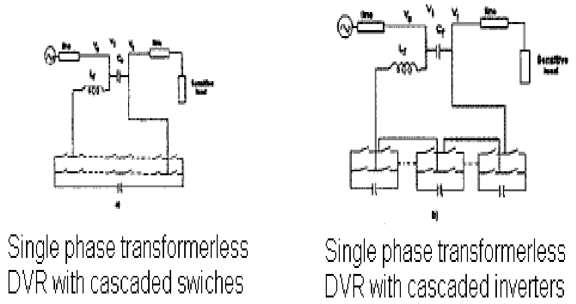

Fig. 8. *single phase Transformer less DVR*

The injection transformer used in the conventional DVR is expensive, occupies more space and contribute towards losses. From the design, operation maintenance point of view, the transformer is an added complexity to the restorer. The transformer less DVR can satisfactorily mitigate the voltage sag problems. The design is promising, less costly restorer and compact in size to conventional DVR. Transformer less DVR posses' superior voltage regulation property with less loss.

4.4.5. Filter

The filtering scheme in the Dynamic Voltage Restorer can be placed either line side or inverter side of the booster transformer. Due to the inverter switching operations harmonics are produced which should be filtered before the load. Using a properly designed filter, harmonic voltages can be attenuated.

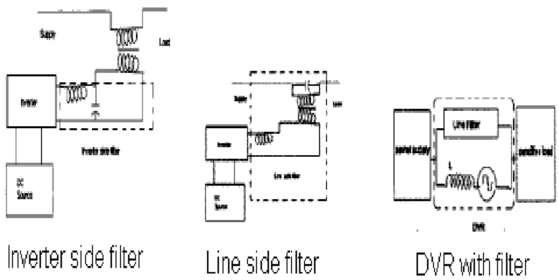

Fig. 9 *Different filters*

4.4.6. Dynamic SAG Correcter (Dy.SC)

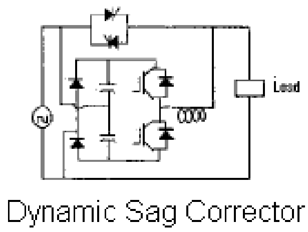

Fig. 10. *Dynamic sag corrector*

The series parallel connected Dynamic Sag Corrector provides statistically significant protection at greatly reduced cost. Above figure shows the schematics of a Dy.SC which is performing the DVR operation i.e.

eliminating voltage excursions. Dy.SC units have been shown to be smaller in size and lower cost, while providing a high level protection. Correction for sag down to 50% as well as protection from momentary loss of power has been demonstrated. Operating efficiency greater the 99%, response time is less than 1/8 cycles, long operation life of at least ten years. The Dy.SC is rated from 1.5kVA one phase to 2000kVA three phase and features a single stage power conversion circuit with minimal stored energy.

4.5. Features of DVR

- Extremely fast response less than $1/4^{th}$ cycle
- Expandable modular design
- Low maintenance
- High reliability
- Protection is available up to 120MVA

4.6. Compensation Techniques of DVR

After the detection of the voltage dip, the DVR starts *to* inject the correct three phase voltage to keep the load voltage unchanged. The response time of the control unit dedicates the transient time of the DVR. During the dip, the DVR works at a steady state, injecting the missing voltage in the grid until the grid recovers to its initial state before the dip. The operation of the DVR in steady state can be obtained via different compensation strategies. Such compensation strategies are illustrated in this section.

4.6.1. Voltage Difference Compensation

This is also called as pre-sag compensation. With the voltage difference compensation strategy, the injected voltage U_i is calculated by subtracting the grid voltage U_g from the reference of the load voltage U^*_L

$$\underline{U}_i = \underline{U}^*_L - \underline{U}_g$$

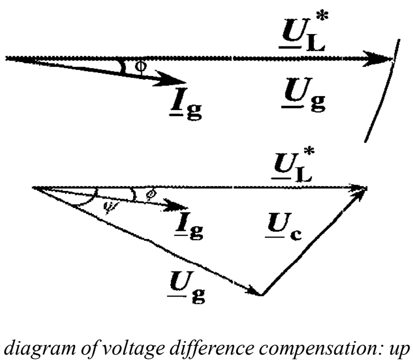

Fig. 11. Vector diagram of voltage difference compensation: up (before dip, bottom) after dip.

