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ENHANCEMENT OF VOLTAGE PROFILE USING DYNAMIC VOLTAGE RESTORER

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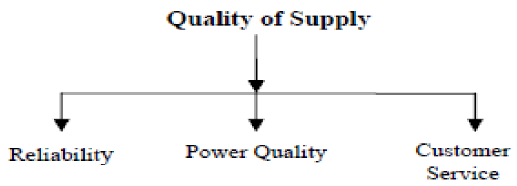
Abstract: Numerous type of power quality issues and power problems each of which might have varying and diverse causes. Typical power quality problems include voltage sag, voltage swell, harmonics, notching etc. Control of power quality problems involves cooperation between network operator (utility), customer and equipment manufacturer. A Dynamic Voltage Restorer (DVR) is a distribution voltage DC-to-AC solid-state switching converter that injects three single phase AC output voltages in series with the distribution feeder and in synchronism with the voltages of the distribution system. A DVR is interface equipment between utility and customer connected in series between the supply and load to mitigate the three major power quality problems, namely, the voltage sags, swells, and interruptions.

I. INTRODUCTION

A. Back Ground:

Power quality may be defined as any power problems manifested in voltage, current or frequency deviations that results in failure or mis -operation of customers equipment. Both electric utilities and end users of electrical power are becoming increasingly concerned about the quality of electric power. Power quality is an umbrella concept for multitude of individual types of power system disturbances. The issues that fall under this umbrella are not necessarily new. What is new is that engineers are now attempting to deal with these issues with a systems approach rather than as individual problems. One important and noticeable change seen is that the quality of electricity supplied is now subject to legislation which considers it to be no different from other goods and services. Quality of Supply may be categorized as below:



Just a few years ago, momentary power outages, sags, swells, surges had relatively little effect on most industrial processes. Today, manufacturing systems, sensitive telemetry, and precision electronic equipment can be disturbed, halted, or even damaged by voltage sag of two or three electrical cycles. Production losses can soar. Power Quality problems evidence themselves in a variety of ways such as: Computer shut down, malfunction of errors, PLC (Programmable Logic Controller) malfunction or errors, variable speed drives tripping out, racing or blinking digital clocks, etc. These can give problems ranging from inconvenience to loss of manufacturing capability with substantial loss in income Understanding Power Quality and the range of associated problems becomes very important to mitigate the problems. The ideal power supply to a low voltage customer is 240 / 415 V at 50 Hz with a sinusoidal wave shape. The electricity supplier through his local network cannot keep the supply exactly at the ideal due to a range of disturbances outside its control and attempts to maintain its voltage within specified ranges. Power Quality problems arise when these ranges are exceeded and this can occur in three ways

a) Frequency events: change of the supply frequency outside of the normal range

b) Voltage events: change of the voltage amplitude outside its normal range (may occur for very short periods or be sustained)

c) Waveform events: distortion of the voltage waveform outside the normal range.

Actual voltage varies from the normal range because of disturbances on the supply system, within customer's plant and / or within nearby plants. These disturbances can

i. Damage sensitive data processing, control and instrumentation equipment

ii. Interrupt supply

iii. Trip out variable speed drives

iv. Cause data processing, control and instrumentation equipment to malfunction

v. Cause capacitors, transformers and induction motors to overheat

vi. Cause annoying light flicker

While the electricity supplier (local network operator) has the responsibility of keeping the power supply voltage within specified limits, Customers have two basic responsibilities:

1) To ensure that their equipment is able to tolerate the normal range of supply disturbances (in accordance with the regulations)

2) To ensure that their equipment does not cause disturbances which will propagate into Supply system at an excessive level (this is very important aspect of power quality)Frequency, Voltage and Waveform events are the basic types of power quality disturbances. The frequency of a power system is established by the rotational speed of the power station generators and it is very rare that this frequency is significantly varied and it is not further discussed in this paper. Waveform events result in distortion of the normal sinusoidal wave shapes of the mains voltage.

