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Dynamic Voltage Restorer Based on Multilevel Inverter

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Abstract - *Nowadays, there is rapid rise of non-linear load because of advancement of electronic devices and their application in different sectors. With the introduction of non-linear loads, power quality becomes an imperative matter for electricity suppliers, equipment manufactures and customers. The compensation is performed by dynamic voltage restorer (DVR) based on multi-level inverter using a Diode Clamped Topology with Phase Disposition (PD) pulse width modulation Technique. The paper is focused on the analysis of research works on mitigation of voltage sag problems in medium voltage with secondary distribution networks configuration. The DVR (Dynamic Voltage Restorer) is a power custom device used to restore the load voltage to pre-sag voltage conditions during sag event. The DVR normally installed between the sources voltage and critical or sensitive load .DVR has to automatically detect and inject required voltage into the system whenever power quality problems occur. The Dynamic Voltage Restore (DVR) has become widely accepted as a cost effective key for the protection of sensitive loads from disturbances. The main aim is to get better the power quality and to compensate the voltage drop occurring due to abnormal disturbances at different faults condition.*

Key Words: Dynamic voltage restorer (DVR), Voltage sag, Power quality, PI controller, Synchronous Reference Frame Theory (SRF theory).

1. INTRODUCTION

In the 19th century, with the introduction of electrical energy, after undergoing considerable technological advancements the present day electric power systems have been built. These electric power systems have been developed in complications and these days they are the outcome of a huge network of distribution system. In the last century the quality of life has increased significantly due to these technological progress and many other technical accomplishments. However, there has been a start of damage the power generation systems because of the ever growing population, the industry development, the increased generation sources at the load and the network's intrinsic volatility. This results in voltage fluctuations (dips and interruptions) in electricity supply. Electronic component which are used in modern power systems are sensitive to perturbations of voltage waveform, even a slight non-conformity of power quality delivered by the electricity companies, can cause consumers suffer huge financial losses and the end of comfort.[1] Voltage dips and interruptions in electrical distribution system is one of the key factors for arise such problems. Equipment based on power electronic components can be used in power distribution systems with assistance for providing solution for a wide range of problem in electricity. These types of power electronic equipments, known as Custom Power Devices, are capable to improve the quality of power. Dynamic Voltage Restorer (DVR) is one such custom power device capable to provide the necessary voltage control at common union point with the electricity distribution network for voltage quality improvement. [2]

1.1 Medium Voltage Distribution Network with Secondary Distribution Structure

A secondary distribution configuration means an auxiliary medium voltage connection substation as shown in figure 1 this connection substation is provided with two power supplies, a main supply and a backup supply. With two power supply, this connection substation may be offered with an automatic transfer switch in between the main supply and backup supply and automatically the power supply will be restored if a permanently fault occurs on the mains power supply.

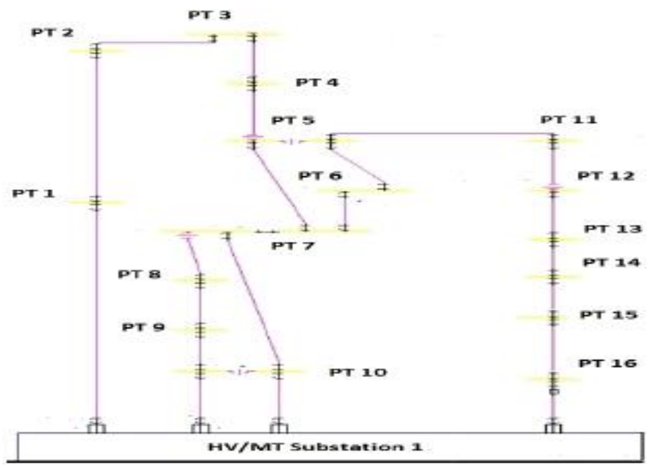


Fig.1 Primary distribution network configuration

On the other hand, a secondary distribution configuration means a further medium voltage connection substation as is shown in figure 2. This connection substation has two power supply, one main and another backup supply. Main power supply is provided through a double-circuit underground cable connected to a medium voltage bus bar of the power stations. The backup power supply is the one provided through another double circuit underground cable connected to a dissimilar power station bus bar from an additional section of the bus bar of the initial HV/MV power stations with same medium voltage level, if this power station is provided with at least two HV/MV transformers with same medium voltage level. [1]

