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A Review on Dynamic Voltage Restorer in power systems concerned to the issues of Power Quality

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Abstract. Power Quality issues are the important concepts for all types of electricity usage consumers due to increase in power demand at different levels. For achieving power demanded, the power grid is incorporated with single or integrated renewable energy sources which resembles in rise of additional power quality issues than in regular isolated system. In this, a detailed review on different nature of power quality issues, monitoring devices of power quality & power quality mitigation especially by the dynamic voltage restorer-DVR has been explained .A review on DVR for power quality issues like voltage swell, sag, flickers, imbalance, reactive power imbalance and harmonics with distinct power circuit structure and the detailed control strategies for mitigating the mentioned issues is presented in this paper.

1. Introduction

By considering limitations of standards, it is very crucial in maintaining the electrical power quality. If the quality of power is not maintained, then it leads additional power losses, increase in harmonic content, interference with the telecommunication lines, reduction in system efficiency and also overall stability. With the increase in development of power electronics, quality of power can be maintained from different power quality issues particularly the in industrial customers voltage disturbances are the common. A power electronic converter is nothing but a DVR, connected in series for mitigation of disturbances/issues related to power quality. This DVR used in the scheme of flexible AC Transmission systems (FACTS) at transmission level as well as at level of distribution for custom power devices. Both voltage problems in steady state condition and dynamic state condition can be compensated by DVR and is also efficient in generating or consuming the reactive power by the energy storing elements used in DVR. DVR can also enhance the transient stability by compensating the reactive power along with this, disturbances like voltage sag/swell/flickers/imbalance can also be mitigated which are may be caused due to dynamic load changes. In the DVR, series injection of voltage can be achieved by voltage source converter VSC (inverter)-VSI's which consists of IGBT's (Insulated Gate Bipolar Transistor) with anti parallel connected diodes , which is supported by a capacitor stored by DC. This entire schema is linked between point of common contact (PCC) and at the receiving point. The study of DVR has been reviewed emphatically for past few years and a tremendous composition, which is available on the distinct topology and control methods. In this paper a review on DVR on different power circuit structures and control strategies has been clearly explained [1], [11].

2. Different Types of Power Quality Problems & its Mitigating Devices

2.1. Voltage Sag or Voltage dips

As per the IEC standard, the voltage Sag or voltage dips are defined as the sudden voltage reduction in electrical systems at a point pursued by a recovery voltage later a short recovery of time from a 0.5 cycle to a few seconds as shown in Figure. 1. In IEEE standards it is represented as the 20% variations of normal voltage.

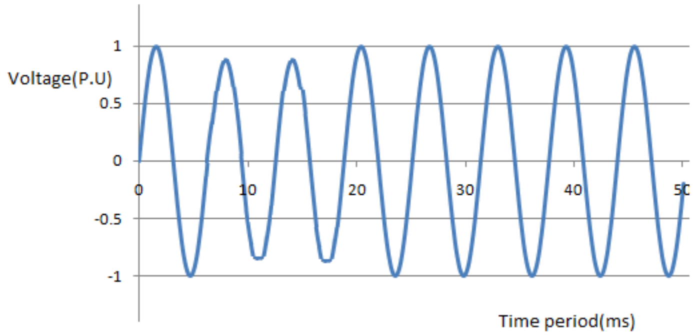

Figure. 1. Voltage sag or Voltage dips

2.2. Voltage Swell or Rise

Voltage swell is the inverse of voltage sag. With sudden removal of load under normal operating conditions, at terminal voltage may be higher than the input voltage which is nothing but Ferranti effect as displayed in Figure. 2.

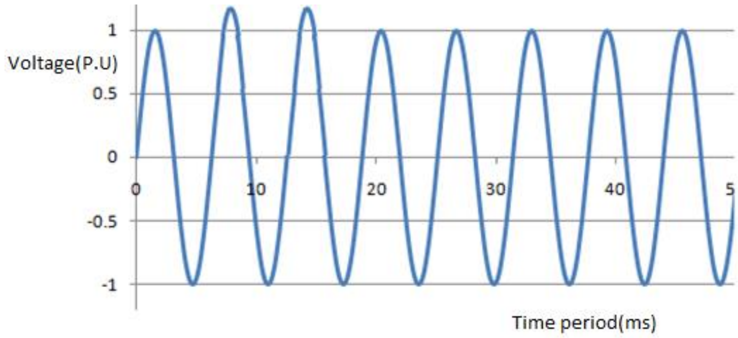

Figure. 2. Voltage Swell or Rise

2.3. Voltage Spikes

Generally voltage spikes are very short pulses of energy in power lines which contains very high voltages (it may also thousandths or millionths of a second high voltages) and it cause damage to the power electronic device easily which are incorporated in the system as represented in Figure. 3.

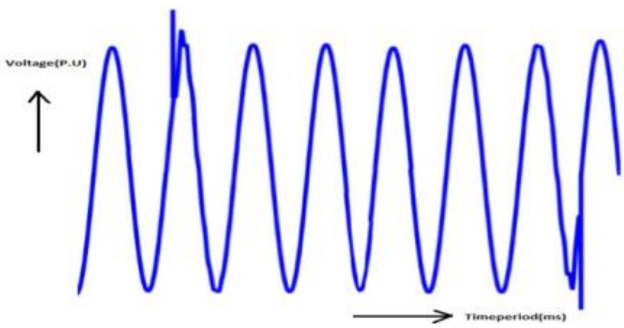

Figure. 3. Voltage spikes

2.4. Voltage Fluctuations and Voltage Flickers

As represented in Figure. 4, voltage fluctuations and voltage Flickers may be due to the surges or lightning's at the power grid but whereas coming to the grid connected renewable energy sources, this voltage fluctuations or power fluctuations are appeared due to solar irradiation which are caused by passing clouds. These voltage fluctuations and voltage flickers are comparatively very small i.e., shorter than $\pm 5\%$ variations in the RMS line voltage.

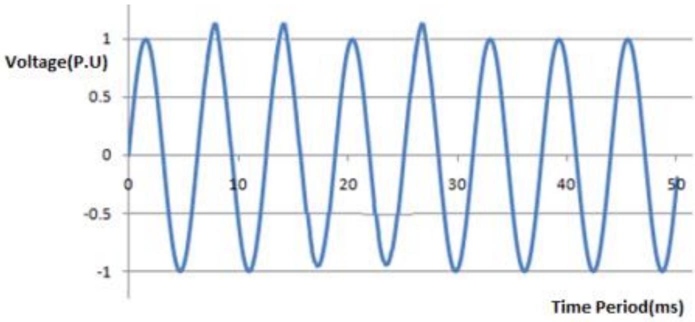

Figure. 4. Voltage Fluctuations and Voltage Flickers

2.5. Voltage Unbalance

Voltage unbalance or voltage imbalance is the change in magnitudes of single/three phase voltages in approximation among one another as displayed in Figure. 5.

