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Series Compensation Technique for Voltage Sag Mitigation

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ABSTRACT: *- Modern industrial processes are based on a large amount of electronic devices such as programmable logic controllers and adjustable speed drives. Unfortunately, electronic devices are sensitive to disturbances, and thus, industrial loads become less tolerant to power quality problems such as voltage sags, voltage swells, and harmonics. Voltage sags are an important power quality problem for which the dynamic voltage restorer (DVR) is known as an effective device to mitigate them. The dynamic voltage restorer (DVR) has become popular as a cost effective solution for the protection of sensitive loads from voltage sags and swells. A control method is used in this paper that is Phase Locked Loop.A phase locked loop is used to keep the load voltage synchronized continuously and track the source voltage. It is shown that the proposed method improves the performance of the DVR.*

This paper deals with modeling and simulation of a Dynamic Voltage Restore (DVR) for mitigation of voltage sags. Effectiveness of proposed technique is investigated through computer simulation by using MATLAB/SIMULNK software.

Key words: *- DVR, Phase Locked Loop, Voltage Sag, Voltage swell.*

I. INTRODUCTION

1.1 Problems in Distribution System

Nowadays, more and more power electronics equipment, so-called “sensitive equipment”, are used in the industrial process to attain high automatic ability. Susceptibility of these end-user devices draws attention of both end customers and suppliers to the questions of power quality, especially, short duration power disturbances, such as voltage dips, swells and short interruptions. The most common form of power quality disruption is the voltage sag, which accounts 70% of all power disturbances.

Several voltage sags can result in total equipment shutdown having the same effect as outage sag of normally below 20% of nominal voltage will result equipment shutdown and the voltage sags that occurs during the operation of the equipment will cause a reduction in the life span and efficiency of these devices. Voltage sags are classified as temporary voltage disruptions that result in a voltage wave form at the terminals of a load that is less than the nominal voltage, which can be between 0.1 and 0.9 per units rms. This reduction in voltage magnitude typically lasts equipment shutdown anywhere between 5 to 30 cycles. Its magnitude and length of duration are important characteristics in determining the severity of the voltage sag.

II. VOLTAGE SAG AND MITIGATION TECHNIQUES

2.1 Voltage Sag

A Voltage Sag as defined by IEEE Standard 1159 - 1995, IEEE Recommended Practice for Monitoring Electric Power Quality, is a decrease in RMS voltage at the power frequency for durations from 0.5 cycles to 1 minute, reported as the remaining voltage.

The measurement of a Voltage Sag is stated as a percentage of the nominal voltage; it is a measurement of the remaining voltage and is stated as a sag to a percentage value. Thus a Voltage Sag to 60% is equivalent to 60% of nominal voltage, or 264 Volts for a nominal 440 Volt system. Voltage sag for a three phase system is shown in fig (2.1).

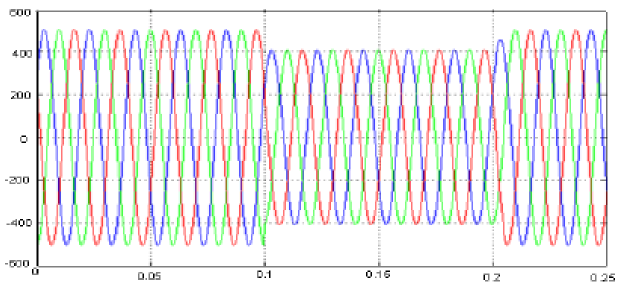


Figure 2.1: Three phase voltage sag

2.2 Multi Phase Sags and Single Phase Sags

They are three types of sags based on the number of phases are as follows.

2.2.1 Single Phase Sags

The most common voltage sags, over 70%, are single phase events which are typically due to a phase to ground fault occurring somewhere on the system. This phase to ground fault appears as a single phase voltage sag on other feeders from the same substation. Typical causes are lightning strikes, tree branches, animal contact etc. It is not uncommon to see single phase voltage sags upto 30% of nominal voltage or even lower in industrial plants.

2.2.2 Phase to Phase Sags

Two Phase, phase to phase sags may be caused by tree branches, adverse weather, animals or vehicle collision with utility poles. The two phase voltage sag will typically appear on other feeders from the same substation.

2.2.3 Three Phase Sags

Symmetrical three phase sags account for less than 20% of all sag events and are caused either by switching or tripping of a three phase circuit breaker, switch or recloser which will create three phase voltage sag on other lines fed from the same substation. Three phase sags will also be caused by starting large motors but this type of event typically causes voltage sags to approximately 80% of nominal voltage and is usually confined to an industrial plant or its immediate neighbor.