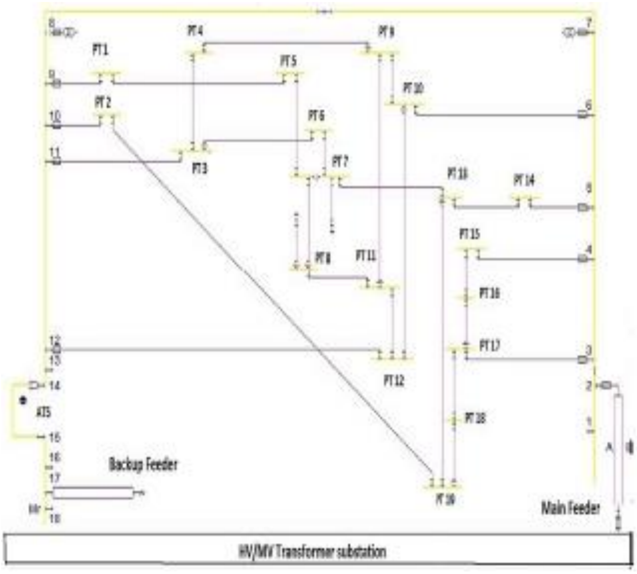


Fig 2 Secondary distribution network configuration

In this medium voltage connection substation, the backup power line is connected to a backup bus bar, which can supplies another power line that provides power backup for a second medium voltage connection substation.

With two power supply, this connection substation can be provided with an automatic transfer switch between the main supply and backup supply and automatically the power supply will be restored, if a permanently fault occurs on the main power supply. The main bus bar of the connection substation feeds up to eight distribution branches. This connection types allows a better flexibility in the choice of opening stage for the network. [1]

1.2 Multi-Level inverter

Numerous of the industrial and commercial applications require medium and high power equipment in the range of megawatt (MW). Used for all such applications a single switch shouldn't be connected and so a family of switches has to be connected. The introduction of multilevel inverter which can be practically efficiently is high as well as for medium power applications. These inverters are made up of an arrangement of capacitors voltage sources, power semiconductor from which they tend to generate stepped output voltage waveforms.

❖ **Topologies of Multilevel Inverter**

In the modern era many different multilevel inverter topologies were proposed. There are mainly three different basic topologies which remain the basis for many of the modern ones proposed. They are

[1] Diode Clamped inverter multilevel
[2] Flying Capacitor or Capacitor Clamped Inverter
[3] Cascaded H-bridge Multilevel Inverter

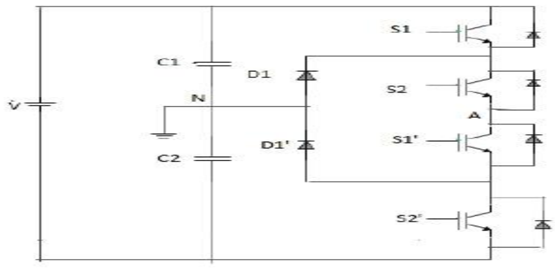


Fig. 3 Diode Clamped Multilevel Inverter

[1] Diode Clamped Multilevel Inverter

Now for this inverter topology the clamping purpose is served by using a diode as in fig.3. The output required set of steps voltage waveform. Figure shows linking series of capacitors in the 3 level diode clamped inverter. Multiple voltages will be provided for the M level inverter each of the capacitor has a voltage of V_{DC}/m-1. As a result of capacitor voltage balancing issues, the diode-clamped inverter implementation has been mostly limited to the three-level. In this topology, maximum output voltage which can be obtained is half of the input DC voltage. This has been the main drawback for this topology. But this problem can be overcome by increasing the number of switches, capacitors, diodes. Three level inverters of this type are extensively being used in industries these days.
Applications

- They are used for Harmonic compensation purpose
- They are used for motor drives with variable speed.
- High voltage DC, AC transmission lines use them.

1.3 Pulse Width Modulation Techniques

A semiconductor device are required to be switched off and on in such a manner that desired fundamental is obtained with minimum harmonic distortion to prepare multi-level output AC voltage by unlike levels of DC inputs. The different techniques are exercised to choose switching technique in multilevel inverter like Phase-opposition-disposition (POD), Phase- disposition (PD), Alternative Phase-opposition-disposition (APOD), Variable Frequency (VF).

For an m-level inverter (m-1) having same frequency fc and same peak-to-peak amplitude Ac are used. The reference waveform having amplitude Am, frequency fm and positioned at zero reference is constantly compared with each of the carrier signals. If the reference wave is greater than a carrier signal, in that case the active devices related to that carrier are switched ON. Otherwise, the device switched OFF

$$m_f = f_c / f_m$$
$$m_a = 2A_m / (m-1)\, Ac$$

1.4 Phase Disposition (PD) PWM Technique

In this technique all the carrier waveforms are in same phase. The theory of PDPWM technique uses the numerous carrier waves with single modulating waveform. Fig.4 represents the PWM generation using SIMULINK developed for PD Control technique of 5-level of Diode clamped MLI topology.