The vector diagram of voltage-difference compensation is shown in Figure Provided that the energy storage and the rated voltage of the DVR are large enough, the grid voltage can be placed anywhere inside the circle whose radius is the magnitude of the reference load voltage. Both the load voltage magnitude and phase angle are exactly the same as before the dip occurs. The disadvantage of this strategy is that it necessitates a big size of the energy storage, particularly if the DVR is sized to compensate for deeper dips.

4.6.2. In-Phase Compensation

With in-phase compensation strategy, the injected voltage is placed in phase with the grid voltage during the dip. The magnitude of the injected voltage is calculated by subtracting the magnitude of the grid voltage from the reference load voltage;

$$U_i = U^*_L - U_g$$

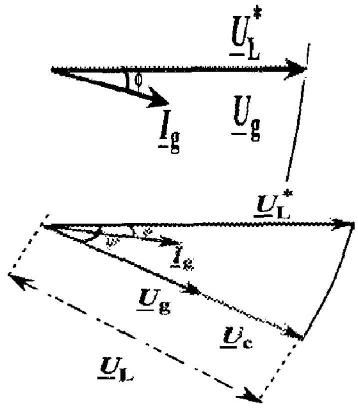

Fig. 12. Vector diagram of in-phase compensation: up) before dip, bottom) after dip.

If the grid voltage during the dip has a phase-angle jump, the load voltage will have a phase-angle jump as well. In other words, by this strategy only the magnitude of the load voltage is restored as depicted in Figure. The restored load voltage *CL* has the same phase jump as the grid voltage. In-phase voltage compensation results in maximum voltage boost. The magnitude of the injected voltage is minimized since there is no phase difference: between the input and the output voltage. According to the fact that in-phase compensation introduces a phase-angle jump to the load voltage, this phase angle jump may cause waveform discontinuity and inaccurate zero-crossings, which may cause, for instance, nuisance tripping of adjustable speed derives. In-phase compensation minimizes the magnitude of the injected voltage, or equivalently the rated voltage of the DVR, but its puts more demand on the size of the energy storage compared to voltage difference compensation. This is true in case of voltage dips with phase angle jump. If the voltage dip is not associated with a phase angle jump, the two methods (voltage difference and In-phase compensation) are equivalent.

4.6.3. ADVANCED Phase Compensation

It is also called as Energy optimal compensation. The injected active power can be: minimized by injecting a voltage into the grid with a phase advance with respect to the grid voltage during the dip. Zero injected active power can be realized when the injected voltage is orthogonal to the load current. This case is not always possible or it will result in partial compensation of the load voltage.

The vector diagram of the advanced phase compensation is depicted in Figure. Where the injected voltage $\underline{U}_C$ has a phase advance angle of β with respect to the grid voltage. The reduction in active power is subsidized by an increase in the reactive power, which is generated internally by the VSC of the DVR. This strategy demands lower energy storage compared with the voltage difference and in-phase compensation strategies. On the other hand, it introduces a phase-angle jump that will cause waveform discontinuity and inaccurate zero-crossings.

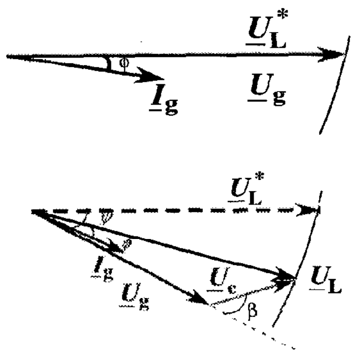

Fig. 13. Vector diagram of advanced phase compensation up a) before dip, bottom b) after dip.