2.3 Sag Mitigation Techniques

Different devices are currently available for the mitigation of power quality problems. Correct understanding of their features, as well as that of load requirements, is needed for their proper application. To provide voltage sag ride-through capability, the different solutions available always include some kind of energy storage. Some methods of sag mitigation techniques [9] are described bellow.

2.3.1 Flexible AC Transmission Systems (FACTS) Devices

FACTS devices can be divided into three categories such as series controller, shunt controller, and combined controller.

Series connected controllers:

Static Synchronous Series Compensator (SSSC), Thyristor-Switched Series Capacitor (TSSC), Thyristor-Switched Series Reactor (TSSR), Dynamic voltage restorer (DVR), etc.

Shunt connected controllers:

Static Synchronous Generator (SSG), Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Reactor (TCR), Thyristor-Switched Capacitor (TSC), etc. Combined controllers: Unified Power Flow Controller (UPFC), Thyristor- Controlled Phase Shifting Transformer (TCPST), etc.

2.3.1.1 Series Compensation Method

A dynamic voltage restorer (DVR) was introduced for mitigating a voltage sag. The DVR shown in Fig 2.2 is based on an Voltage source converter (VSC) system that has energy storage for supplying active power, an output filter to make output voltage wave sinusoidal, and a step up transformer connected in series with line.

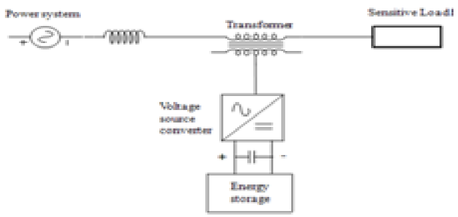


Fig 2.2Configuration of DVR

A DVR is configured as a series-connected voltage controller. To control the output voltage of the DVR, the inverter supplies the missing load voltage using self-commutable electronic switches such as a gate turn-off thyristor (GTO), or an insulated gate bipolar transistor (IGBT), or an insulated gate commutated thyristor (IGCT). A DVR injects the missing voltage in series; it can be called a series voltage controller, but the term DVR is commonly used now. The advantages of the DVR are fast response, ability to compensate for a voltage sag and a voltage phase shift using an inverter system.

Three schemes can be used to generate the missing voltage in series with the source voltage for compensating the voltage sag such as,

- In-phase voltage injection
- Phase-invariant voltage injection
- Phase advanced voltage injection

In the in-phase voltage injection scheme, the injecting voltage has the same phase angle of the source voltage. Therefore, the magnitude of the injected voltage is the smallest among three compensation schemes. However, this scheme requires the largest active power. In case of the phase invariant voltage injection scheme, the DVR injects the missing voltage that keeps the magnitude of the voltage as well as the phase of the supply voltage. This scheme needs a large injected voltage and may cause over injection of reactive power. Since the size of energy storage is closely related to the requirement of active power, various compensation methods to reduce the requirement of active energy have been proposed.

If the injected voltage is in quadrature with the load current, the DVR does not inject active power. This scheme is highly dependent on the load power factor and may generate a sudden jump of the voltage phase angle. To avoid sudden phase angle jump, the phase of the injected voltage should be gradually changed at the beginning of the compensation as well as at the restoration in order not to disturb the operation of sensitive loads. The high-speed PWM switching and output filter makes it possible to achieve a fast response with less harmonic distortion. However, DVR are expensive because of the converter systems, the inserting transformer, and energy storages to supply active and reactive power for the missing voltage.

2.3.1.2 Shunt Compensation Method (D-STATCOM)

A distribution static synchronous compensator (D-STATCOM) is shown in Fig2.3. which controls the load voltage in a shunt configuration. The D-STATCOM injects a current to compensate the load voltage variation.

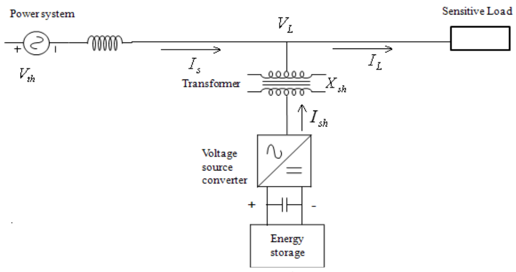


Figure2.3: Schematic of a D-STATCOM

D-STATCOM mainly consists of the inverter circuit with Xsh coupling inductance, The leakage inductance of the transformer. Also, the D-STATCOM, a shunt-connected voltage controller, is connected to the critical load with system impedance. The effectiveness of D-STATCOM depends on the source impedance Zth and the fault level. When the phase of the Vsh is in quadrature with the Ish, without injecting real power the D-STATCOM can achieve the voltage sag mitigation. The shunt injecting current Ish and V_L can be expressed as

$$I_{sh} = I_L - I_s = I_L - \frac{(V_{th} - V_L)}{Z_{th}} \qquad (2.2)$$

$$V_L = V_{th} + (I_{sh} - I_L) Z_{th} \qquad (2.3)$$

Fig2.4 shows the equivalent circuit diagram where Zs is source impedance, ZL is load impedance, I, is shunt compensation current and ΔV change in voltage