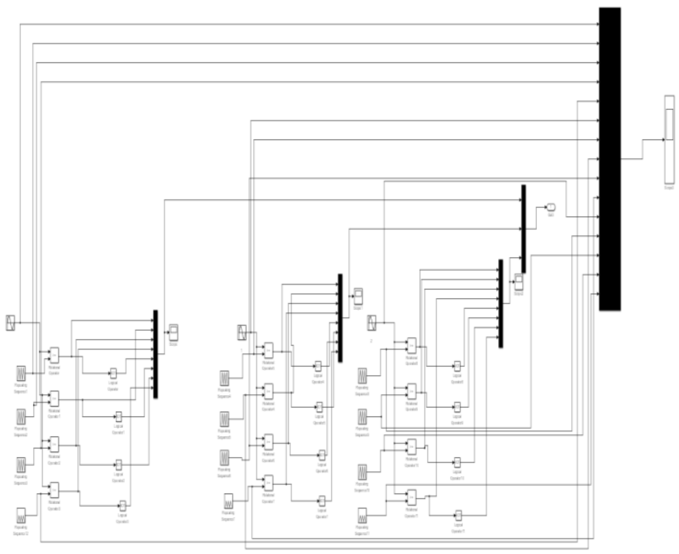


Fig.4 PD Control technique of 5-level Diode clamped MLI topology

1.5 Phase Opposition Disposition (POD) PWM Technique

For phase opposition disposition (POD) modulation all carrier waveforms above zero reference are in phase and are 180° out of phase with those below zero. The considerable harmonics are located around the carrier frequency fc for both the phase and line voltage waveforms. The POD method provides one fourth wave evenness for even mf and odd symmetry for odd mf. Fig.5 represents the PWM generation using SIMULINK developed for POD Control technique of 5-level of Diode clamped MLI topology.

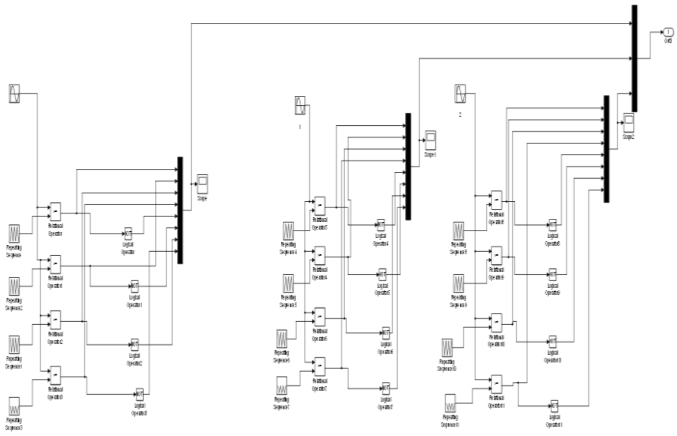


Fig. 5 POD Control technique of 5-level Diode clamped MLI topology

2. DYNAMIC VOLTAGE RESTORER

DVR is one of the excellent "custom power" devices in distribution network which is connected in series with transmission line. Load voltage gets balance by injecting three phase controlled voltages during disturbance in the power system. DVR is based on injection of requisite voltage when ever voltage sag occurs to compensate it. Functionally, DVR can be categorized as two types: Standby mode and Injection mode. In the standby mode a low voltage is injected into the network to compensate voltage sag caused by transformer reactance. In injection mode, DVR injects appropriate voltage to sensitive load to compensate voltage sag. DVR circuit consists of 5 main components. They are shown in Fig. 6

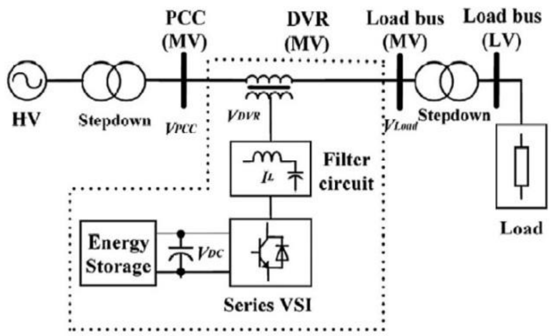


Fig. 6 Basic Structure of DVR

(1) Series transformer: Its primary winding is linked to the inverter and its secondary winding is linked to the end sensitive load and distribution network.

(2) Voltage inverter: The inverter is attached to the injection transformer. In this inverter, energy storage equipment has been well thought-out. This inverter includes IGBT switches self-commutating by shunt diodes and PWM control technique is used.

(3) Energy storage equipment: Power storage resources like capacitor banks, batteries, flywheels and SMES which

have been used for supplying adequate voltage, active power and compensating sag.

(4) Passive filter: It is linked to the high voltage side of inverter to get rid of harmonics produced by switching.
(5) Control system: Voltage sag detection is the basic logical fundamental of control system providing appropriate switching strategies for inverter.

Control system uses the abc-dq transformation to calculate V_d and V_q. In balance condition, the voltages V_d = 1 and V_q = 0. But in fault condition, these voltages change. We can control the variations of these signals by comparing these voltages with their references and giving their error signals to a PI controller.