It is worth noting that the magnitude of the injected voltage with the advanced phase compensation is larger than the one in case of in-phase compensation. As the phase advancement angle needs to be determined in real time, the control system is complex. There could be significant increase in the reactive power supplied by the DVR depending in the advance angle and nature of sag.

4.6.4. Progressive Advanced Phase Compensation

To overcome the problems associated with the phase angle jump introduced by the advanced phase compensation, the progressive advanced phase compensation has been proposed, but it has not been implemented yet. The strategy is based on making the phase advance of the injected voltage progressively in such a way that the load will not sense a rapid phase-angle jump. This is done by dividing the phase advance angle β(in above Figure) into small steps. The phase advance caused by this strategy should be removed after the distribution system recovers to its initial state before the dip. This is done through small backward steps. The response time of the DVR is longer, compared with other strategies, because of the delay introduced by the progressive phase advance.

4.7. Design Criteria and Rated Power Calculations

4.7.1. Design Criteria

The design of the DVR is affected by the load, the supply characteristics and by the expected voltage-clip characteristics. When designing for a DVR for certain application, the following items should be considered:

- Maximum load power and power factor: The load size strongly affects the current rating of the voltage-source converter and the injection transformer as well as the amount of energy storage needed.
- Maximum depth and duration of voltage dips to be corrected: These characteristics, together with the load size, dictate the necessary storage capacity of the energy storage device. The maximum depth determines the voltage rating of the voltage-source converter and the injection transformer. The maximum depth and duration of voltage dips to be corrected is determined by the statistics of the voltage dips at the DVR location and by the acceptable number of equipment trips.
- Maximum allowed voltage drop of the DVR during the standby mode: This affects the control mode during normal operation and indirectly the reaction speed at the beginning of a voltage dip.
- Coupling of the step-down transformer: (Y/Δ or Y/Y…..etc.) at input and output sides of the DVR.
- Parameters of the step-down transformers: Coupling of the step-down transformer *CIA* or *YIY,*. . .etc.) at input and output sides of the DVR.
- Harmonic requirements of the load and of the system: These affect the harmonic filtering needed for the DVR and also influence the choice of charging method for the capacitors.
- At the first instance when designing a DVR, some assumption could be made to simplify the analysis, such as:
  - Ideal switches
  - DC-side capacitors are large enough to maintain a ripple free DC bus voltage, even for unbalanced input voltage.
  - Series transformer and output filter components are ideal.

In order to design a DVR, the concept of "boost rating" is introduced to define the maximum voltage that the DVR is capable to inject into the power line with respect to the nominal distribution system voltage. This boost ratio is defined as

$$B = \frac{U_C}{U_{sl}/\sqrt{3}}$$

Here, U_{sl}, is the nominal line-to-line voltage of the supply.

4.7.2. Rated Power Calculations

The DVR function, in case of voltage dips, is to exchange real power between the power system and the energy storage. Reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without any ac passive reactive components. The real power injected by the DVR is an important feature to precede its design process. To calculate the active and the reactive power, a factor & is defined to indicate the reduction of the positive sequence voltage with respect to the nominal voltage of the load. For a certain supply voltage U, and required load voltage UL, the DVR injected voltage is written as:

$$\underline{U}_c = \underline{U}_L - \underline{U}_s = (1-\underline{M}_F)\,\underline{U}_L$$

The range of the modulus of $\underline{M}_F$ is defined by the maximum variation of $\underline{U}_s$, for which the DVR is designed. So, in normal operation $\underline{M}_F$ will be unity and $\underline{U}_c$ is zero.

$$\underline{M}_F = \underline{U}_s / \underline{U}_L$$

Considering the fact that the DVR current should be designed to be the same as the rated load current, the apparent power required by the DVR is then calculated in terms of the apparent load power, $\underline{S}_L$ and $\underline{M}_F$ by the following formula.