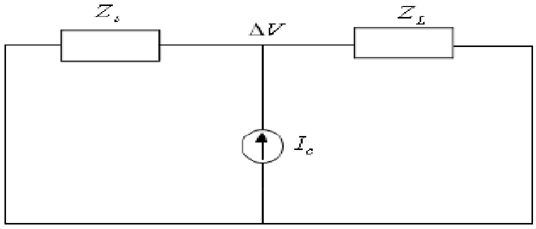


Figure2.4: Circuit diagram of shunt current injection scheme

$$\Delta V = V_{load} - V_{dip} \quad (2.4)$$

$$I_c = \frac{Z_s Z_L}{Z_s + Z_L}(V_{load} - V_{dip}) \quad (2.5)$$

The complex power developed in the D-STATCOM controller to support the load voltage is given as

$$S_{sh} = V_L I_{sh}^* \quad (2.6)$$

2.3.1.3 Combined Compensator

The Unified Power Quality Conditioner (UPQC) consists of two VSCs: one is shunt connected to the power system, another is series connected to the load. The two converters are connected by a common dc bus, as shown in fig.2.8.

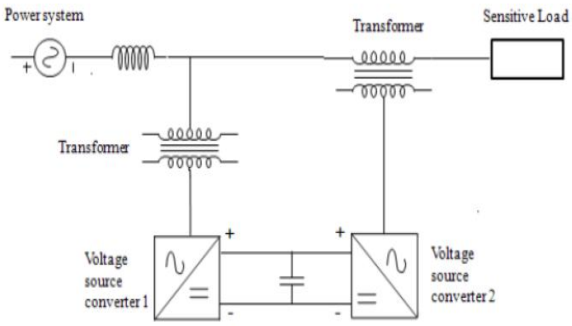


Figure 2.5: Unified power quality conditioner

During the voltage dip, the controllable voltage, both magnitude and phase angle, is injected by the UPQC to maintain the load terminal voltage and the required energy at the dc bus is provided by the shunt connected VSC, which extracts the energy from the power system. As the power drawn by the shunt connected VSC is kept equal to the power delivered to the series connected VSC, the energy storage device at the dc bus is not necessary in the UPQC. However, the power coming from the power system will be greatly reduced during the dip. The shunt connected VSC must be designed to operate correctly with reduced or even unbalanced input voltage. The UPQC also can eliminate the harmonics in the supply current besides mitigating the voltage dip in the power system.

III. DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer (DVR) is a series voltage injection device. It is used to improve the power quality condition in the transmission as well as in distribution line. DVR is basically a power electronic device comprising of an inverter, energy storage device and a LC filter at the output of inverter. This basic structure may have coupling transformer to couple it with transmission or distribution line. In a transmission line, it is used to improve maximum transmissible power, voltage stability, transient stability and damp the power oscillations. In distribution system it is used to mitigate sag and also used as an active filter for harmonic compensation. In this thesis sag mitigation aspect of DVR in distribution system has been taken into consideration. First, the basic DVR topology has been discussed. Different voltage injection methods have been presented. Detailed modeling of DVR is then derived and control strategy for the DVR is discussed in detail. Control strategy with DVR model has been simulated in MATLAB Simulink.

3.1 Series Voltage Injection

AC power transmission over long line was primarily limited by the series reactive impedance of the line as per the following equation.

$$P = \left(\frac{Vs.Vr}{Xl}\right)\sin\delta$$

Where,

V_s = sending end voltage
V_r = receiving end voltage
X_l = Line inductance
δ = Power angle

To increase the power transmission earlier series capacitive compensation was introduced. This basically cancel a portion of reactive line impedance and thereby increase the maximum transmissible power. If we take the compensation factor k as

$$k = X_c/X_l \qquad 0 \le k < 1,$$

power flow in the line can be written as

$$P=\left(\frac{Vs.Vr}{(1-k)Xl}\right)\sin\delta.$$

Series capacitive compensation reduces the line inductance and thereby increases the line current. This can be seen by in an other way. To increase the line current, voltage across the line impedance must be increased. Capacitor also does the same thing as voltage across the capacitor is in opposition to the voltage drop in the line impedance. So the physical nature of series circuit element is irrelevant as long as it produces the desired compensating voltage. Thus an alternate compensating circuit may be envisioned as an ac voltage source which directly injects the desired compensating voltage in series with the line. This injected ac voltage can be controlled as per the required compensation level. Basic diagram of a variable series voltage compensated line is shown in Fig.3.1.