3. PROPOSED CONTROL STRATEGY

Equations related to DVR

The System impedance Z_{th} depends on the fault level of the Load bus. When the System Voltage (V_{th}) drops, the DVR injects a series Voltage V_{DVR} through the Injection Transformer so that the desired Load Voltage Magnitude V_L can be maintained. The series injected Voltage of the V_{DVR} can be written as

$$V_{DVR} = V_L + Z_{TH} I_L - V_{TH} \quad \text{............ (1)}$$

Where
V_L: The desired Load Voltage Magnitude
Z_{TH}: The Load impedance.
I_L: The Load Current
V_{TH}: The System Voltage during fault condition

The load current I_L is given by,

$$I_L = \frac{[P_L + JQ_L]}{\text{V}} \quad \text{..... (2)}$$

If the load voltage is considered as a reference, then equation (1) can be written in the following form:

$$V_{DVR}(\cos\alpha + j\sin\alpha) = V_L(\cos 0 + j\sin 0) + Z_{th}.I_L\big(\cos(\beta - \theta) + j sin(\beta - \theta)\big) - V_{th}(\cos\delta + j sin\,\delta) \quad \text{..... (3)}$$

Where: α, β and δ are the phase-angles of the V_{DVR}, Zsh and Vth Vectors and θ is the load Power factor, computed with:

$$\theta = \tan^{-1}\frac{Q_L}{P_L} \quad \text{.... (4)}$$

The complex power injection of the DVR can be written as,

$$S_{DVR} = V_{DVR} I_L \quad \text{.... (5)}$$

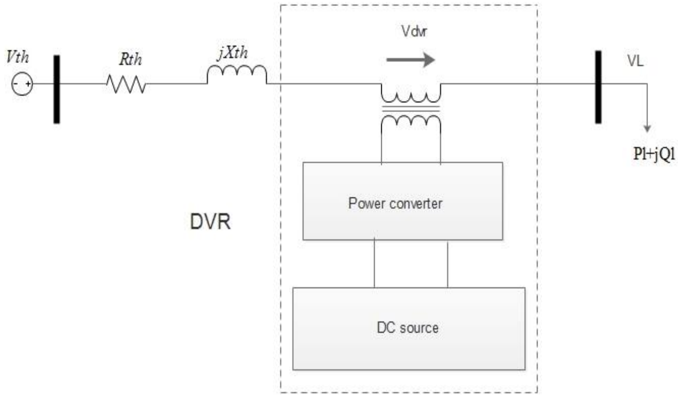
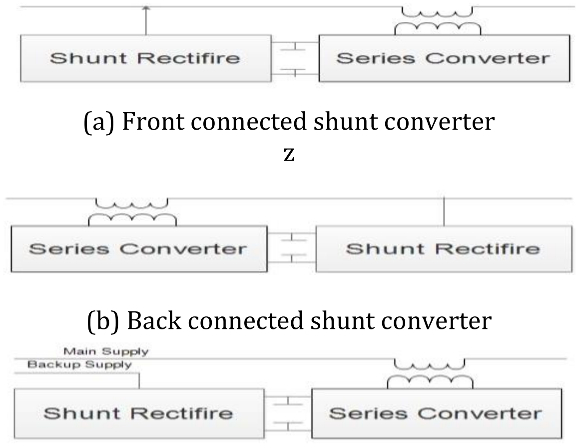


Fig. 7 the DVR schematic connection diagram to the electricity Distribution network



(a) Front connected shunt converter
z

(b) Back connected shunt converter

(c) Rectifier supplied through backup feeder

Fig.8 Types of connections to power source of the DVR: (a) front connected shunt converter; (b) back connected shunt converter; (c) rectifier supplied through backup feeder

The single-phase equivalent circuit of the DVR with a LC filter is applied on the converter side of the Transformer with the purpose of preventing switching frequency harmonics from entering the system and is presented in figure 9. Here L_T indicates the leakage inductance of each of the Transformers, $u.V_{dc}$ indicates the switching voltage generated at the inverter output terminal. The copper loss of the Transformers and the switching losses of the inverter are modeled by the resistance R_T whereas, C_f and L_f represents the filter capacity and inductance.

In order to construct the state space model of the system from equivalent circuit, we define a state vector as $x^T = [\,V_f \; i_{ac}]$, where V_f is the voltage at the capacitor terminals and i_{ac} is the DVR current.

Using Kirchhoff's laws for the equivalent circuit from the figure 9, after some mathematical manipulations, the state space model is expressed by the following equations system:

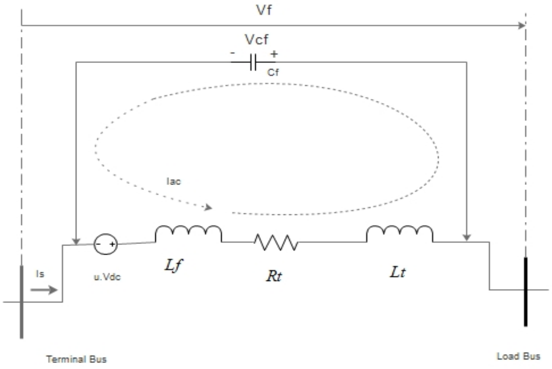


Fig.9 Single phase equivalent circuit of DVR with capacitor filter placed on the converter side of the transformer

$$\dot{\overline{x}} = A.\overline{x} + B.\overline{u}$$
$$y = C.\overline{x} + D.\overline{u} \quad \text{........ (6)}$$