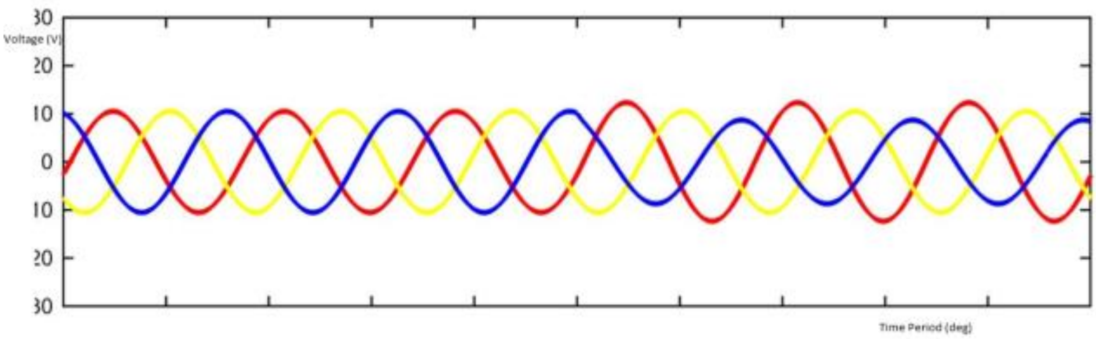

Figure. 5. Voltage Unbalance

2.6. Frequency Variations

One of the ultimate significant power quality problem is frequency variations which are appeared due to different reasons like harmonic instability, dynamic load changes etc.,. The permissible range of frequency variations is $\pm$5% variations of fundamental frequency as displayed in Fig. 6.

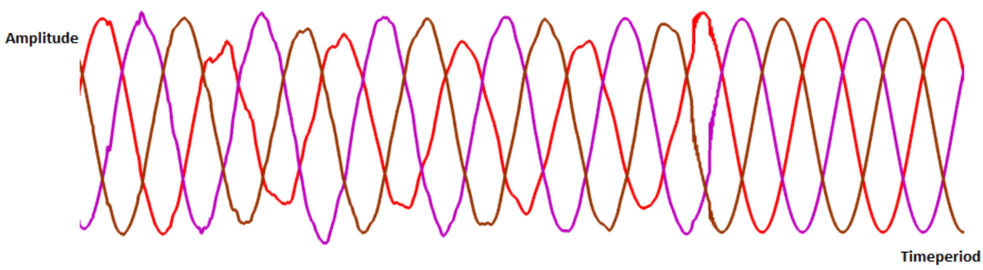

Figure. 6. Frequency Variations

2.7. Harmonics & Harmonic Distortions

Harmonics are defined as the Integral multiple of fundamental frequency. Harmonic Distortions or Total Harmonic Distortions (THD) are to be considered because it affects mainly the power quality specifically in grid connected renewable energy sources. Due to the choice of inverters in renewable energy sources for DC to AC conversions, which results in injection of voltage as well as current harmonics as represented in Figure. 7.

THD represented as

$$THD = \frac{\sqrt{\sum_{m=2}^{\infty} V_m^2}}{V_1}$$

Vm – Voltage Magnitude of Harmonic Component (For m = 2 to ∞)

V_1 – Fundamental Voltage

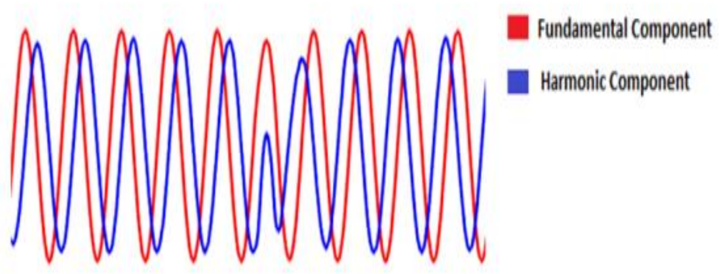

Figure. 7. Harmonic Distortions

Table 1. Mitigating equipments for power quality issues

Nature of Disturbances / Device	Power Quality Isssues							
	Transient	Swell	Sag	Frequency Deviations	Flicker	Harmonic Distortion	Noise	Interruption
SPS	×	×	×	×	×	×	×	✓
Voltage Regulator	×	✓	✓	×	×	×	×	×
Isolation Transformer	✓	×	×	×	×	×	✓	×
Filter	×	×	×	×	×	✓	✓	×
UPS	✓	✓	✓	✓	✓	✓	✓	✓

Passive Filter-PF	×	×	×	×	×	✓	×	×
Fixed Capacitor-FC	×	×	✓	×	×	×	×	×
Active power filter-APF	×	×	×	×	×	✓	×	×
Surge Suppressor	✓	×	×	×	×	×	×	×
Hybrid Active Power Filter-HAPF	×	×	×	×	×	✓	×	×
Power Conditioner	✓	✓	✓	×	×	×	✓	×
Static Var Compensator-SVC	✓	✓	✓	✓	×	×	×	×
UPQC	✓	✓	✓	✓	✓	✓	✓	✓
Static Synchronous Compensator-STATCOM	✓	✓	✓	✓	×	×	×	×