Voltage source inverter (VSI) can be used to generate the ac voltage at desired frequency with controllable amplitude and phase angle. This generated voltage can’t be directly fed into the line as inverter output voltage has switching harmonics. DVR is the combination of VSI and filter. DVR is primarily used to mitigate the sag swell problems in receiving end voltage. In a transmission system, it can be used to improve the voltage stability, transient stability and to damp the power oscillations.

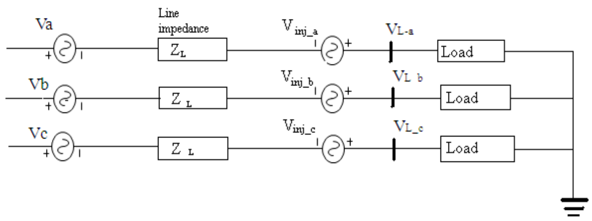


Figure 3.1: Basic Series Voltage Compensated Line

A typical DVR connection is shown in Fig.3.2. It is connected in series with the distribution feeder-2 that supplies a sensitive load. For a fault clearing or switching at point A of the incoming feeder or fault in the distribution feeder-1, the voltage at feeder-2 will sag. Without the presence of the DVR, this will trip the sensitive load causing a loss of production. The DVR can protect the sensitive load by inserting voltages of controllable amplitude, phase angle and frequency (fundamental and harmonic) into the distribution feeder via a series insertion transformer shown in Fig.3.2. It is however to be mentioned that the rating of a DVR is not unlimited.

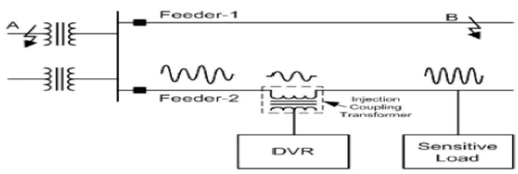


Figure 3.2: DVR in Line to Protect Sensitive Load

3.2 DVR Structure

The DVR is made of solid-state dc to ac switching power converter (inverter), usually a voltage source inverter (VSI) that injects a set of 3-phase ac output voltages in series and synchronism with the distribution feeder voltages. The dc input terminal of the DVR is connected to energy source or an energy storage device of appropriate capacity. The reactive power exchanged between the DVR and the distribution system is internally generated by the DVR without ac passive reactive components. The real power exchanged at the DVR output ac terminals is provided by the DVR input dc terminal by an external energy source or energy storage system. DVR is shown in Fig.3.3.

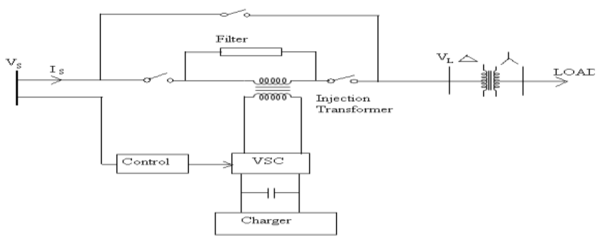


Figure 3.3: Dynamic Voltage Restorer

3.2.1 Voltage Source Converter

This could be a 3phase – 3wire VSC or 3phase – 4wire VSC. The latter permits the injection of zero-sequence voltages. Either a conventional two level converter (Graetz bridge) or a three level converter is used. This VSC is connected to the network through three single phase transformers.

3.2.2 Boost or Injection Transformers

Three single phase transformers are connected in series with the distribution feeder to couple the VSC (at the lower voltage level) to the higher distribution voltage level. The three single phase transformers can be connected with star/open star winding or delta/open star winding. The latter does not permit the injection of the zero sequence voltage. The choice of the injection transformer winding depends on the connections of the step down transformer that feeds the load. If a Δ-Y connected transformer (as shown in Fig 3.3) is used, there is no need to compensate the zero sequence voltages. However if Y-Y connection with neutral grounding is used, the zero sequence voltage may have to be compensated.