Where:

$$A = \begin{bmatrix} 0 & \frac{1}{C_f} \\ -\frac{1}{L_T} & -\frac{R_T}{L_T} \end{bmatrix} \ \boldsymbol{B} = \begin{bmatrix} 0 & \frac{1}{C_f} \\ \frac{V_{dc}}{L_T} & 0 \end{bmatrix} \quad \text{... (7)}$$

$$C = [1 \ \ 0] \quad D = [1 \ \ 0]$$
$$\text{y} = V_{DVR} \quad \text{.....(8)}$$

V_{DVR} Is the series voltage injected by DVR.VDC is the voltage across the DC capacitor bank.

The control vector is uT = [$uc \quad i_S$], where the uc is the control variable and i_S the current that flows through the Power system.

The transfer function is determinate from the state space representation {A, B, C, D} by apply the Laplace transform to the equation system described in (6), assuming null initial conditions. Then, the following equations system is obtained:

$$s.\overline{X}(s) = A.\overline{X}(s) + B.\overline{U}(s)$$
$$\overline{Y}(s) = C.\overline{X}(s) + D.\overline{U}(s) \quad \text{...... (9)}$$

From the first equations of system (9) we obtain the $\overline{X}(s)$ Term as:

$$\overline{X}(s) = (s.I - A)^{-1}.B.\overline{U}(s) \quad \text{.... (10)}$$

Substituting (10) in second equation of (9), we obtain:

$$\overline{Y}(s) = (C.(s.I - A)^{-1}.B + D).\overline{U}(s) \quad \text{.... (11)}$$

The transfer matrix function of the system is:

$$\overline{G}(s) = (C.(s.I - A)^{-1}.B + D) \quad \text{... (12)}$$

Control technique of Dynamic voltage restorer (DVR)

The control scheme of DVR compensator is realized in Matlab/Simulink and is exhibited in figure 10 the control method is designed in a defined way that the symmetrical load voltage (V_L) vectors should be appearing at output terminals of controller. It is considered that zero sequence components are absent, all quantities is transformed to Synchronous-Rotating dq- reference outline.

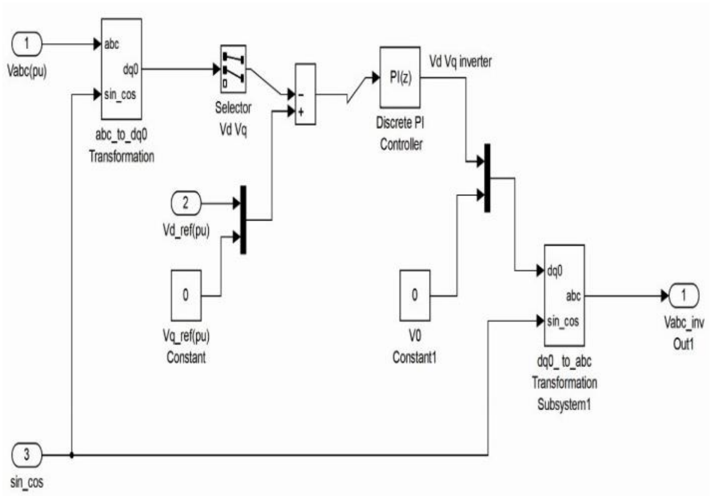


Fig. 10 the voltage regulator control scheme implemented in Matlab/Simulink

Therefore, the new coordinate system is described with the d- axis for all time coincident with the instantaneous voltage vector (vd=\v\, vq=o). Consequently, the d-axis component supplies to the instantaneous active power and q- axis component supplies to the instantaneous reactive power. This operation permits to design a simpler control system than using abc-component by PI controller. Hence according to this theory, the load voltage vector is altered into the dq-reference frame.

The conversion of the 3-phase instantaneous voltage frame to the synchronous-rotating dq-reference frame makes use of Park's transformation as follows

$$[\overline{u}_{dq0}] = [T_{dq0}].[\overline{u}_{abc}]$$

Where the Park's transformation matrix $[Tdq0]$ is defined as

$$[T_{dq0}] = \frac{2}{2}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

In equation we note with θ the transformation angle calculated as in with relation:

$$\theta(t) = \theta(0) + \int_0^t \omega(t)\,dt$$

and with ω is the angular speed of the dq-reference frame.

The control strategy is intended to ensure a symmetric load voltage vector and a unitary power factor to the output terminals of controller. Therefore the q component of the reference voltage is selected as zero and the dq component of the reference voltage is 1.

The dq components of the load voltage are compared with the reference voltages and the PI controller work out the errors, thus obtaining dq component of the inverter. The inverter voltage is converted into the abc -frame.