$$\underline{S}_c = \underline{S}_L\,(1-\underline{M}_F)$$

Consequently, the active and reactive powers are calculated by separating $\underline{S}_c$ into its real and imaginary parts as

$$\mathbf{P_c} = S_L\{\cos(\phi_L) - |\underline{M}_F|\cos(\phi_S)\}$$

$$\mathbf{Q_c} = S_L\{\sin(\phi_L) - |\underline{M}_F|\sin(\phi_S)\}$$

Where $\cos(\Phi_S)$ is the source power factor and $\cos(\Phi_L)$ is the load power factor.

$$\mathbf{P_c} = P_L\left\{1 - \frac{U_S\cos(\phi_L+\psi)}{\cos(\phi_L)}\right\}$$

In the above equation, the load voltage is assumed to be constant and equal to 1pu. So, the required active power of a DVR depends on the magnitude and the phase-angle jump of the supply voltage as well as the load power factor.

4.8. Control Strategies

Different control techniques to control the DVR have been reported in literature. Both the feed forward and feedback techniques have been implemented in the control unit of the DVR applications. Feed forward control technique does not sense the load voltage and it calculates the injected voltage based on the difference between the pre-dip and during-dip voltages. The load voltage is sensed in case of using feedback technique and the difference between the voltage reference of the load and actual load voltage is injected. Feedback structures however have inherent delay in responding to power system disturbances. To optimize the dynamic performance, a direct feed forward control should be used. The feed forward technique has been applied by measuring the supply voltages and computing the appropriate compensation voltages. The required voltage reference is obtained by synchronization with the phase voltage, without performing symmetrical component decomposition. The proposed control algorithm is implemented in a DSP as illustrated in below figure. The algorithm consists of the following steps: 1) calculation of the phase angle of the synchronization signal; 2) generating the reference voltages, and 3) computing the modulating signal. The proposed technique involves the calculation of the RMS of the fundamental voltage, which requires at least one half periods at the grid frequency. The switching frequency used in this *DVR* application is 20 kHz, which is considered to be a very high frequency. Higher switching frequencies lead to smaller current ripple which allows for a reduction in filter size.

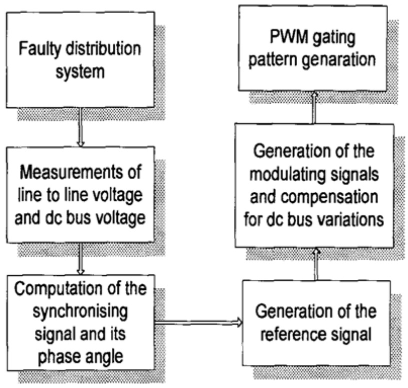

Fig. 14. *Feed forward control algorithm*

Vector control has been proposed to control the injected voltage by the DVR in order to improve the dynamic performance and rapidly restore the load voltage to the desired value. The principle of vector control is explained with the aid of Figure below. The grid voltage $u_1(t)$, $u_2(t)$, $u_3(t)$ is sampled and converted to the dq-frame (synchronous reference frame). It is desired that the d, and the *q* components of the load voltage are set as 0 and 1 pu respectively. The injected voltage is calculated by subtracting the grid voltage from the desired load voltage in the dq-frame and it is converted back to the three-phase frame. The voltages $\Delta u_1(t)$, $\Delta u_2(t)$, $\Delta u_3(t)$ are the voltage that the VSC should generate to restore the load voltage to the desired value.

This technique has a shorter response time compared with RMS calculation. However, only balanced voltage dips have been considered. To compensate for unbalanced dips, a separation technique for the positive and the negative sequence should be included in the control algorithm, or alternatively, a high switching frequency has to be used.