3.2.3 Passive Filters

The passive filters can be placed either on the high voltage side or the converter side of the boost transformers. The advantages of the converter side filters are

- **i.** The components are rated at lower voltage
- **ii.** Higher order harmonic currents (due to the VSC) do not flow through the transformer windings.

The disadvantages are that the filter inductor causes voltage drop and phase (angle) shift in the (fundamental component of) voltage injected. This can affect the control scheme of DVR. The location of the filter on the high voltage side overcomes the drawbacks (the leakage reactance of the transformer can be used as a filter inductor), but results in higher ratings of the transformers as high frequency currents can flow through the windings.

In the filter structure of Fig 3.4, a capacitor filter is connected across the line side of the transformer. This prevents the switching frequency harmonics from entering into the system. Also the leakage reactance of the transformer can be used to aid the filtering characteristic. The main drawback of this system is that the direct connection of VSI to the transformer primary results in loss in the transformer. The high frequency flux variation cause significant increase in transformer iron losses. To avoid this, a switch frequency LC filter is placed across the inverter side of the transformer. The high voltage side of the transformer is directly connected to the feeder.

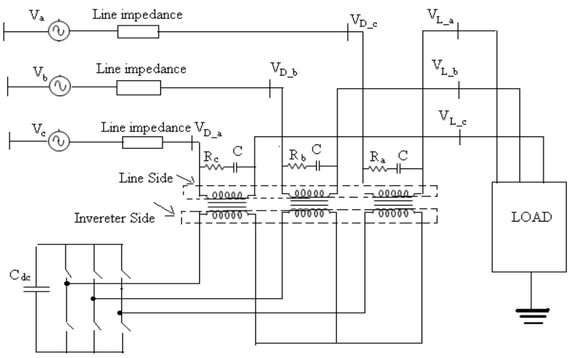


Figure 3.4 DVR with Capacitive Filter

These will constraint the switching frequency harmonics to remain mainly in the primary side of the transformer. Another advantage of inverter side filter is that it is on the low voltage side of the series transformer and is closer to the harmonic sources. However the introduction of the filter inductor causes a voltage drop and a phase angle shift in the inverter output voltage.

3.2.4 Energy Storage

This is required to provide active power to the load during deep voltage sags. Lead-acid batteries, flywheel or SMES (super conducting magnetic energy storage systems) can be used for energy storage.

It is also possible to provide the required power on the DC side of the VSC by an auxiliary bridge converter that is fed from an auxiliary AC supply.

3.3 Voltage Injection Techniques

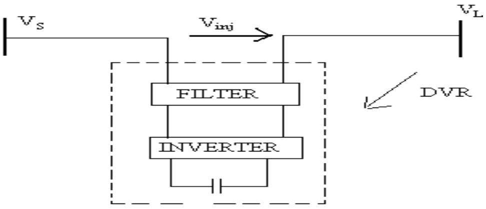


Figure 3.5 Block Diagram of Series Compensation

Fig.3.5 shows the general topology of DVR connected in series with the line. V_S denotes the source voltage, VL denotes the load voltage and V_{inj} denotes the series voltage injected by the DVR. Depending on the reactive amplitude and phase of the injected, injection techniques are classified in three broad categories. Aim of all these techniques is to maintain the load voltage magnitude at a nominal value of V_{nom}. These techniques posses various degrees of accuracy in terms of voltage magnitude and phase shift correction. Selection of the appropriate technique in a given situation is primarily decided by the load.

i).Minimal Energy Injection Technique
ii).In Phase Compensation Technique
iii).Pre-sag Compensation Technique

IV. MODELING OF DVR

The compensation of voltage sag/swell can be limited by a number of factors, including finite DVR power rating, loading conditions, power quality problems and types of sag/swell. If a DVR is a successful device, the control is able to handle most sags/swells and the performance must be maximized according to the equipment inserted. Otherwise, the DVR may not be able to avoid tripping and even cause additional disturbances to the loads.

4.1 Mathematical Modeling for Voltage Injection by DVR System

Consider the schematic diagram shown in Figure 4.1

$$Z_{th} = R_{th} + X_{th} \quad (4.1)$$

$$V_{DVR} + V_{th} = V_L + Z_{th}I_L \quad (4.2)$$

When dropped voltage happened at V_L, DVR will inject a series voltage V_{DVR} through the injection transformer so that the desired load voltage magnitude V_L can be maintained. Hence

$$V_{DVR} = V_L + Z_{th}I_L - V_{th} \quad (4.3)$$

$$I_L = \left(\frac{P_L + jQ_L}{V_L}\right)^* \quad (4.4)$$

When V_L is considered as a reference, therefore;

$$V_{DVR}\angle\alpha = V_L\angle 0^0 + Z_{th}I_L\angle(\beta-\theta) - V_{th}\angle\delta \quad (4.5)$$