The voltage infused by DVR is synchronized with the framework voltage utilizing a Phase Locked Loop (PLL) module. Coordinate changes from abc to dq segments in the voltage estimation framework are likewise synchronized through the PLL. The sign acquired from voltage controller is balanced utilizing Pulse Width Modulation (PWM) procedure. One of the best choices for DVR converter is viewed as the PWM, since lessens the sounds substance and prompts a quick reaction. The PWM Generator offers the terminating beats for the inverter IGBTs. [16]

5. Test System

The Test Distribution Power System used to approve the proposed model and control system is executed in Matlab/Simulink (figure 11). A 110 MVA 110/20 kV power Substation is supplied through a 10 km high Voltage line from the transmission Power System that is spoken to by the high Voltage Power source. A DVR is actualized in Substation associations so as to restore the Voltage level on the principle Transport Bar of Substation. The DVR arrangement exhibited in figure 8(c) is picked.

The main feeder and reinforcement feeder of association Substation are associated into the same medium Voltage Bus Bar of the HV/MV Substation. This is a disadvantageously association for the two feeders of the associations Substation furthermore, is utilized to demonstrate the capacities of the DVR compensator to repay Voltage Sags when a Fault happens in the Distribution system.

The Inverter side information terminals of the DVR are associated at the principle feeder Bus Bar of the association Substation, the yield terminals are associated with the principle Bus Bar of the association Substation and the Rectifier side terminals are supplied from the reinforcement feeder Bus Bar.

IMPLEMENTED MATLAB MODEL

The compensator incorporates 3 single-stages 20/10 kV Transformers associated in star design on the Inverter side. The Rectifier is associated with the reinforcement feeder Bus Bar through a tree-stage 20/10 kV Transformer.

A first three phase to ground Fault happens on the high Voltage system on a contiguous line at time t = 0, 2 s. This two-stage Fault is evacuated by the System insurances after 0.15 s.

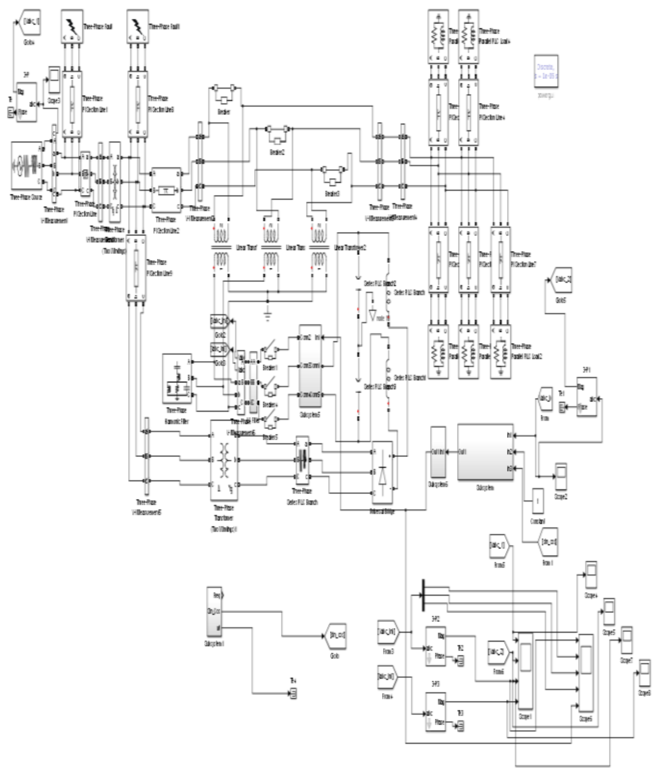


Fig.11 with DVR Model
DVR based diode clamped MLI with PD technique

A second three phase Fault happens in the medium Voltage system, at time t = 0.6 s, on another medium Voltage link supplied from the medium Voltage Bus Bar of Transformer station. The three phase Fault is evacuated by the insurances System of the high Voltage/medium Voltage Substation after 0.4 s. These Faults that show up on nearby lines lead to Voltage plunges felt by purchasers encouraged through sound Power lines. The effect of utilizing the DVR as a part of the association Substation can by broke down by recreation results from the Matlab/Simulink of all model respectively.

Table 1, Lists the system parameters

System Parameters	Values
Three phase source voltage	110×10^3 V (Phase-to-phase rms voltage)
System frequency	50 Hz
First Fault name at (Line-2)	Three phase to ground
Three-phase PI section Line (Line-2)	13 km
Three-phase PI section (Line-1)	10 km

Three phase transformer (two winding Line-1)	[110/20 kV, 50 Hz],[ABC (Y_g)-abc(D_1)]
Second Fault name at (Line-3)	Three phase fault
Three-phase PI section line (Line-3 feeder)	6 km
Three-phase PI section line (Line-4 backup Feeder)	6 km
Three-phase PI section line (Line-5 main feeder)	6 km
Three phase transformer (two winding Line-4)	[20/10 kV, 50 Hz],[ABC (D_1)-abc(Y_g)]
Three- phase Harmonic Filter	Nominal L-L voltage (Vrms) and frequency (Hz),Quality factor 40×10^6,50,16
Injection transformer(DVR)	40 (MVA) and 50frequency(Hz) 10/20(kV)
Three -phase parallel RLC Load	11000×10^3 W (Active power)
System Parameters	Values
Three phase source voltage	110×10^3 V (Phase-to-phase rms voltage)