3. DVR System Configuration & Its Operation

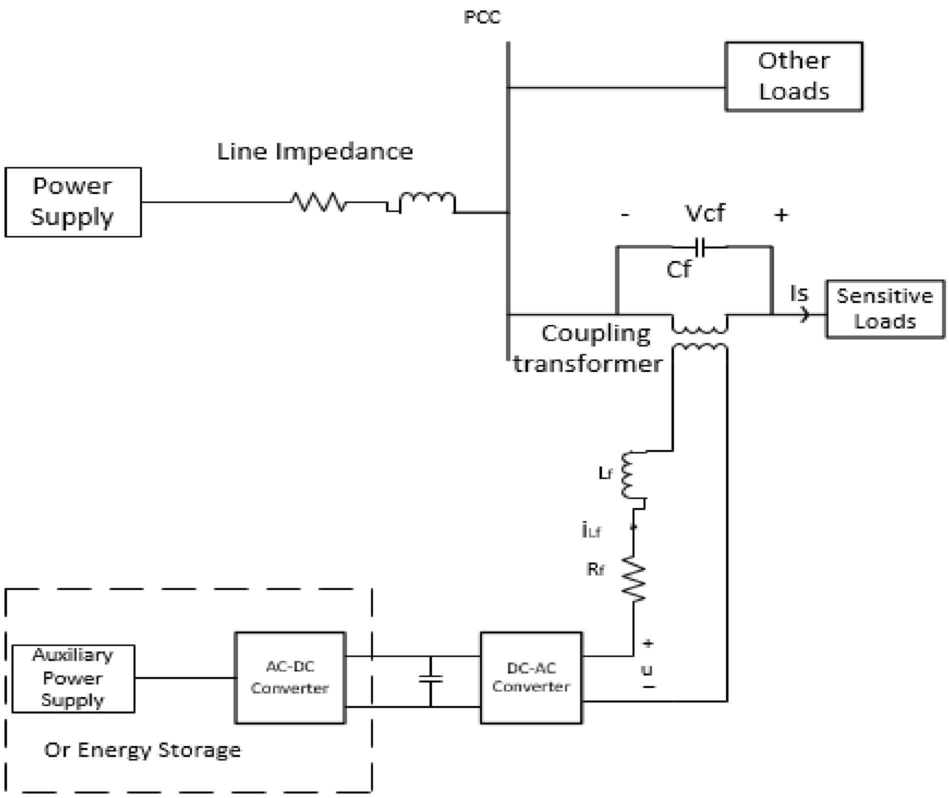

Figure. 8. DVR with a power system configuration

The compensator which inserts voltage in series with the line by protecting the sensitive loads opposing to power quality issues such as voltage Swell, Sag, flickers, imbalance e.t.c., is a dynamic voltage restorer. From Fig. 8, the simplified single line diagram of DVR is shown. Even though if the input AC of the power system may distorted or not, the voltage across the receiving end be constant owed to the dynamic injection of voltage control by DVR. This DVR performs the dynamic operations via transformer i.e., consumes the reactive power from the line and stores this energy in a dc capacitor (in rectifier mode) under voltage swell conditions and similarly generates the stored energy by balancing reactive power in the line (inverter mode-controlled case) which is under voltage sag conditions. Finally with this dynamic response from the DVR the voltage across the line can be constantly maintained by balancing the reactive power which is done through the voltage source converter. With the use of filter which is series connected with VSC, the harmonic elimination can be done. DVR will be short circuited by a switch when there are no disturbances in voltage so it resembles in minimizing losses and maximize cost effectiveness. Thus the DVR eliminates voltage sag/swell/imbalance/flickers, compensates reactive power & harmonic elimination and reduces the risk of load tripping and also maintaining the quality power.

4. Classifications Of DVR depending on Power Circuit Configuration

4.1. Multifunctional DVR in Distribution Systems

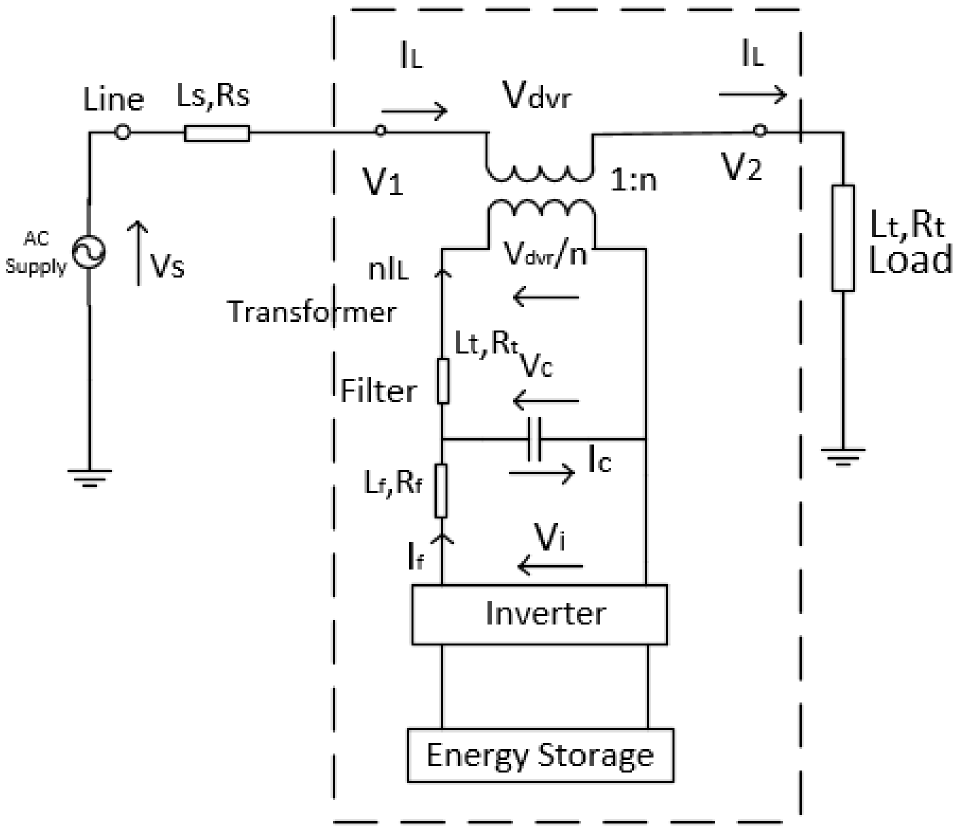

Figure. 9. DVR with Distribution system

In this Figure. 9 shown, the support of voltage level from medium to group of consumers by DVR is done. If there exists disturbance in consequent DVR's feeder, huge current flows through the system then the DVR controls the fault current without entering fault current to the line/parallel feeders by protecting load with breakers and isolators. Due to extreme fault current, the voltage across PCC may

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fall and loads which are connected to feeders may also affect. During voltage compensation, DVR also commit voltage sag at PCC if control is not done properly, this leads to additional increase of fault condition. For this case, a flux charge model is best suited for limiting the fault current by the DVR in which DVR acts as virtual impedance. In this method, the DC link capacitor and battery is protected by DVR and there will not be any consumption of real power from other sources/elements in this system by DVR [3].