Here ◎, ◎and δ are the angle of V_{DVR}, Z_{th} and V_{th}, respectively and θ is the load power factor angle with

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

The power injection of the DVR can be written as

$$S_{DVR} = V_{DVR}I_L^* \quad (4.6)$$

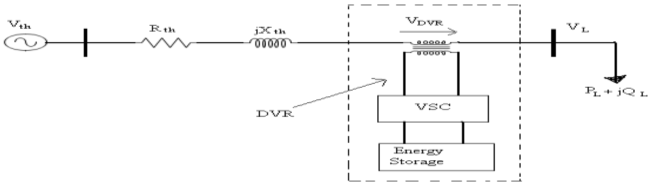


Fig 4.1: Calculation for DVR Voltage Injection

4.2 Phase Locked Loop (PLL)

A PLL is a device which causes one signal to track another one. It keeps an output signal synchronizing with a reference input signal in frequency as well as in phase. More, precisely the PLL is a servo system, which controls the phase of its output signal in such a way that the phase error between out phase and reference phase reduce to a minimum.

The phase angle of the utility voltage is a critical piece of information for the operation of most apparatuses such as controlled ac/dc converters, Static VAR compensators, cyclo-converters, active harmonic filters and other energy storage system coupled with electric utility. This information may be used to synchronize the turning on/off of power device, calculate and control the flow of active/ reactive power or transform the feedback variable to reference frame suitable for control purposes. The angle information is typically extracted using some form of phase locked loop (PLL). The quality of phase lock directly affects the performance of the control loops in all the above applications. Voltage unbalance, frequency variation and phase jumps are common disturbances faced by equipment interfaced with the electric utility. For application purposes, frequency can vary from 47 Hz to 51 Hz. Any PLL used under such condition should not only be able to phase lock as quickly as possible but also provide an output with low distortion.

4.2.1 Principle of Operation

As the phase information of a periodic input signal is not directly measurable, the phase angle (θ) has been estimated from measured instantaneous values of the input. Since phase angle (θ) is related to the angular frequency (ω) as

$$\theta = \int_0^t \omega . dt \qquad (4.7)$$

The plant equation is $G(s) = \frac{1}{s}$

Which is shown in Fig 4.2

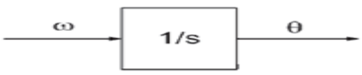


Figure 4.2: Plant Model

The objective here is to compute an accurate estimate ($\hat{\theta}$) of the actual phase (θ) of the input waveform. The accuracy of estimation is indicated by the estimation error (Δθ), defined as

$$\Delta\theta = \hat{\theta} - \theta \qquad (4.8)$$

To obtain a relation between the estimation error in terms measured variables, the SRF approach is adopted.

Let V_a, V_b, V_c be a set of balanced, three phase voltage signals, defined as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V \cos\theta \\ V\cos(\theta - \frac{2\pi}{3}) \\ V\cos(\theta + \frac{2\pi}{3}) \end{bmatrix} \qquad (4.9)$$

These are first transformed with respect to a stationary, Cartesian reference frame using the following transformation.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3/2} & \sqrt{3/2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (4.10)$$

The transformed voltages are then referred to a rotating reference frame, which has same angular phase as the estimator output, $\hat{\theta}$. This transformation is defined as

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} \cos\hat{\theta} & -\sin\hat{\theta} \\ \sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \qquad (4.11)$$

Successively substituting (4.9) in (4.10) and the result of (4.10) in (4.11), the transformed quantities are

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \sqrt{\frac{3}{2}} V \begin{bmatrix} \cos(\hat{\theta} - \theta) \\ \sin(\hat{\theta} - \theta) \end{bmatrix} = \hat{E} \begin{bmatrix} \cos(\Delta\theta) \\ \sin(\Delta\theta) \end{bmatrix} \qquad (4.12)$$

Where,

$$\hat{E} = \sqrt{\frac{3}{2}} V$$

As, for small values of (Δθ), $\sin(\Delta\theta) \approx (\Delta\theta)$ (4.13)

(4.2)is linearized as $\begin{bmatrix} V_d \\ V_q \end{bmatrix} \approx \hat{E} \begin{bmatrix} 1 \\ \Delta\theta \end{bmatrix}$ (4.14)

An indication of the estimation error, (Δθ), is there by obtained from the q-axis equation of (4.13). This offers immediate possibility to lock onto the utility phase by regulating V_q to zero by a suitable controller H(s). The estimation error is also made immune to magnitude variations of utility voltage. Fig.4.3 shows the schematic of the control model of estimation loop and Fig.4.4 shows the schematic of simplified control model of estimation loop.