Harmonics, Inter-harmonics, notching, transients, noise disturbance etc. and these are mostly caused by the consumers of electricity due to their equipment, particularly power electronic related equipment and induction motors. These are also not further discussed in this paper. The third type of power quality disturbance, viz, Voltage events are considered in this paper. The role and certain deign aspects of Dynamic Voltage Restorer (DVR) to mitigate the power quality problems related with the voltage events are presented here. The voltage is normally held in the range of ± 6%

Voltage variations can be divided into several categories:
i. Long term variations lasting more than 1 minute,
ii. Short term variations of duration less than 1 minute, called sags (voltages between 10% and 90% of nominal) or swells (voltage greater than 110% of nominal). These are shown in
iii. Voltage unbalance where the voltage on each phase conductor is different.
iv. Continuous or random fluctuations that are observed as light flicker
v. Interruptions where supply is lost completely
vi. Neutral-ground voltage rises that are usually
Associated with poor grounding/earthing practices.

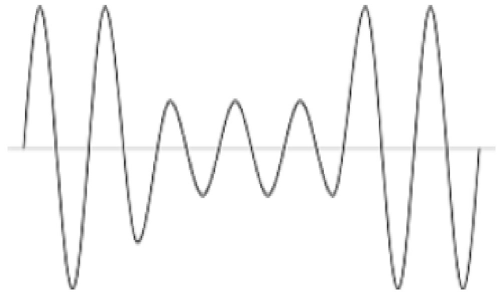
Power quality problems can originate at the supply system, or the customer's plant or even a neighboring installation which could propagate via the supply. Some effects of power quality disturbances for the voltage events are shown in the following Table

Disturbance	*Effect*
Over voltage	Overstress insulation
Under voltage	Excessive motor current
Unbalance	Motor heating
Neutral-ground voltage	Digital device malfunction
Interruption	Complete shut down
Sag	Variable speed drive & computer trip-out
Swell	Overstress insulation
Fluctuations	Light flicker

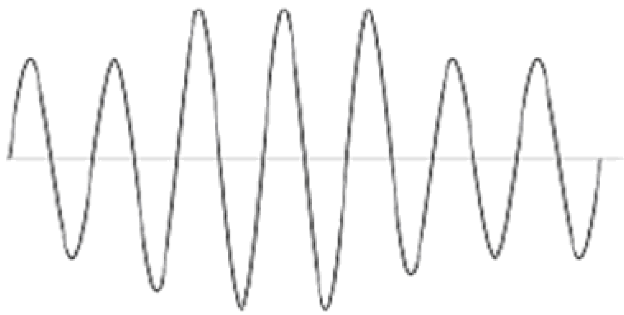
Disturbance Effect
Over voltage Overstress insulation
Under voltage Excessive motor current
Unbalance Motor heating
Neutral-ground voltage Digital device malfunction
Interruption Complete shut down
Sag Variable speed drive & computer trip-out
Swell Overstress insulation
Fluctuations Light flicker

II. VOLTAGE SAG / SWELL

Voltage sag/swell that occurs more frequently than any other power quality phenomenon is known as the most important power quality problems in the power distribution systems. And Voltage sag is defined as a sudden reduction of supply voltage down 90% to 10% of nominal. According to the standard, a typical duration of sag is from l0 ms to 1 minute.