Implemented diode clamped inverter

The diode clamped inverter are used in matlab model and this is show in figure

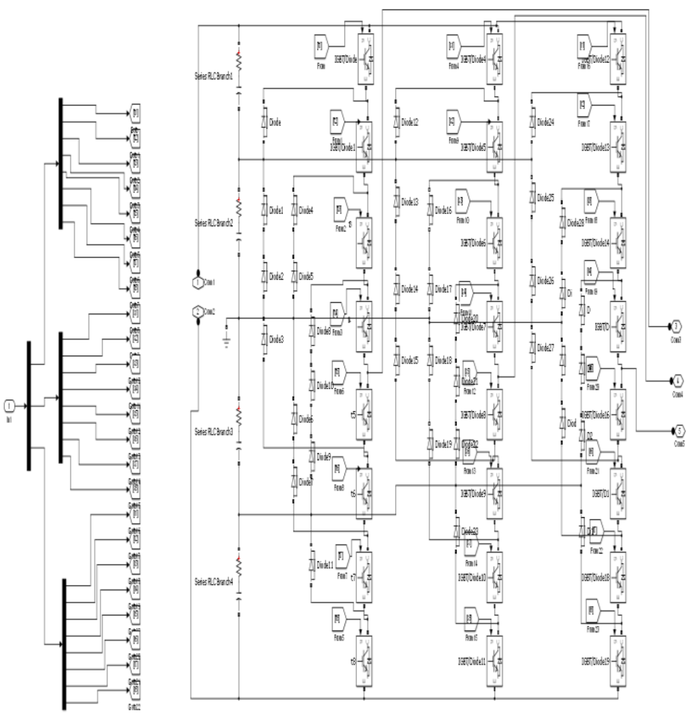


Fig.12 Implemented 5 level diode clamped inverter

5 level MLI based DVR

In this case, 5-level MLI with Diode clamped topology and Phase Disposition (PD) control technique based DVR is implemented. Simulated diagram of Implemented 5-level MLI with Diode clamped topology and PD control technique is represented in fig.11 and results shows in fig.13.

Impact of DVR

The impact of employing the DVR in the connection substation can by examined by simulation results from the figure 13 and 14. The good performances attained by employing the voltage compensator are depicted by the rapid compensation of the voltage on the load bas bar. In condition of Faults, though the ac voltage level at the rectifier terminals decreases, the DVR effectively compensates the voltage drop at the load terminal.

It is significant to observe that, in the absence of DVR ,the voltage magnitude on the main bus bar of connection substation would vary as in the diagram of fig.14(a) as the bus bar is directly fed by main feeder.

The obtained results demonstrate the performances of used control technique and MLI based DVR model in mitigating voltage sags as applied to power network with secondary distribution network configuration.

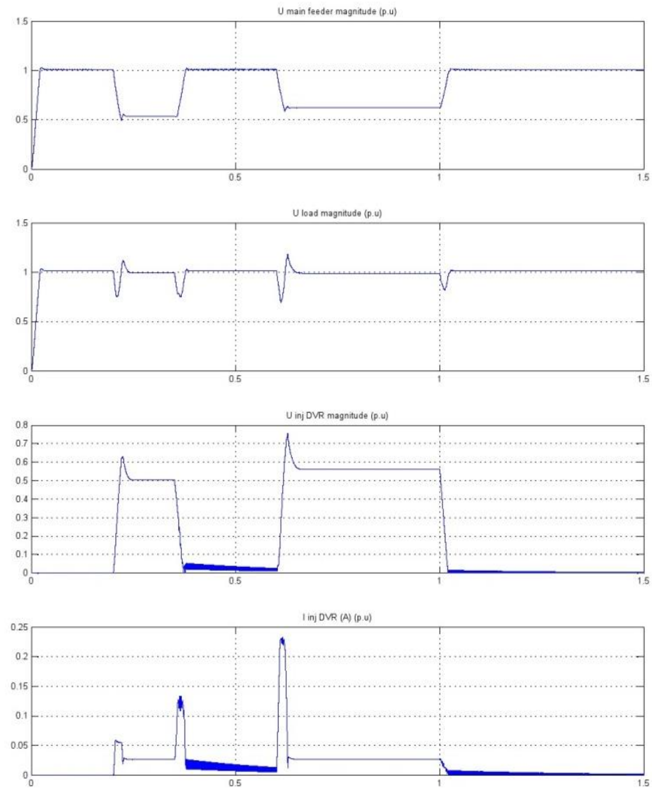


Fig.13 simulation results : main feeder magnitude (p.u),U Load magnitude (p.u),U inj DVR magnitude(p.u),I inj DVR (A)

