CHAPTER-5

DESIGN AND IMPLEMENTATION OF ISOGI-PLL BASED
CONTROL ALGORITHM FOR DVR
5.1 INTRODUCTION

In this thesis, the control of dynamic voltage restorer (DVR) for power quality enhancement during various power quality issues such as voltage sags, swells, phase jumps, harmonics and voltage unbalance etc. are studied and simulated using MATLAB/Simulation for a three-phase distribution system.

The DVR is connected in series with the source and load for maintaining constant load voltage under source voltage variations. For example, a DVR injects required voltage during voltage sags and maintains a constant load voltage and also avoids frequent tripping of the loads as explained in Fig. 5.1.

![Fig. 5.1 Line Diagram of a DVR operation.](image)

Voltage sags are classified based on single-phase, three-phase (balanced and unbalanced) sags. These voltage sags or dips are caused by the faults occurred at the customer end because of installation of various
equipment in the distribution line. These sags are also produced due to sudden starting of heavy motors or loads, faults across distribution lines and energizing of transformers. Voltage sags are expressed in terms of RMS voltage variations or the voltage accompanied with phase jumps. DVR was introduced in early 1990’s and still the research is being done for good dynamic capabilities when connected between sensitive load and source for the compensation of voltage sags and swells and restoring the load voltage to a rated nominal value within shortest period of time (few cycles).

5.2 BASIC PRINCIPLE OF DVR

The DVR injects three single-phase voltages or three-phase voltages in series with the source and load end for the compensation of sags and swells by calculating the difference between the faulty and normal voltages. All these injected voltages are controllable with respect to amplitude and phase angle. During the normal operating condition, the DVR should be short-circuited using a by-pass switch or the two switches in common leg should be switched on with low conduction losses. Harmonics and inter-harmonics are compensated with a proper control algorithm, filtering and PWM switching strategy. The energy required during faulty conditions is supplied by the DC energy storage which acts as input to the DVR. These conditions decide the rating and performance of the DVR:

➢ Short circuit impedance across the injecting transformers
➢ Maximum allowable voltage drop across the DVR
➢ Duration and amplitude of voltage sag or swell to be compensated.
➢ Maximum loading and power factor.
➢ Balanced and unbalanced magnitude and phase compensation.

The DVR basically consists of power and control circuit. The power circuit mainly comprises of:

➢ Voltage Source Inverter (VSI)
➢ Injecting Transformer
➢ Filters
➢ DC Link Capacitance and Energy Storage (Additional).

The control circuit should generate required phase angle and magnitude for generating required gating signals to the DVR. Based on the gating signals, the DVR will inject the voltage into the line for maintaining constant load voltage.

5.2.1 Voltage Source Inverter

The basic operation of VSI is to produce an AC voltage from DC voltage supplied by the DC link capacitance or energy storage. An injection transformer is used to inject this converted voltage to the supply mains. A pulse width modulation (PWM) strategy is developed by the control algorithm to generate required gating pulses to the VSI. A Graetz bridge circuit or H-bridge circuit or a neutral clamped inverter based circuits are used as VSI for the operation of DVR. The PWM techniques used for VSI
may be sinusoidal PWM, Space Vector PWM or Hysteresis PWM based on the control circuitry employed for DVR.

**5.2.2 Injecting Transformer**

Normally, a step-up transformer or an isolation transformer (1:1) is used as injecting transformers based on the ratings of the DVR and load. The primary winding of the transformer is connected in series with the source and load and secondary winding of the transformer is connected to DVR. For single-phase applications, one single-phase transformer is used whereas for a three-phase transformer, either three single-phase transformers or a three-phase multi winding transformer can be used as injecting transformers. Based on the voltage requirements, the multi winding transformer can be used a star/open or delta/open winding configuration as shown in Fig. 5. 2.

![Connection Diagram of Injection Transformer (a-Delta/open) (b-Star/open).](image-url)
In general, star/open configuration is employed as injecting transformer to pass all the sequence components (positive, negative and zero) when a three-phase unbalanced fault occurs across the secondary. The function of injecting transformer is also to isolate the DVR from source and load and to inject the voltage to the desired level. The rating of transformer should be decided according to the rating of the DVR and the load to be compensated. The leakage inductance is also to be considered which decides the voltage drop across the transformer during the design of transformer.