On the other hand, voltage swell is defined as a sudden increasing of supply voltage up 1l0% to 180% in rms voltage at the network fundamental frequency with duration from 10 ms to 1 minute



Voltage sag/swell often are caused by faults such as single line-to-ground fault, double line-to ground fault on the power distribution system or due to starting of large induction motors or energizing a large capacitor bank. Voltage sag/swell can interrupt or lead to malfunction of any electric equipment which is sensitive to voltage variations

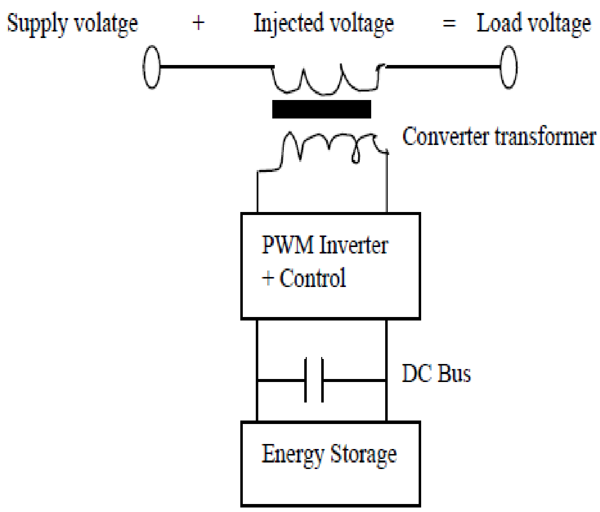
A. Mitigation of Power Quality Problems:

Power quality problems can be mitigated with the following practices: Proper earthing and its verification, Uninterruptible Power supplies (UPS), Local or embedded generation (such as diesel generators, microturbines, fuel cells, stirling engines, etc), Transfer switches, Static breakers, Active filters, Static VAR compensators (SVC), Passive filters, Energy storage systems, Ferro-resonant transformers, DVRs etc. The interface between the system and the equipment is the most common place to mitigate sags and interruptions. A DVR is one of such utility-customer interface equipment designed to mitigate the power quality problems associated with voltage sags, swells and interruptions,

III. DYNAMIC VOLTAGE RESTORER

A DVR, Dynamic Voltage Restorer is a distribution voltage DC-to-AC solid-state switching converter that injects three single phase AC output voltages in series with the distribution feeder, and in synchronism with the voltages of the distribution system. By injecting voltages of controllable amplitude, phase angle, and frequency (harmonic) into the distribution feeder in instantaneous real time via a series-injection transformer, the DVR can restore the quality of voltage at its load side terminals when the quality of the source side terminal voltage is significantly out of specification for sensitive load equipment. It is designed to mitigate voltage sags and swells on lines feeding sensitive equipment. A viable alternative to uninterruptible power systems (UPS) and other utilization solutions to the voltage sag problem, the DVR is specially designed for large loads of the order of 2 MVA to 10 MVA served at distribution voltage. A DVR typically requires less than one-third the nominal power rating of the UPS [6]. DVR can also be used to mitigate troublesome harmonic voltages on the distribution system.

DVR comprises of three main parts:
1. Inverter
2. DC energy storage
3. Control system
The basic block diagram of a DVR is shown in Figure 3