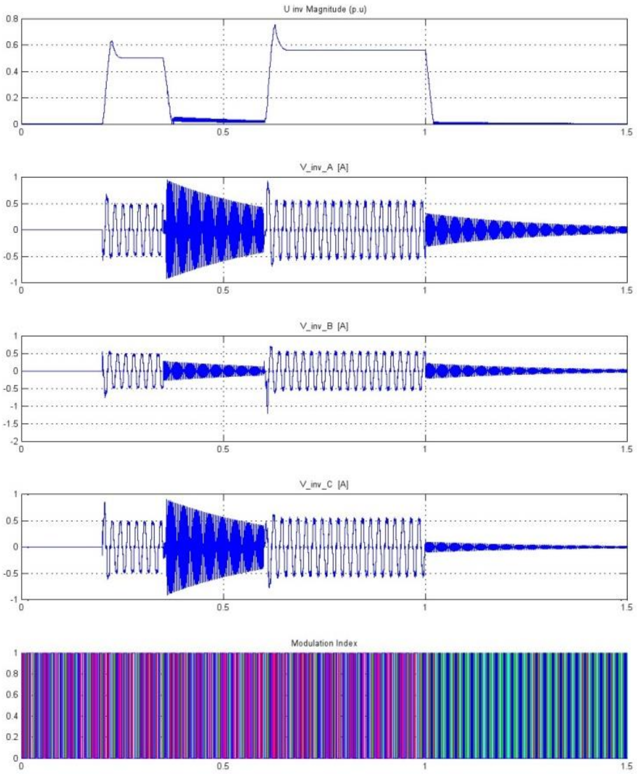


Fig.14 simulation results: the injected inverter voltage magnitude in p.u, the inverter voltage curves and firing angles

Load voltage magnitude Wave form

The load voltage magnitude of the U main feeder at time of fault, after Compensation some changes in voltage waveform, the DVR based model responses Fig 13 model of their output of load voltage compensated.

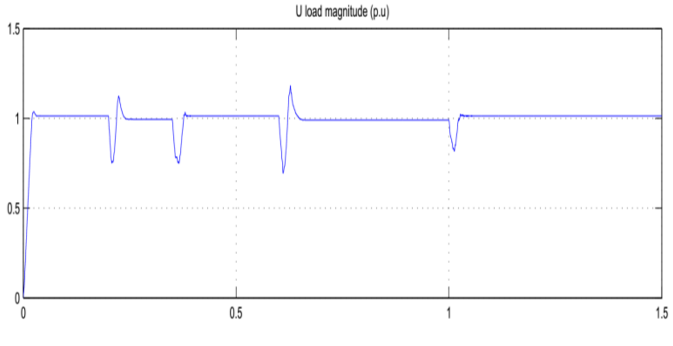


Fig.13 (b) U Load magnitude (p.u) DVR based 5-level diode clamped MLI with PD technique

INFERENCE:
The output voltage magnitude across the load in case of fault, withot DVR based 5-level diode clamped MLI with PD technique is shown in Fig.13 (a)
In the next waveform with the same fault the load voltage with DVR based 5-level diode clamped MLI with PD technique Fig.13 (b)

From this we are observing DVR based 5-level diode clamped MLI with PD technique. The load magnitude is prominently successfully compensated the voltage dip at the load terminal shows Comparison of load voltage magnitude Wave form Fig.13 (b)

6. CONCLUSIONS

In this paper, Dynamic voltage restorer (DVR) based multilevel inverter (MLI) is utilized to lessen the voltage sags, thereby improving the power quality of system. The used scheme are employed & tested for medium voltage (MV) distribution network with secondary supply system. The 5-level MLI based DVRs are connected step by step in the compensated feeder to evaluate their performances. The efficacy of different control techniques of MLI has been investigated. As seen from load voltage waveform & frequency spectrum, the THD level is reduced effectively from 40.16% as in case of 3-level DVR based on MLI to a much less value of 28.95% as in case of 5-level MLI based DVR.. Simulations outcome indicate to facilitate 5-level MLI based provide better compensation to the system and also there is considerable improvement in power quality also.

Power Quality improvement

This section aims to present the substantial improvement in power quality with incorporation of MLI based DVR for voltage compensation and to reduce harmonic. Different configurations are compared for the same.

Simulations are performed for 5 level MLI and corresponding % THD are presented in table 2. Simulated results presented in table indicate that with the increase of level of MLI there is considerable reduction in percentage of total harmonic distortion.

Table-2 THD Comparison between Three levels and Five levels Diode clamped Inverter:

S.No	DIODE CLAMPED TOPOLOGY	PULSE WIDTH MODULATION TECHNIQUE THD%	
		POD	PD
1	3 Level Multilevel Inverter	40.16%.	37.88%.
2	5 Level Multilevel Inverter	29.97%.	28.95%.

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