4.2. Interline DVR in Distribution Systems

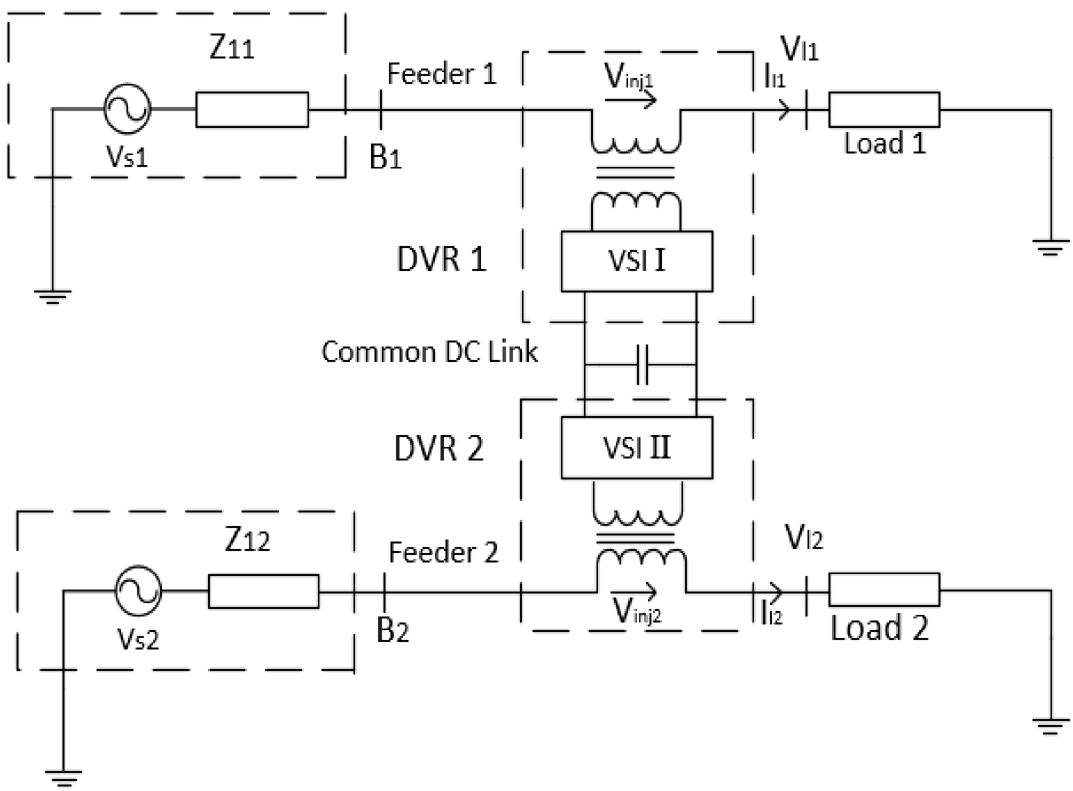

Figure. 10. Interline DVR in a 2 feeder system

Interline DVR system consists of distinct DVR's in distinct feeders, with sharing of a common dc link. Interline DVR with two line feeder system as shown in Figure 10, employs two DVR's connected to two distinct feeders which originates from two substations grid. This two feeders may consists of different or same level of voltage. If one of the DVR's compensate voltage sag, then the other DVR in the Interline DVR, which is operating at power flow mode of control to restore energy storage in the dc link which is depreciated due to real power consumption by DVR which is works on voltage sag compensation mode. Proposition of voltage sags occurs due to the power system faults, which depends on many factors such as fault current, voltage level, transformer in the Proposition track and their connection setup, etc.,. Voltage sags are likely to be in action to a larger electrical length of distance rather than in distribution system and because of these factors, two feeders of the Interline DVR system as shown in Figure. 10 are connected to two distinct substations grid, and is reasonable to consider that voltage sag in Feeder 1 can have a lower effect on Feeder 2. Consequently, the demanding generation transmission system can be considered as two independent sources for the two feeders [5], [52].

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4.3. DVR in Distributed Grid with Ultra capacitor