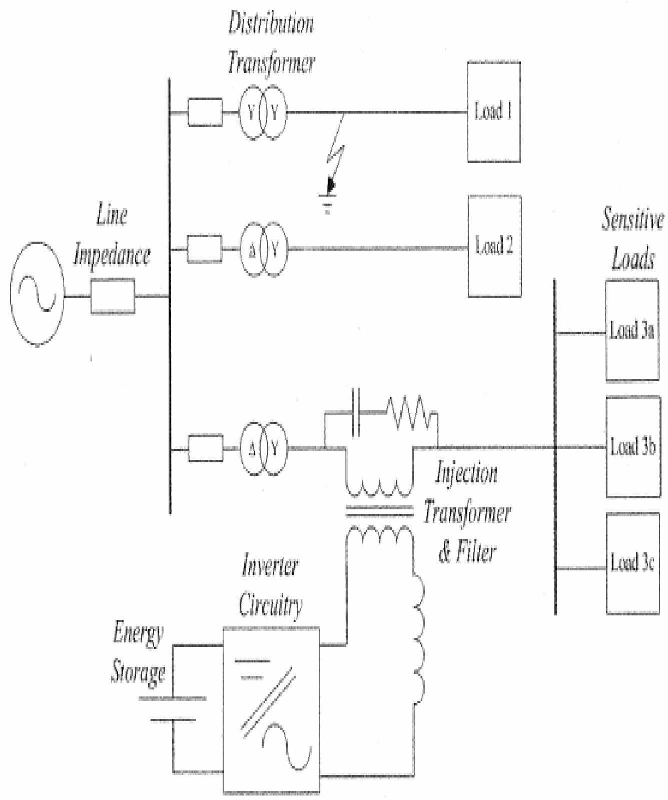


A. Basic Principle

The basic idea of a DVR is to inject the missing voltage cycles into the system through series injection transformer whenever voltage sags are present in the system supply voltage. As a consequence, sag is unseen by the loads. During normal operation, the capacitor receives energy from the main supply source. When voltage dip or sags are detected, the capacitor d elivers dc supply to the inverter. The inverter ensures that only the missing voltage is injected to the transformer. A relatively small capacitor is present on dc side of the PWM solid state inverter and the voltage over this capacitor is kept constant, by exchanging energy with the energy storage reservoir. The required output voltage is obtained by using pulse-width modulation switching pattern. As the controller will have to supply active as well as reactive power, some kind of energy storage is needed. In the DVRs that are commercially available now large capacitors are used as a source of energy. Other potential sources are being considered are: battery banks, superconducting coils, and flywheel.

IV. CONSTRUCTION OF DVR

fig shows placing of DVR in system

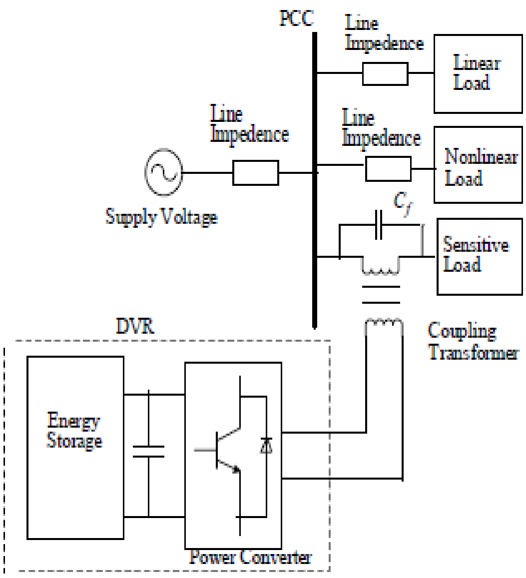


V. DVR COMPONENTS

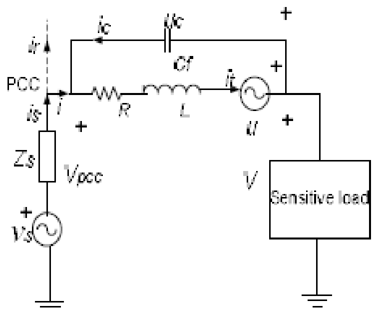
With reference to Fig. the main components of DVR are
1) Energy Storage Unit: The required energy for compensation of load voltage during sag can be taken either from an external energy storage unit (batteries) or from the supply line feeder
Through a rectifier and a capacitor.
2) Inverter Circuit: Since the vast majority of voltage sags seen on utility systems are unbalanced, mostly due to single-phase events, the VSC will often be required to operate with unbalanced switching functions for the three phases, and must therefore treat each phase
Independently. Mitigation of Voltage Sags in a Refinery with Induction Motors Using Dynamic Voltage Restorer (DVR) 121 Moreover, a sag on one phase may result in a swell on another phase, so the VSC must be capable of handling both sags and swells simultaneously. The variable output voltage