5.2.3 Filters

A low-pass filter is used for filtering and a sinusoidal voltage is fed to the transformer primary for effective compensation. These filters can be placed in either winding (primary or secondary) of the transformer. A RC based filter is used as the ripple filter to eliminate higher order harmonics and this can be placed at the inverter side to prevent harmonics but, produces a phase shifted output across the secondary. Hence, it is preferred to add a filter at the load or primary side of the injecting transformer.

5.2.4 DC-Link Capacitance or Energy Storage

The compensation ability of the VSI depends on the amount of real power delivered by the DC link. The DC link is connected to a capacitor bank or energy storage or the supply line itself. Energy storage devices are
preferred when the duration of the fault exceeds some predetermined time or when maximum compensation required. But, if the sag/swell remains for few cycles (1 to 10 cycles) then the capacitor itself acts as energy storage and called as self-supported DVR.

A By-pass switch is used additionally to protect the inverter circuit from a downstream fault which allows high current through it. This switch is a crow-bar circuit that senses the current and operates when the current goes beyond the rated current and bypasses the DVR and its circuit components.

5.3 COMPENSATION TECHNIQUES OF DVR

As studied in the literature, the control strategies employed for DVR are used to track and synchronize with the supply voltage continuously at presag condition to know the fault such as sag/swell in the distribution line. Voltage sags are sometimes accompanied with phase angle jumps in addition to voltage magnitude variations. Therefore, the control technique employed for the DVR should be capable of compensating the voltage under magnitude variations, phase angle shift and also eliminating harmonics for sinusoidal waveform. Based on the sensitivity of the load, tracking parameters can be altered because of the influence of load on system parameters.

Based on the type and level of compensation, the types of compensation techniques are basically divided into three methods.
Presag Compensation: In this method of control, the source voltage is continuously monitored and the source voltage under normal condition is termed as presag voltage \( V_s = V_{\text{presag}} \). Because the load voltage and source voltage are constant and no injection is done by DVR. During voltage sags or swells, the DVR injects the required voltage and the load voltage is fully compensated to rated value \( V_L = V_{\text{presag}} \). This method finds the difference between the sag voltage and presag voltage and the identified error voltage with phase angle is injected by the DVR. This method is suitable for non-linear loads but not effective because, the DVR rating gets exhausted.

In-phase Compensation: This method is suitable for linear loads because, only magnitude is considered for compensation and phase angle is not considered. This minimizes the overall compensation of DVR. In this method, the supply voltage is in phase with the injected voltage and irrespective of load current.

Energy Optimal Compensation: This method requires load current signal to reduce the depletion of energy storage. Because, this method makes the real power minimized or zero by injecting the voltage phase shifted by 90° with load current. This method of compensation requires high rated inverter and transformer because of higher voltage injection.

The compensation of magnitude and phase can also be achieved with the combination of different techniques to attain higher efficacy and
control. Most of the applications use in-phase and energy optimal compensation techniques because of minimal requirement of real power injection and hence storage. In addition to the above-mentioned techniques, a method should be employed to track the magnitude and phase of the input signal in the normal condition to detect adverse conditions such as sags and swells etc. Some of the following compensation techniques are:

➢ Fourier based transforms
➢ Phase Locked Loops (PLL)
➢ Wavelet Transforms
➢ Peak Detection Techniques.

Peak detection technique extracts only magnitude of voltage signal but not phase information and hence this method can be combined with Fourier transforms, PLL or wavelet transforms. Conventional PLL method tracks phase information only and not the magnitude information and hence wavelet and Fourier based methods are mostly used in earlier days. Due to the advancement of PLL structures, PLLs are also used for magnitude, phase and frequency detection to reduce the computational effort.
5.4 SRF THEORY BASED CONTROL ALGORITHM FOR THREE-PHASE DVR

An SRF based control strategy for a three-phase self-supported DVR is shown in Fig. 5.3. This control strategy is simple and common for both linear and non-linear type of loads. Because, the design of controller is independent of load connected. The controller is able to maintain a sinusoidal voltage with desired amplitude, phase and voltage quality even under grid voltage disturbances such as unbalance, harmonics, sags, swells etc. SRF theory uses transformations and PI controller for the overall control operation such as reference voltage extraction and a PWM generator for generating the gating signals to the DVR. Initially, a three-phase SRF-PLL is used to extract the phase information from the grid voltage signal and then it is further processed for transformations. Clarke’s or Park’s transformations are applied to transform a-b-c variables to d-q-0 variables. The transformation equations are already explained in chapter 4. The line diagram of the DVR with the SRF control algorithm is shown in Fig. 5.3.