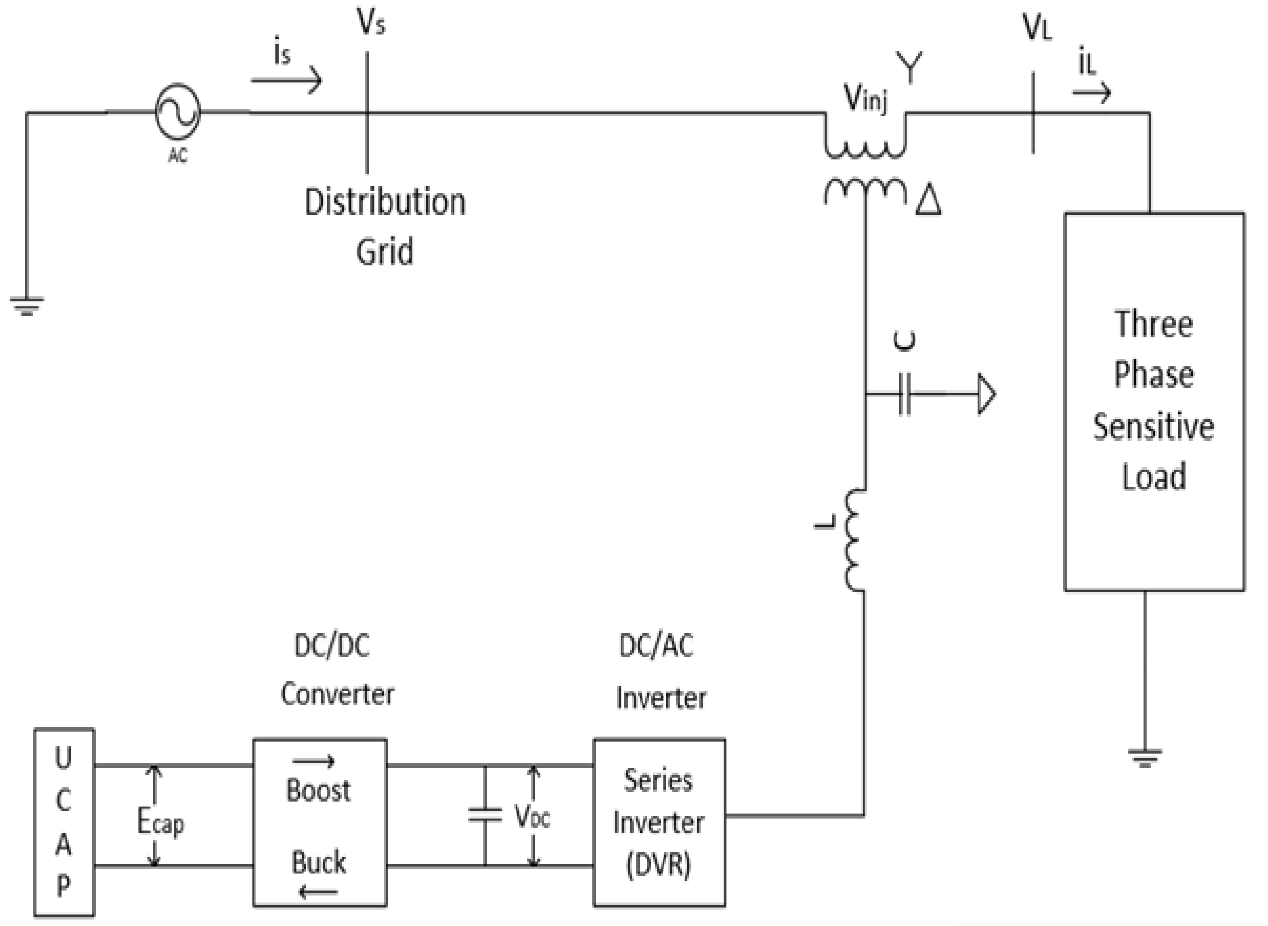

Figure. 11. DVR Single line diagram with Ultra Capacitor Energy Storage-UCAP

Out of technologies in rechargeable energy storage, active power support in milli-seconds to seconds timescale, Ultra Capacitors are best suited represented in Figure. 11. Accordingly, Ultra capacitor used integration in to DVR system is ideal, due to milli-seconds to seconds range duration of instantaneous voltage sags and voltage swells. Generally these ultra capacitors have the energy with lower density and ideal characteristics for the compensation of voltage swell and sag with high power density in which these combined functions are requires large amount of power in small time period. When compared to energy storing elements, ultra capacitors posses' large number of charge/discharge cycles even for equal size of modules which leads to ease of integration. The applications of DVR with integration of ultra capacitors can be given as.

i. For compensating voltage sag and swell in the line, the capability of generating real power to the system is done.
ii. DC-DC converter, Inverter Interface with control, and ultra capacitors preliminary demonstration can be done.
iii. To compensate voltage swell and sag in the distribution grid can be done by development of inverter and DC-DC converter.
iv. Hardware Integration and their performance validation of Ultra capacitor DVR system [13].

4.4. DVR in power system without Transformer

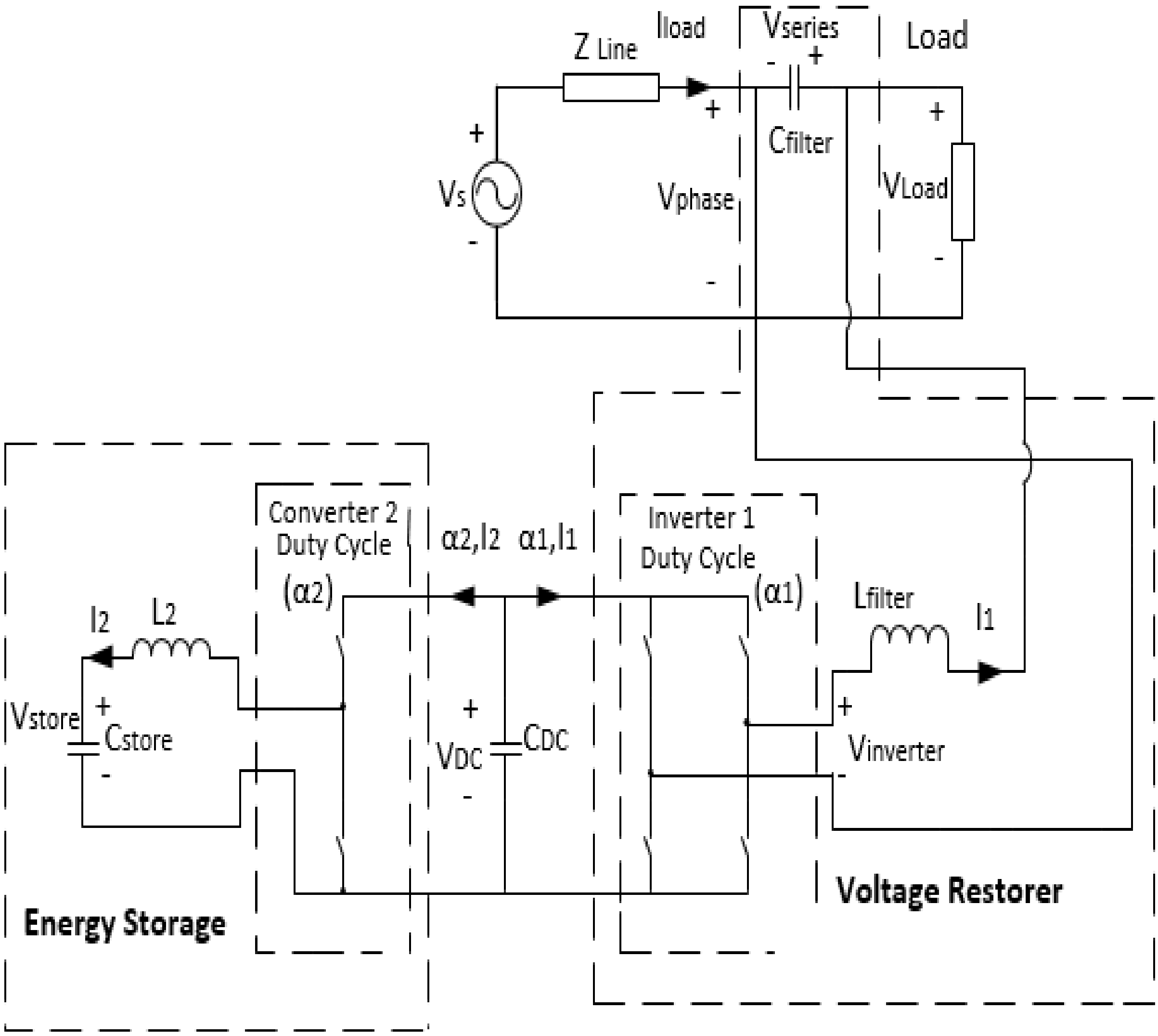

Figure. 12: Transformer less DVR

Equivalent voltage and impedance is represented in upstream source as displayed in Figure. 12. Here Load is pretended to be constant. DVR output is series inserted among the load and source and can further be segregated into the energy storage unit and voltage restorer unit which are connected by dc-link capacitor. The series injected voltage is controlled by the Restorer. In Normal operating conditions, either by a bypass switch which is connected in parallel or the voltage restorer inverter controls by maintaining 0V. Required amount of series voltage compensation is provided under sag conditions and this restorer has distinct functional modes for normal and sag conditions which can be classified as self charging and voltage restoration modes respectively. Here, the loss in phase voltage is restored by the Inverter1 which can be achieved through voltage control. When there exists healthy operating conditions, then it shifts to self charging mode [72], [77].