of the inverter is achieved using PWM scheme.
3) Filter Unit: The nonlinear characteristics of semiconductor devices cause distorted waveforms associated with high frequency harmonics at the inverter output. To overcome this problem and provide high quality energy supply, a harmonic filtering unit is used. This can cause voltage drop and phase shift in the fundamental component of the inverter output, and has to be accounted for in the compensation voltage.
4) Series Injection Transformers: Three single-phase injection transformers are used to inject the missing voltage to the system at the load bus. To integrate the injection transformer correctly into the DVR, the MVA rating, the primary winding voltage and current ratings, the turn-ratio and the short-circuit impedance values of transformers are required. The existence of the transformers allow for the design of the DVR in a lower voltage level, depending upon the stepping up ratio. In such case, the limiting factor will be the ability of the inverter switches to withstand higher currents.
5) Controller and auxiliary circuits: By-Pass switches, breakers, measuring and protection relays are some auxiliaries to the DVR block, in addition to the controller of the DVR.

VI. EQUIVALENT CIRCUIT DIAGRAM



System configuration with DVR



Equivalent circuit diagram of DVR connected with circuit configuration

Equivalent circuit of the test system connected with DVR is shown in Fig. Supply voltage is represented by vs, Zs represents the line impedance, is is the current injected by the supply which splits at the PCC into the current flowing through the sensitive equipment i and the current injected to the loads ir. The voltage Vpcc is the voltage across the PCC and the DVR can be modeled as an ideal voltage source and is represented by u, the resistance and leakage inductance of the coupling transformer are represented by R and L. Cf is the capacitor used together with the coupling transformer leakage inductance to filter out the high- frequency harmonics. The voltage across the sensitive equipment is

$$v(t) = V_{pcc}(t) + u_c(t)$$

where v(t) and uc(t) are the voltage across the sensitive equipment and filter capacitor respectively. The state variable model for the coupling transformer and the capacitor set is

$$\frac{d}{dt}\begin{bmatrix} it(t) \\ uc(t) \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \frac{1}{L} \\ \frac{1}{Cf} & 0 \end{bmatrix}\begin{bmatrix} it(t) \\ uc(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{Cf} \end{bmatrix}\begin{bmatrix} u(t) \\ i(t) \end{bmatrix}$$

where, it(t) and uc(t) are the state variables , u(t) represents the control input and i(t) is a disturbance input.

VII. DVR OPERATION

The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without any AV passive reactive components, i.e. reactors and capacitors. For deep sags (large variations) in the source voltage, the DVR supplies partial power to the load from a rechargeable energy source attached to the DVR dc terminal. The DVR with its three single phase independent control and inverter design is able to restore line voltage of critical loads during sags caused by unsymmetrical line to ground, line to line, double line to ground faults, as well as symmetrical three phase faults on adjacent feeders or disturbances that may originate many kilometers away on the higher voltage interconnected transmission. During normal line voltage conditions following sag, the energy storage device is recharged from ac supply system by the DVR. Even without stored energy the DVR can compensate for the variations of terminal voltage due to load variations by injecting a lagging voltage in quadrature with the load current thus providing continuously variable series capacitive line compensation. The DVR can also limit fault currents by injecting voltage vector during the fault that opposes the source voltage and maintains the fault current to an arbitrary low value. Voltage dips or sags can originate with faults at customer site, the local distribution system, or the transmission system. Studies have shown that transmission faults, while relatively rare in the basis of faults per mile of transmission, can cause widespread sags that may constitute source of process interruptions for very long distances from the faulted point Distribution faults are considerably more common but the resulting sags are more geographically limited. A DVR is primarily for use at the distribution level, where the basic principle is to inject a voltage in series with the supply when an upstream fault is detected. Loads connected downstream of the DVR are thus protected from any voltage sags caused by faults elsewhere on the network. Typical location of a DVR in a power network is shown in Fig Such a location eliminates the need to control the zero sequence in a 3-phase distribution system. The Dynamic Voltage Restorer (DVR) is a promising and effective device for power quality enhancement due to its quick response and high reliability. Associated with the DVR is its energy-saving compensation control method which is considered to be attractive. It necessitates the injected voltage to effect a phase angle adjustment in the load-side voltage so as to maximize the use of the stored energy of the DVR