Initially, amplitude and phase are estimated of source voltage signal and then transformed to d-q variables (active and reactive components). Then, the load voltage magnitude is calculated as shown below:

\[
v'_L = \sqrt{\frac{2(\text{v}_{La}^2 + \text{v}_{Lb}^2 + \text{v}_{Lc}^2)}{3}}
\]  

(5.1)
The estimated load voltage \( (v'_{L}) \) is then passed to a low-pass filter for elimination of ripples and compared with the reference load voltage to calculate the error. The error is the reactive component that was supplied to a PI controller to estimate the reference reactive component of voltage.

\[ \text{Fig. 5. 3 Design of Three-Phase DVR with SRF Control Theory} \]
The DC link voltage is sensed and compared with the reference DC bus voltage and the error is fed to a PI controller for estimating the active component of voltage and summed with the active component of the source voltage.

The voltage error is fed to PI controller to regulate the DC bus voltage of the DVR. At \( n^{th} \) sampling instant, the output of the PI controller is as:

\[
V_d(n) = V_d(n-1) + k_{pt} \{ V_{d_{cer}}(n) - V_{d_{cer}}(n-1) \} + k_{it} V_{d_{cer}}(n)
\]  

(5.2)

Where, \( K_{pt} \) and \( K_{it} \) are the proportional and integral gain constants of the PI controller. \( V_{de}(n) \) and \( V_{de}(n-1) \) are the voltage errors of the DC bus in \( n^{th} \) and \( n-1^{th} \) instant and \( V_d(n) \) and \( V_d(n-1) \) are the amplitudes of active power component of the fundamental reference voltage at \( n^{th} \) and \( (n-1)^{th} \) instant. An observation is made in this control algorithm was the active component of voltage has a nominal value during balanced conditions and when the source voltage undergoes an unbalance, then the \( v_d^* \) has two components namely, positive sequence components and negative sequence components. The amplitude of voltage signal is passed through low-pass filter to extract the fundamental positive sequence component of voltage. The \( V_d^* \) and \( V_q^* \) thus generated are transformed back to a-b-c variables (\( V_{sabc}^* \)) using the source phase angle. The estimated source voltage signal (\( V_{sabc}^* \)) is then compared with the actual source voltage and the error is fed to a PWM controller to generate gating pulses to the DVR.
5.5 ISOGI BASED CONTROL ALGORITHM FOR THREE-PHASE DVR

The proposed ISOGI based control for three-phase DVR is expected to achieve a constant load voltage with sinusoidal in shape even under grid distortions such as voltage sags, swells, unbalance, harmonics etc.

![Diagram of Three-Phase DVR with ISOGI Based Control](image)

*Fig. 5.4 Design of Three-Phase DVR with ISOGI Based Control*

To achieve this objective, the DVR should inject the required voltage and phase using an injecting transformer that is connected in series between source and load. The ISOGI based control algorithm is employed to generate the reference load voltages for generating gating signals to the
DVR as shown in Fig. 5. 4. Usually, there are three building blocks for the entire design of proposed control algorithm.

- Phase angle and Magnitude estimation from load voltage signal using ISOGI-PLL.
- DC Voltage Control Loop
- SOGI-QSG based active and reactive component extraction.

### 5.5.1 Estimation of Phase and Magnitude from Load Voltage Signal using ISOGI-PLL

Initially, three-phase load and source voltages are measured and the control algorithm uses these voltages to extract and estimate the magnitude and phase of the voltage signals. Each of the load voltage signals \((V_{La}, V_{Lb}, V_{Lc})\) are supplied to three single-phase ISOGI-PLLs to estimate the three phases \((\theta_a, \theta_b, \theta_c)\) respectively. The SOGI-QSG structure also produces magnitude of each signal and all the estimated voltages are summed up and the average is calculated. The resultant is then supplied to low-pass filter to eliminate any ripples present in the signal as shown in Fig. 5. 5.
The ISOGI-PLL structure is already discussed in chapter 3. The phase angle is estimated from the PLL and magnitude is estimated from the QSG. i.e.,

\[ V_{La} = \sqrt{(V_{L_{\alpha a}}^2 + V_{L_{\alpha \beta}}^2)} \]

\[ V_{Lb} = \sqrt{(V_{L_{b a}}^2 + V_{L_{b \beta}}^2)} \]

\[ V_{Lc} = \sqrt{(V_{L_{c a}}^2 + V_{L_{c \beta}}^2)} \]

\[ |V_L| = \frac{V_{La} + V_{Lb} + V_{Lc}}{3} \] (5.3)

The estimated magnitude is then compared with the reference load voltage and the error is fed to a PI controller. The output of the PI controller is the estimated loss of the reactive component of voltage and is summed up with the extracted reactive component of voltage through SOGI based active and reactive component extraction block to calculate the total reactive component.