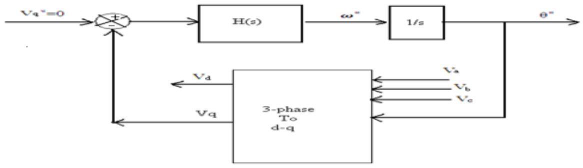


Figure 4.3: Control Model of PLL System

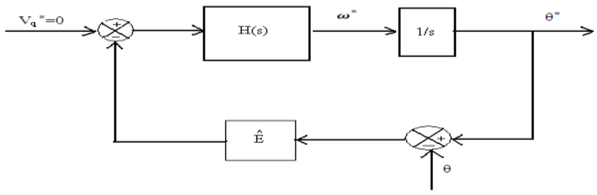


Figure 4.4 Simplified Control Model of PLL System

4.4 Summary: This chapter has presents the modeling of the DVR and the principle of phase lock loop (PLL) and its requirement in DVR system.

V. SIMULATION RESULTS

Simulation of the DVR is performed in MATLAB SIMULINK using the above control technique. MATLAB SIMULINK is a very popular tool for mathematical computation and model based design and SIMULINK Model is in generally pictorial representation of an application created using blocks provided by MATLAB as well as third parties.

Minimal energy compensation technique, discussed in section 3.3.1, is adopted to control the rms value of load voltage. Decoupled active power and reactive power control strategy is adopted to control the DVR output voltage and DC bus voltage. In this control strategy, in d-q frame, d-axis reference voltage depends on the DC bus voltage error and the q-axis voltage reference depends on the error in the rms value of load voltage. So the voltage injection is in quadrature with the load current. Simulation is performed under two loaded conditions, i.e balanced load and unbalanced load condition.

5.1 Balanced Voltage Sag

In order to understand the performance of the DVR along with control, a simple distribution network is taken as shown in Figure 5.1.

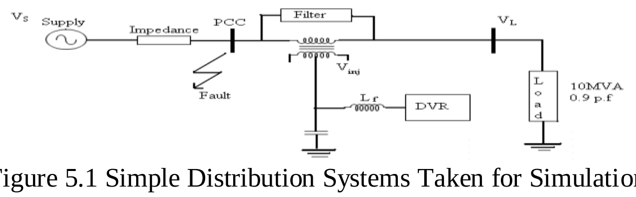


Figure 5.1 Simple Distribution Systems Taken for Simulation

Voltage sags are simulated by temporary connection of balanced impedances at the supply side bus. A DVR is connected to the system through a series transformer with a capability to insert a maximum voltage of 50% of the phase to- ground system voltage. Apart from this a series filter is also used to remove any high frequency components of power. The load considered in the study is a 10 MVA capacity with 0.9 p.f., lagging. The results are shown in the next section.

Symmetrical sag is simulated by connecting a three-phase reactance (inductance in series with resistance) to the bus bar. The three-phase reactance is a balanced one.

The results are shown in Figure 5.2 (a), (b), (c) are the each phase voltages at point of common connection (PCC). In this the 40 % sag is initiated at 200ms and it is kept until 400ms, with total voltage sag duration 200ms.

As a result of DVR, the load voltage is kept at nominal value throughout the simulation, including the voltage sag period. Observe that during normal operation, the DVR is doing nothing. Fig 5.3 (a), (b), (c) show the 3-phase series injected voltage by DVR, load voltage and source voltage at PCC.