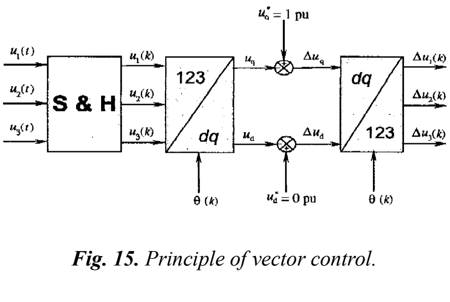

Fig. 15. *Principle of vector control.*

The DVC (Double Vector control) algorithm is implemented in the dq-frame and incorporates both current and voltage controllers with an inner current control loop and outer voltage control loop. However, only balanced voltage dips can be compensated. In case of unbalanced dips, the *d*- and q-components are not dc quantities and thus a conventional PI controller fails to track the reference signal properly. Because most faults are single- or double-phase, this algorithm uses a fast technique for separating positive and negative sequence components of the supply voltage, which are then controlled separately. Thus, two controllers have been implemented for the two sequences, each based on double vector control, i.e. constituted by a voltage-control loop and a current-control loop.

5. Simulation Results and Performance Evaluation

Case1: DVR performance results for symmetrical voltage dip from 320v to 260v at o.05sec to o.15sec

Here the dip in the source voltage is created during the interval 0.05 to 0.15sec. Now by the action of DVR it is injecting a voltage in series with the supply voltage in order to bring the voltage across the load to rated symmetrical voltage.