### 5.5.2 DC Voltage Control Loop

Voltage control loop generates the required component of active component for compensation. The voltage across the DC capacitor \( V_{dc} \) is sensed and compared with the reference DC bus voltage \( V_{dc}^* \) and this error at the \( n^{th} \) sampling instant is expressed as:

\[ V_{dc}(n) = V_{dc}^*(n) - V_{dc}(n) \] (4.18)
This voltage error is fed to PI controller to maintain or regulate the DC bus voltage of the DVR. At $n^{th}$ sampling instant, the output of the PI controller is as:

$$V_{cd}(n) = V_{cd}(n-1) + K_{pt} \left[V_{dcer}(n) - V_{dcer}(n-1)\right] + K_{it} V_{dcer}(n)$$

(4.19)

Where, $K_{pt}$ and $K_{it}$ are the proportional and integral gain constants of the PI controller. $V_{dcer}(n)$ and $V_{dcer}(n-1)$ are the voltage errors of the DC bus in $n^{th}$ and $(n-1)^{th}$ instants and $V_{cd}(n)$ and $V_{cd}(n-1)$ are the amplitude of active power component of the fundamental reference current at $n^{th}$ and $(n-1)^{th}$ instant. The values of PI controller gains for DC voltage control loop are shown in Table 5. 1.

5.5.3 SOGI-QSG based Active and Reactive Component Extraction

In order to extract active and reactive component of voltages initially, three single-phase SOGI-QSG’s are used for three-phases (a, b, c) respectively. Then the output of QSG’s are supplied to park’s transformation with the three estimated phase angles ($\theta_a$, $\theta_b$, $\theta_c$) to calculate the instantaneous active and reactive components of voltages. The active and reactive components of three-phases are summed up and the average is calculated as shown in Fig. 5. 6. The extracted active component of voltage is added to the loss component of voltage generated by the DC voltage control loop and the reactive component is added with
estimated reactive component from the AC voltage control loop. After calculating the required active and reactive components, the signals are transformed back to a-b-c components using Inverse Park’s transformation to generate the estimated reference source voltage as shown in Fig. 5.6.

![Diagram of active and reactive component extraction based on SOGI-QSG](image)

**Fig. 5.6 Active and Reactive Component Extraction based on SOGI-QSG**

The reference source voltage is then compared with the actual measured source voltage to produce the estimated injected voltage. The estimated injected voltage is then compared with the actual injected voltage to produce an error signal and supplied to a PWM generator for generating gating pulses to the DVR as shown in Fig. 5.4.

### 5.6 RESULTS AND DISCUSSIONS

The structure of the SRF theory and proposed ISOGI based control strategies with the line diagram of three-phase distribution system are shown in Fig's. 5.2 and 5.3 respectively. MATLAB / Simulink (R2013a) is pursued for verifying the efficacy of the proposed control algorithm. In
order to test and validate the reliability, speed and accuracy of the proposed controller, various source voltage variations are taken into consideration.

Initially, the DVR remains in standby mode when there is no fault detected in the source voltage signal. If a fault occurs in the source voltage signal such as sag, swell, harmonics etc. then the DVR will not remain in standby position and switches to active voltage injection mode. The faults are detected with the help of PLL where it continuously tracks the amplitude and phase of the source voltage signal in order to compensate during abnormal conditions. The control is employed in dq0 reference frame to restore the load voltages to a sinusoidal and balanced conditions. The results below show the source voltage, load voltage, injected voltage, load current, DC link voltage and reference voltage generated by PLL control algorithm. To analyze the performance of both the controllers, few test cases are considered using MATLAB simulation.

➢ A linear load with a balanced source voltage is applied.
➢ Voltage sag (30%) is introduced in the source voltage signal (t = 0.5s to 0.6s).
➢ Voltage swell (30%) is introduced in the source voltage signal (t = 0.9s to 1.0s).
➢ Phase-A of the source voltage signal is overloaded (t = 1.3s to 1.4s).
➢ Harmonics (5th and 7th) are injected in the source voltage signal (t = 2s to 2.1s).
Initially, a balanced linear load is fed with a three-phase balanced source voltage is considered. In the steady state condition as the source and load voltages are constant, the controllers will be in standby mode and no voltage is injected by the DVR as shown in Fig. 5. 7. The DC link voltage is tightly regulated in both the controllers with that of the reference voltage. The reference voltage generated by the PLLs are also shown in the results.