4.5. Grid connected DVR with Fault Current Limit

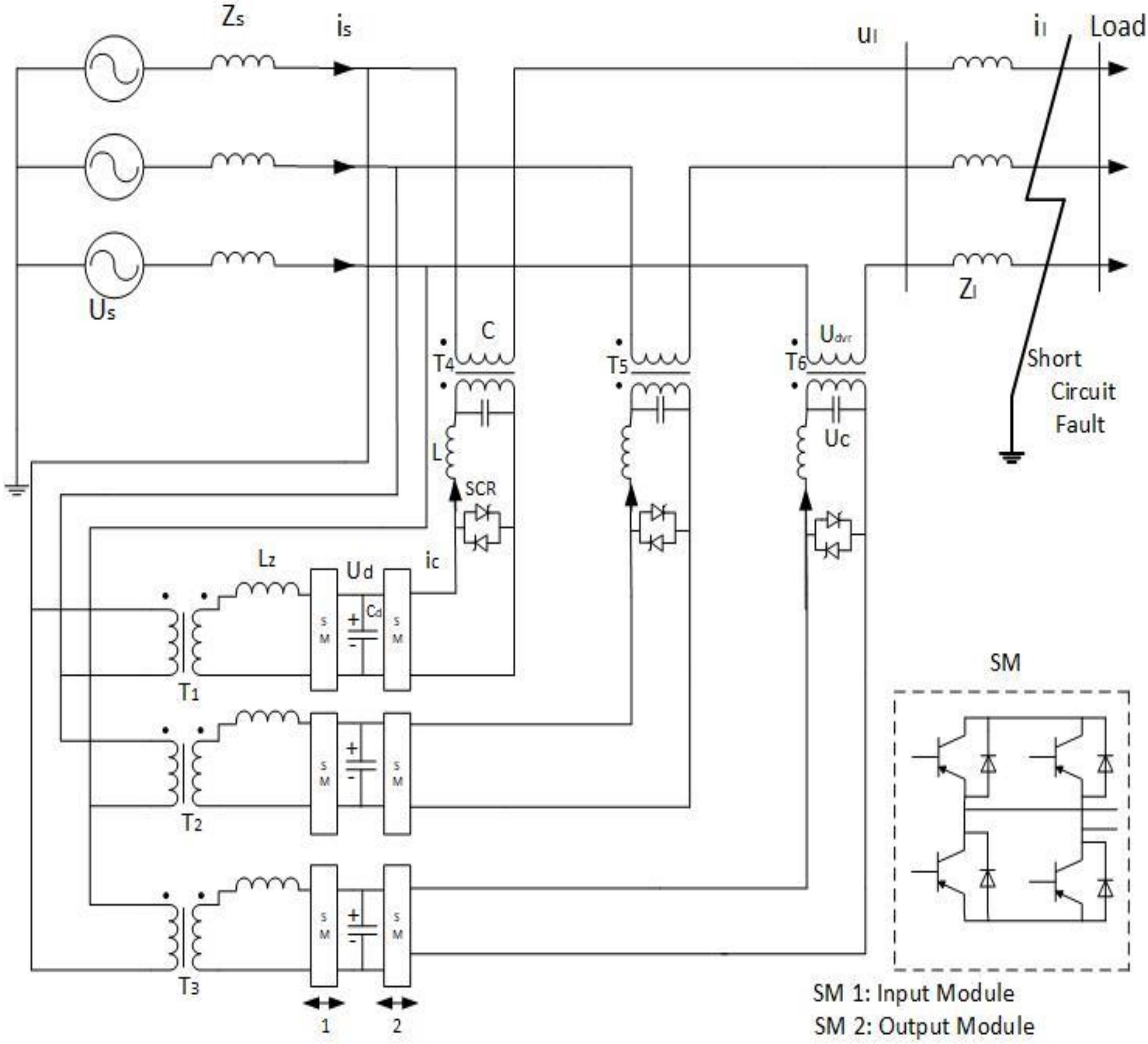

Figure. 13: Fault Current Limiting DVR topology

If, Fault Current Limiting DVR is operated in the mode of voltage compensation, the crowbar bidirectional thyristor is made inactive. Fault current limiting DVR functions as normal like voltage controlled voltage source converter as displayed in Fig. 13. By the Compensation voltage u_l (series connected with supply voltage), the control of fault current limiting DVR is achieved if any voltage unbalance/fluctuations occurs and this leads to enhancement of power quality with maintenance of voltage across load [27]. To provide the voltage across the DC- link, utilization of back to back converter input module is done. In this method, the faulty phase of inverter is non active when short circuit fault arise, crowbar bidirectional thyristor move to active mode. At this instant, on series connected transformer secondary side, insertion of reactor L is done so that the fault current is bounded. This leads to fault current limiting DVR can back to its normal mode with removal of faulty section by supporting the supply voltage with series connected transformer and back-back converter [62], [74].