VIII. DVR INJECTION STRATEGIES

The most popular voltage injection strategies in literature are

A. Pre-sag compensation method

The DVR injects the difference (missing) voltage between during-sag and pre-sag voltages to the system, the DVR must compensate for both magnitude and angle, as shown in Fig. 4(a). It is the best solution to obtain the same load voltage as the pre-fault voltage and is best suited for loads sensitive to phase angle jumps like angle-triggered thyristors-controlled loads. voltage is equal to the load voltage VL, both are equal to 1 p.u. with zero angle. During sag, the system voltage decreases to a value of Vs less than 1 p.u., this reduction in voltage is associated with a phase angle jump δ. The DVR reacts to the sag event and injects a compensating voltage Vdvr to restore the voltage at the load to pre-sag conditions of both magnitude and angle. The method gives nearly undisturbed load voltage. The magnitude of the required voltage by the DVR can be calculated as follows:

$$V_{dvr} = \sqrt{V_L^2 + V_s^2 - 2\, V_L V_s \cos\delta}$$

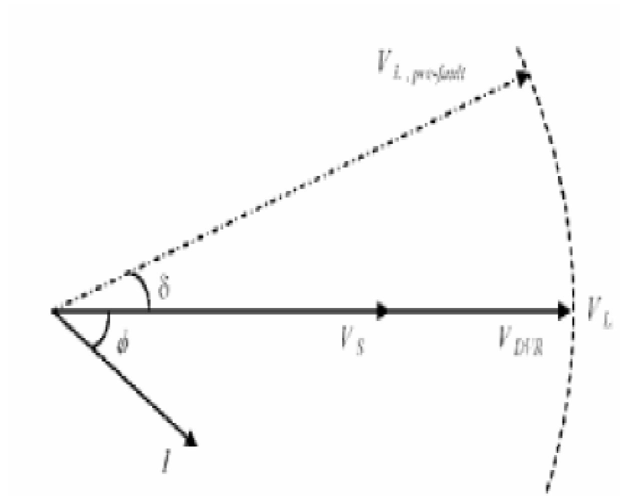
Whereas the required phase angle θ to be compensated can be calculated as follows:

$$\theta_{dvr} = \tan^{-1} \frac{V_s \sin\delta}{V_s \cos\delta - V_L}$$

B. In-phase voltage injection method

The injected voltage is in phase with supply voltage, as shown in Fig. 4(b). The phase angles of the pre-sag and load voltage are different but the most important criteria for power quality that is the constant magnitude of load voltage is satisfied.

Figure: In-phase Compensation (Magnitude compensation only)



In this configuration, the DVR is designed to compensate the voltage magnitude only. Again, the pre-sag voltage is 1 p.u. with zero angle, and during the sag, the system voltage decreases to VL with a phase angle δ. The DVR injects a compensating voltage Vdvr in phase with the system voltage VL, to boost the voltage up to the pre-sag voltage magnitude Vs, with no attention to the angle δ. This method is suitable for loads that can withstand phase angle jumps, which is a typical case for induction motor loads which comprise a large portion of the industrial power system, with no sensitive equipment such as ASDs or any equipment depending in its operation on phase-triggered switches. This method is very simple in implementation, very fast especially in calculating the DVR compensation voltage, which is obviously calculated as:

|Vdvr| = |VL| - |Vs|

And there is no intention for tracking or compensating the phase angle.

IX. MODES OF OPERATION

The DVR may be operated in:

a) Standby mode, where the inverter is not active in the circuit to keep the losses to minimum.

b) Active mode, where the DVR senses the sag and reacts as fast as possible to inject the required three phase compensation voltages.

c) Bypass mode, where the DVR is disconnected and bypassed in case of short circuit occurring inside the facility to protect its sensitive components from excessive short circuit currents.