![Graph showing steady state performance](image)

**Fig. 5. 7 Balanced Source voltage with linear load under steady state condition**

To test the dynamic performance of the DVR, faults are created locally to test the efficacy during these conditions. Initially, 30% of balanced voltage sag is introduced in the grid voltage signal and the controllers will track
the change in amplitude of source voltage signal and the DVR injects the required level of voltage as shown in Fig. 5. 8. The DC link voltage was dropped to a large value in SRF controller compared to proposed control algorithm. The level of compensation is low, tracking of amplitude is not done accurately, slow in process and produces more THD (4.28 %) than the proposed controller (2.13 %). The DC link voltage has no much variation in the proposed method and is maintained approximately constant and the tracking accuracy and level of compensation is high as shown in Fig. 5. 8.

*Fig. 5. 8 Balanced Source voltage sag (30%) is applied.*

Similarly, the source voltage is increased suddenly with 30% of the voltage called as swell to test the dynamic performance of both the
controllers as shown in Fig. 5. The performance of the proposed controller was effective except the DC link voltage is not properly regulated within the limits as in the case of voltage sag. But, still the tracking accuracy and level of compensation is quite better than the SRF method with low overall THD.

Fig. 5. 9 Balanced Source voltage swell (30%) is applied

The controllers are also tested during overloading of one phase and making the source voltage unbalance. The controllers have to track the accurate phase voltage and has to inject the same phase voltage to compensate the load voltage effectively and to make the load voltage balanced and constant with sinusoidal shape. The SRF method of control is unable to inject the proper voltage with accuracy and the proposed
controller injects the required voltage with low THD with proper DC voltage regulation as shown in Fig. 5.10.

The grid voltage is injected with 5th and 7th harmonics (THD = 24.07%) to test the overall efficiency of the controllers. The SRF and ISOGI controllers are compensating the harmonics effectively and maintaining the load voltage constant and sinusoidal. But the THD is more (3.57%) compared to proposed method (1.43%) as shown in Fig. 5.10. After proper testing of all the cases, the proposed controller is found more effective because of tracking accuracy in both magnitude and phase for proper level of compensation with low overall THD (%). The simulation parameters for both the controllers are taken same for proper comparison.
Fig. 5. 11 Harmonics (5th and 7th) injected in the source voltage.

Table 5. 1 Simulation Parameters for DVR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source Voltage, Frequency</td>
<td>430V (Ph-Ph), 50 Hz</td>
</tr>
<tr>
<td>Linear Load</td>
<td>$P_L = 8 \text{ kW}, \quad Q_L = 6 \text{ kW}$,</td>
</tr>
<tr>
<td>Source Impedance</td>
<td>$R_s = 0.5, \quad L_s = 0.5\text{mH}$</td>
</tr>
<tr>
<td>Filter Inductance and Ripple Filter</td>
<td>$L_f = 2.5\text{mH}, \quad R_c = 5\text{Ω}, \quad C_C = 10\text{µF}$</td>
</tr>
<tr>
<td>Injecting Transformer</td>
<td>10 KVA, 1:1 turns ratio.</td>
</tr>
<tr>
<td>DC link Voltage and Capacitance</td>
<td>$V_{dc} = 300\text{V}, \quad C_{dc} = 1200\text{µH}$</td>
</tr>
<tr>
<td>DC Voltage Controller Gains</td>
<td>$K_{pdc} = 0.35, \quad K_{Idc} = 0.12$</td>
</tr>
<tr>
<td>PLL Controller Gains</td>
<td>$K_p = 67.5, \quad K_I = K_R = 100, \quad W_c = 7$</td>
</tr>
</tbody>
</table>
5.7 CHAPTER SUMMARY

In this chapter, a three-phase three-wire distribution system is considered with three-leg VSI as DVR. Various power quality problems such as voltage sag, swell, phase jump and harmonics etc. and their possible solutions are discussed. The solution for these power quality issues with the proposed ISOGI control for a three-phase DVR is explained clearly and also compared with the conventional SRF control during various grid conditions. The DVR functions for sag and swell compensation and also has an additional features such as harmonic compensation and load balancing during fault conditions. The performance of ISOGI based control for DVR is found satisfactory because of tracking accuracy in both magnitude and phase compared to SRF control.