4.6. DVR with Disturbance Filter

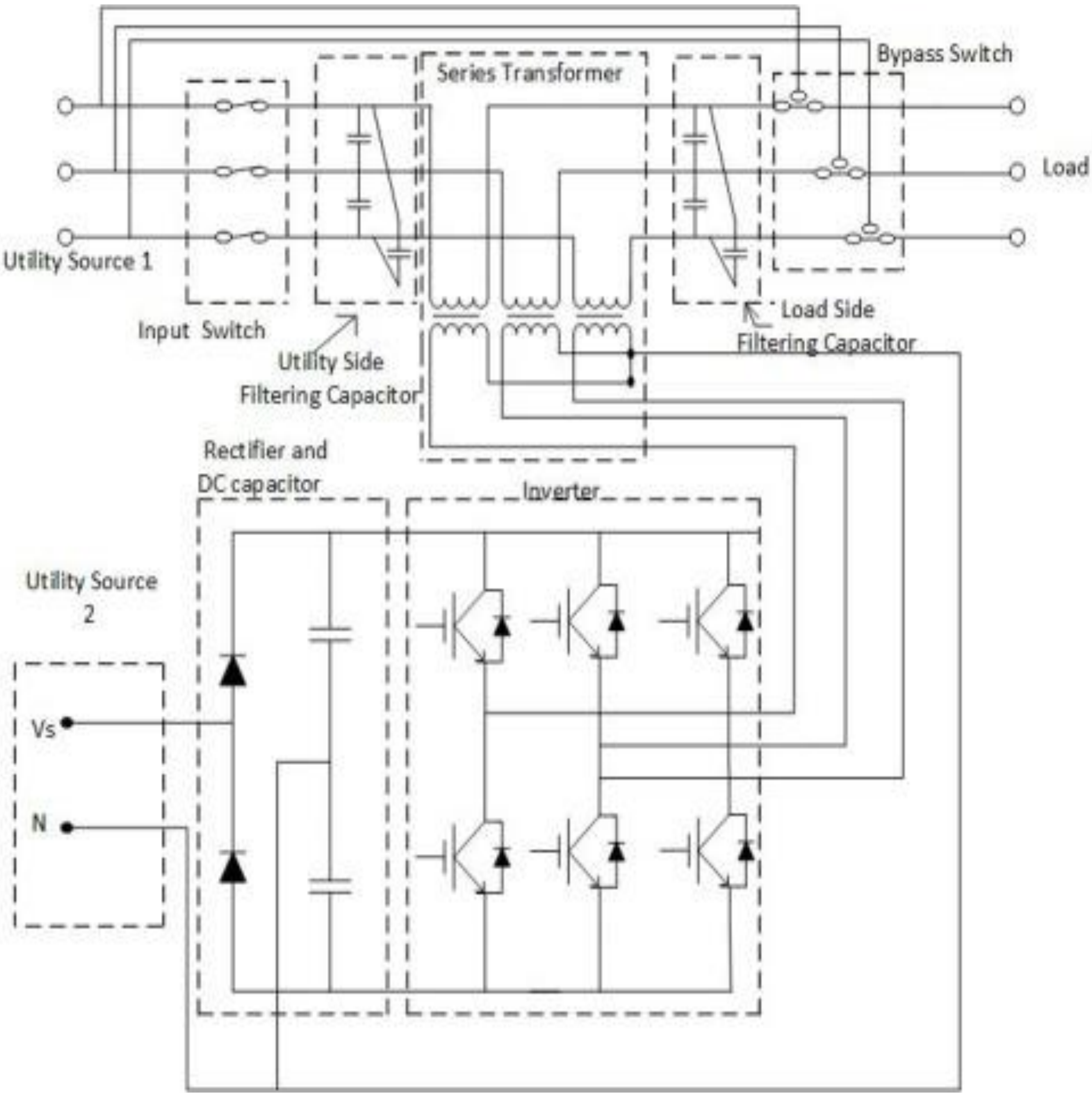

Figure. 14. DVR with Disturbance Filter

As displayed in Figure. 14 shows, the structure of the proposed DVR, where the output terminals of three phase half bridge inverter is connected via (wye) series transformer to the utility supply. To operate under unbalanced circumstances, current path of zero sequence is provided by linking series transformer neutral to ground of the inverter. Here for temporary storage, DC capacitor bank is used for storing the rectified DC power which is converted from AC through Rectifier Unit. For protecting the DVR, bypass switch is used for safe operation. The input switch can detect the fault voltage or current for the disconnection of DVR if there is any circuit fault on load. During this the bypass switch is communicated such that it can transfer load from output of DVR to utility. Thus ends up the bypass procedures. If suppose any voltage disturbance occurs, with the support of the PWM technique the output of inverter can be driven in phase AC source incoming while constant load voltage is maintained. In utility terminals and load terminals the capacitors are shunt connected for the filtering purposes which are named as load side and utility side filtering capacitor respectively. Out of these two, to inhibit the effects of voltages which are non sinusoidal from lowering the utility grid , the utility filtering capacitor is preferable. Therefore the better quality can be ensured to the demand side with such a design by the DVR [31].

4.7. Cascaded H Bridge Inverter

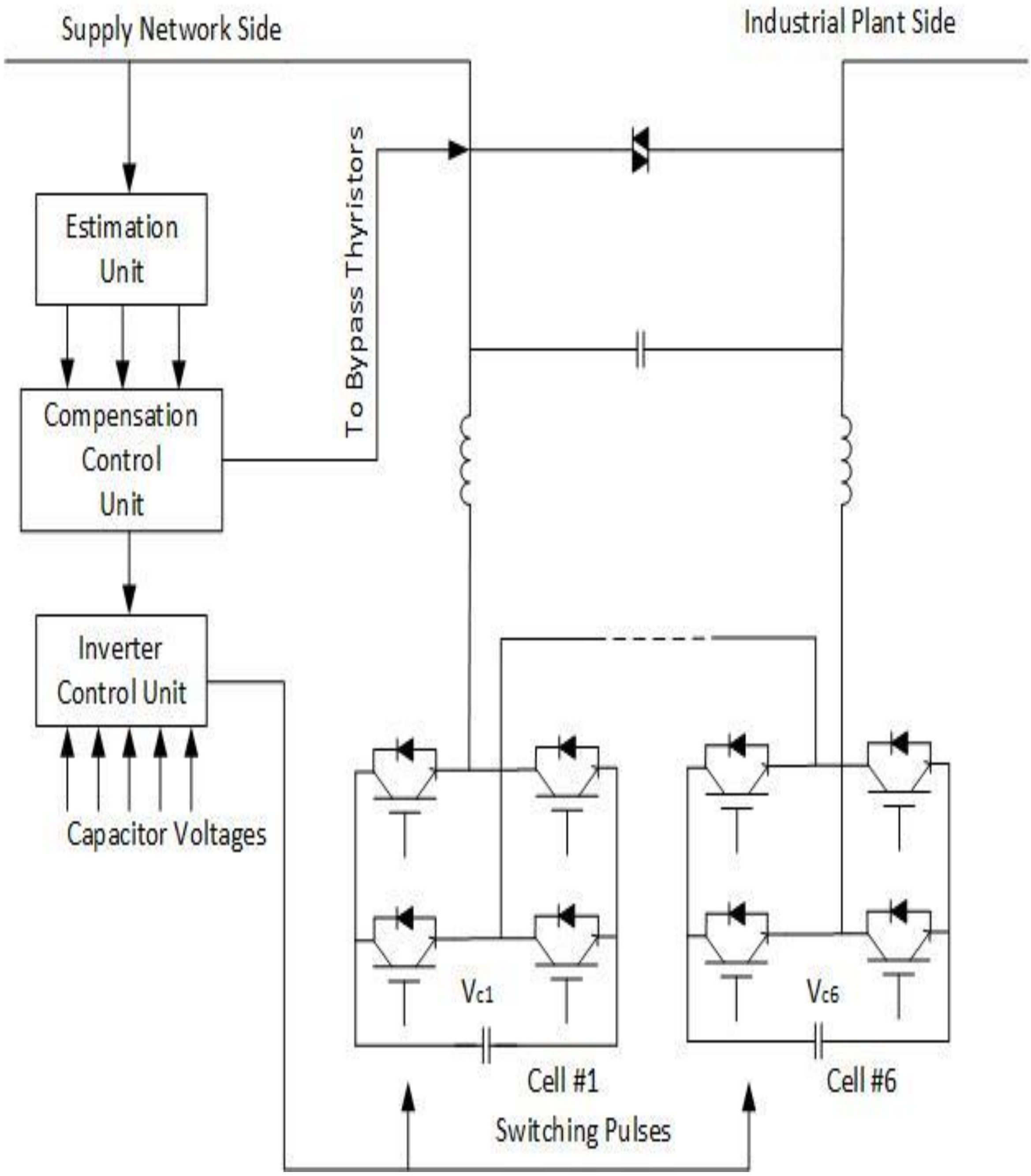

Figure. 15. Cascaded H-Bridge 7-level Inverter

Figure. 15 represents the Conventional Converter which consists series injected transformer, estimation unit, bypass thyristors, control units, control unit and output filters. In order to protect the DVR from losses and electrical faults, the two thyristors (anti parallel connected) will bypass the DVR that to when there exists normal range of voltage. As discussed, the series injected transformer operating frequency be 50/60 Hertz's with its operating voltage across secondary terminals between 20% and 25% of fundamental voltage. At the time of compensation, 10% to 20% of power in load will be passed through this series injected transformer [37].