X. CONTROL STRATEGIES

Control strategies fall mainly in one of the following two categories

a) Linear control methods Comprising the feedback, the feed-foreword, and the combined feed controllers. Mitigation of Voltage Sags in a Refinery with Induction Motors Using Dynamic Voltage Restorer (DVR) 123

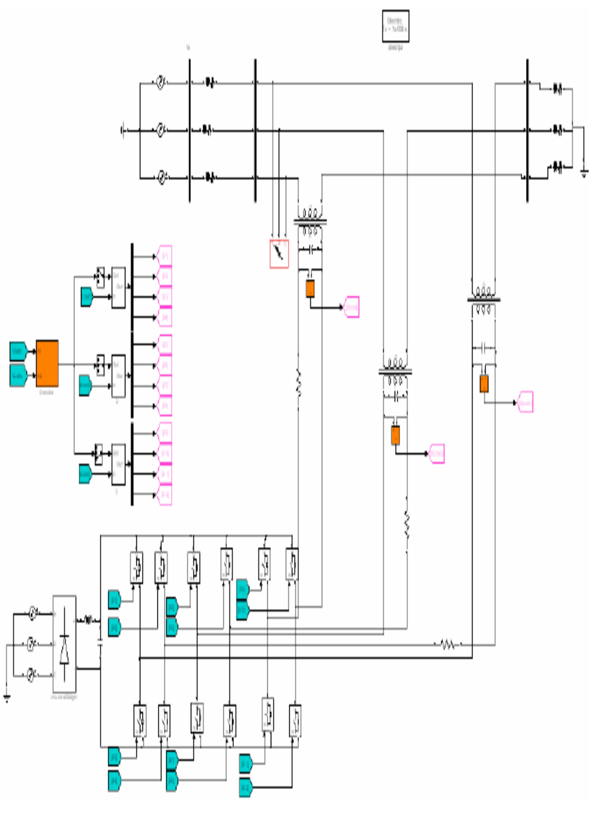
b) Non-Linear control methods Comprising the Artificial Neural Networks (ANN), the Fuzzy

Logic (FL), and the Space Vector (SV) controllers. Although feedback controllers are popular, they require load and source tracking, whereas feedforeword controllers are much simpler yet open-looped, there is no feedback from the load voltage or current.

XI. APPLICATION OF DVR

Voltage sags are voltage reduction events, followed by restoration of the normal supply conditions after a short duration. Voltage sags can cause large induction motors in a continuous process industry (like a refinery) to trip, leading to costly shutdowns. The Dynamic Voltage Restorer (DVR) is a power electronic based device used to boost the voltage supplied to the loads during voltage sags. Only the magnitude of the voltage is tracked and compared with reference voltage aiming at simple controller. The controller is based on feed-foreword control scheme aiming at fast response of the DVR. The DVR is controlled to operate in a standby mode for minimizing conduction losses. The industrial distribution system at Alexandria National Refining and Petrochemicals Co. (ANRPC) is taken as a case study. Simulations using the MATLAB /Simulink are carried out to confirm the validity of the proposed DVR. Simulation results have shown that the proposed DVR is an efficient tool in mitigating both sags and swells within a cycle. It can mitigate consecutive, multistage, balanced and unbalanced sags. The only shortcoming of the DVR is, being a series device, its inability to mitigate complete interruptions.

XII. SIMULATION MODEL OF DVR:



XIII. CONCLUSION

The Dynamic Voltage Restorer (DVR) is a promising and effective device for power quality enhancement due to its quick response and high reliability. The conclusion is that the DVR is an effective apparatus to protect sensitive loads from short duration voltage dips. The DVR can be inserted both at the low voltage level and at medium voltage level. The series connection with the existing supply voltages makes it effective at locations where voltage dips are the primary problem. However, the series connection makes the protection equipment more complex as well as the continuous conduction losses and voltage drop.

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