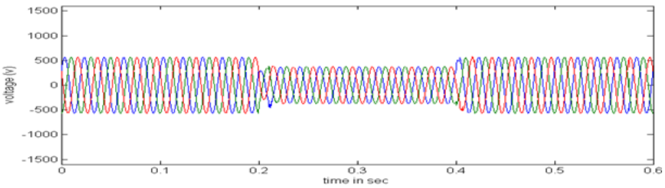


Fig (a) 3-Phase voltage at PCC

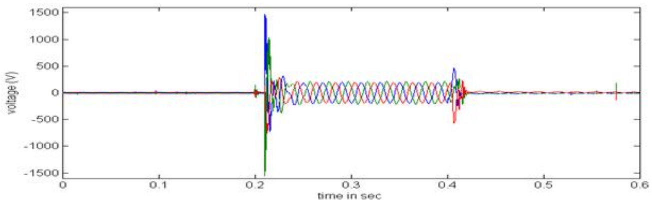


Fig (b) 3-Phase injected voltage

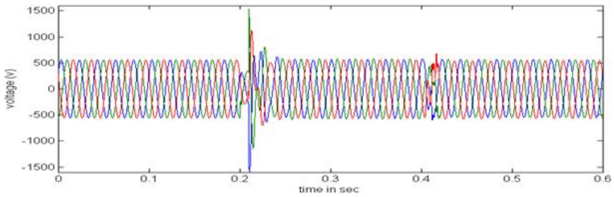


Fig (c) 3-Phase voltage at load point

Figure5.2: Simulation result of DVR response to a balanced voltage sag.

5.2 Unbalanced Voltage Sag

Fig 5.3 shows simulation result of DVR response to unbalanced voltage sag. Here, the breaker is connected at 200ms and opened at 400ms. In this almost the unbalanced voltage sag is corrected to the supply voltage.

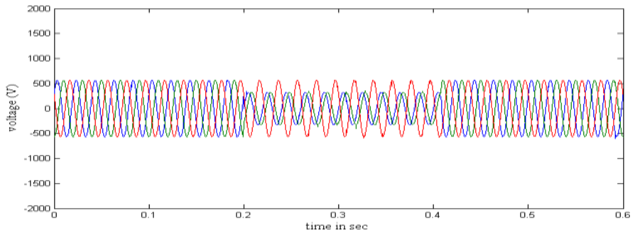


Fig (a) 3-phase voltage at PCC

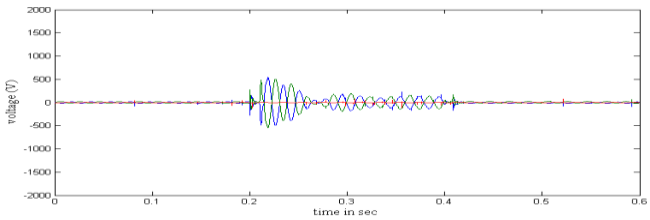
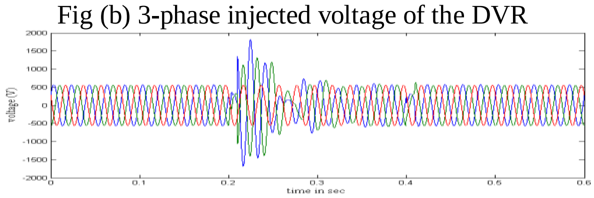


Fig (b) 3-phase injected voltage of the DVR



Figure(c) 3-phase voltages at load point

Fig 5.3 Simulation result of DVR response to unbalanced voltage sag.

VI. CONCLUSION AND FUTURE SCOPE OF WORK

6.1 conclusion

The simulation of the DVR system for mitigation of balanced and unbalanced voltage sag is done in Matlab Simulink and tested the performance for sag mitigation in series compensation technique. In shunt compensation technique The Distribution static synchronous compensator(D-STATCOM) is also simulated and extraction of the sequence components is performed for double phase and three phase faults.

From the simulations we can conclude that the series compensation technique is most reliable compared to shunt compensation as shunt compensation requires more reactive power to be injected to the system for the same sags. And the energy storage required is also more for shunt compensation.

6.2 Future Scope

- Three phase dynamic voltage restorer with auxiliary supply voltage has been used in the simulation study. Instead of auxiliary voltage supply we can also use capacitor bank and study the results.
- In three phase system multi level inverters or a chain of single phase inverters for each phase may be used in the DVR topology and such systems may be studied.
- The super conducting magnetic energy storage systems (SMES) may be used in the DVR structure in large systems. Such systems may be studied.
- Filters may be needed to reduce the total harmonic distortion in the distribution system because of the switching devices used in the DVR. Such filters may be active or passive types. Hybrid type filters may be used to reduce costs. A comparative study of such filters may be carried out.
- PI controllers are used in the simulation study to control the PCC voltage. A major limitation of PI controller is that, it does not guarantee the system stability under varying load conditions. Therefore, it may be desirable to employ advanced control techniques based on Fuzzy, Neural logic and study the system stability.
- Multilevel inverters and H-bridge inverters are used for reducing the harmonic injection. This may be a fruitful extension.
- A study of employing D-STATCOM to comprehensively mitigate at the same time the effects of harmonics, voltage sags/swells, and parasitic effects of switching disturbances and improve power factor has become necessary due to ever increasing use of power electronic equipment.
- One can code the algorithms in the DSP processor and can see the performance of the devices for compensating sag in hardware.

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