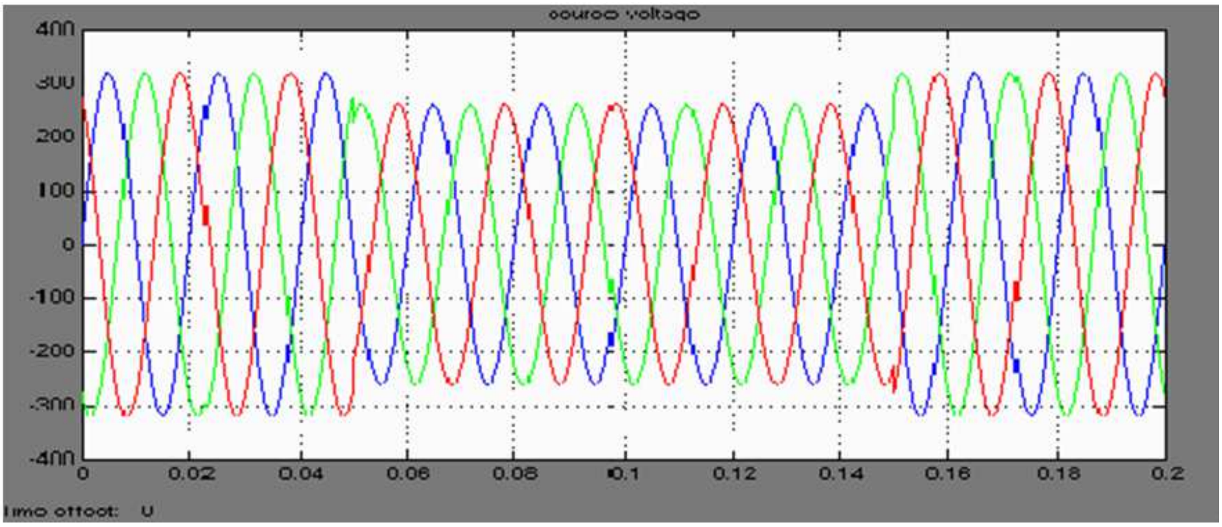

Fig. 16. *Source voltage*

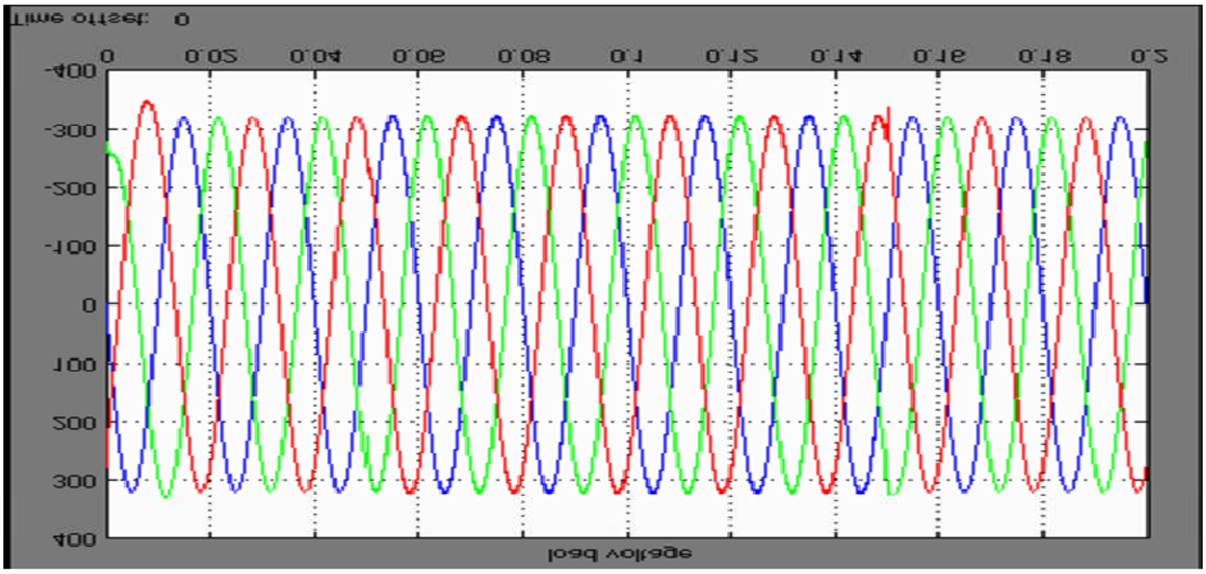

Fig. 17. *Load voltage*

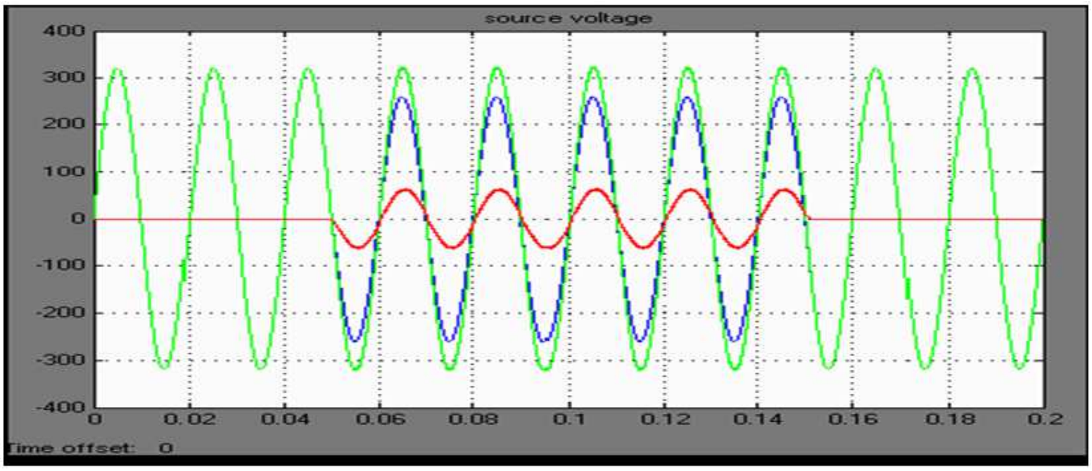

Fig. 18. *Phase 'a' source voltage, load voltage, injected voltage*

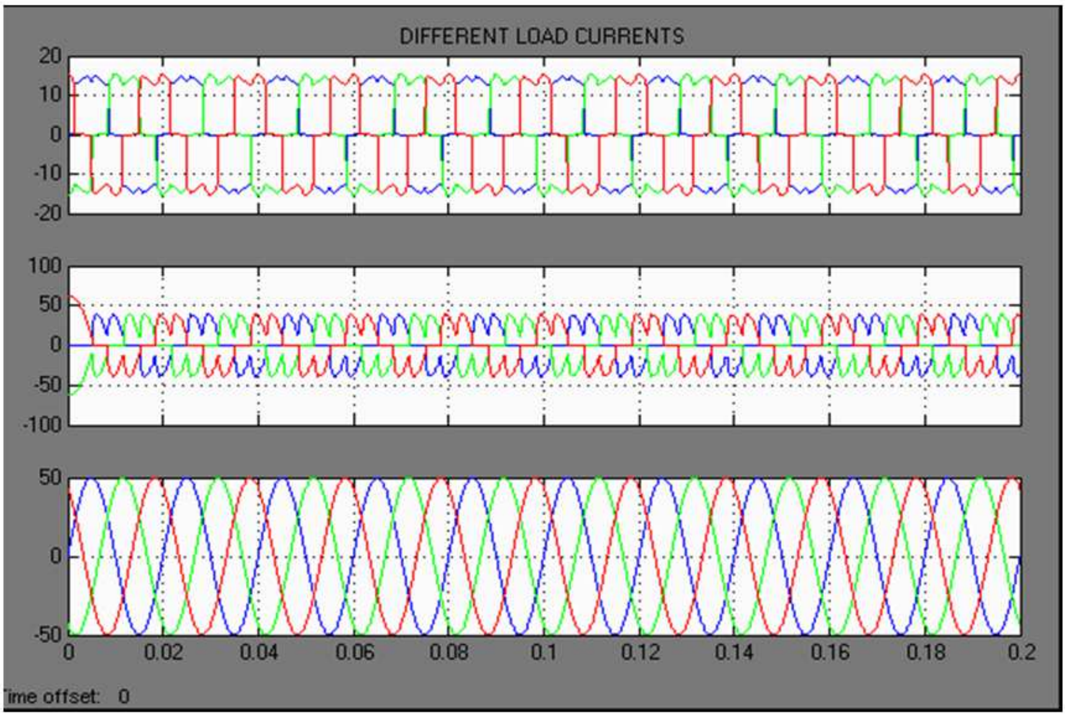

Fig. 19. *Different load currents*

6. Conclusions

This thesis has presented results from a DVR simulated at a low voltage level at a distribution end. The test voltage sags and swells were created using general sine wave generator blocks. The simulation results showed that the DVR could protect a sensitive load on a distribution network for three phase or two phase or single phase sags or swells. This model will yield a performance which simply does not depend on the load current, since this model has no impedance anywhere. But in practice the output voltage will get affected by load harmonics due to two reasons – the inverter output filter will call for harmonic drops when harmonic load currents flow through it and in the absence of feedback control, the system does not correct anything to the right of the inverter. Secondly the finite bandwidth of inverter (due to a finite switching frequency) will make it fail in generating high frequency current produced at the source bus by high frequency component of load currents flowing in source impedance (which is taken as zero in this *simulink* model).

The control of DVR is not a complex problem; field experience justifies feed forward control. However providing a suitable DC side energy source to handle long periods of sag or swell throughout the day will be a problem. If it is a battery it requires a charger. Some researchers have proposed drawing charging power from the line using the same inverter during periods which sag or swell is little and can be handled by 90^0 voltage injection. But that makes the control pretty complex. If it is a AC-DC diode rectifier the DVR can handle only sags and not swells since during swells the inverter will absorb power (in the in phase injection strategy) and dump it on the DC side. So then it has to be a bilateral converter based AC-DC converter and then we get very close to what they call ‘Unified Power Quality Conditioner’- then it is no more a DVR alone, but can easily become a UPQC.

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