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4.8. DVR with Nonlinear and/or Unbalanced Loads:

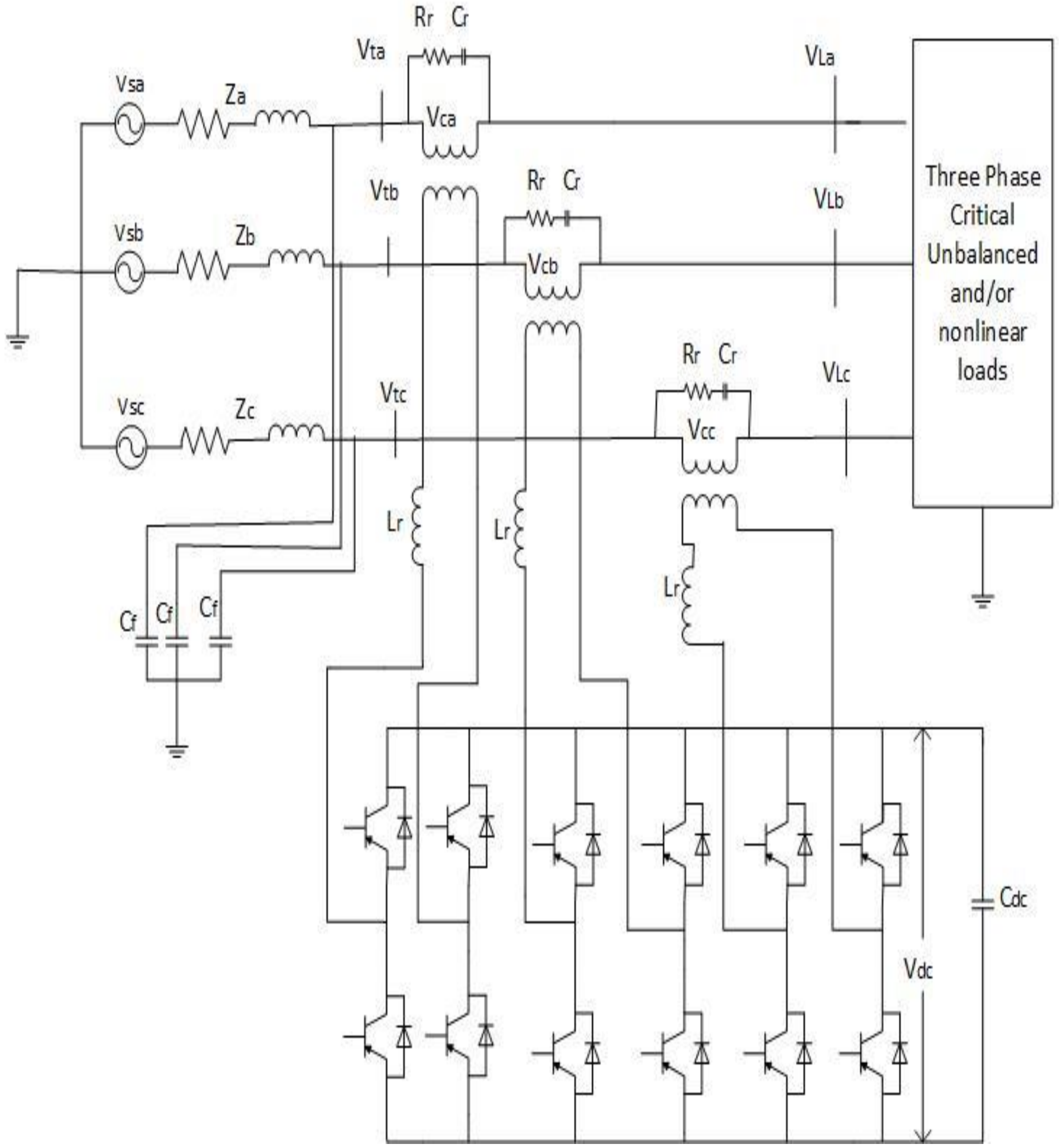

Figure. 16. power circuit of Dynamic Voltage Restorer with Nonlinear and/or Unbalanced Loads

In Fig. 16, distribution feeder of each phase are connected with 3 H-bridge VSCs through revised structure of ripple filter (Cr, Lr, Rr) & injection transformer. This not only shorten voltage required converter, but also contributes isolation among distribution feeder and converter. Shunt capacitor filter (C_f) provides low impedance path to harmonics of load currents which are of higher order, only when the current through the load is nonlinear. To trace the compensating reference voltages, revised filter structure, hysteresis band controller with constant switching frequency is used. Hysteresis band controller with constant switching frequency along with revised filter structure secures all the benefits of band controller and overthrown its difficulties by adaptive hysteresis band and revised filter structure, which is providing constant switching frequency [57], [87].

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Table 2: Classification of DVR according to their compensating Variables

Compensated parameter	Type of Converter	Control/Technique	Control Strategy	Reference
Voltage Sag and also Limit the fault current	12 Pulse VSC	flux-charge model	closed-loop control system	3
Voltage Sags and real power control	2 three level VSC	PWM	Multi Loop Feedback Control System	5
voltage sags and swells	3 Phase 3 leg VSC	PWM	TMS320F28335 DSP based Controller	13
Voltage Restoration and Self Charging	Converter1 single leg and Converter 2 Two Leg	Proportional Controller	closed-loop feedback control system	16
Total time delay of the compensation voltages in DVRs	6 Leg Inverter	Feed forward and state feedback based controller	DSP Control Board TMS320VC33/150Mhz	17
voltage sags and swells	1 phase 2 leg VSI	Switching Frequency Band Controller	Adaptive Hysteresis Band Controller	18
Voltage Sag	3 Leg H-Bridge VSI	SVPWM	Software Phase Locked Loop	20
Voltage Injection	3 phase 3 leg VSI	PWM	Closed loop controller	21
Deep Voltage Sag and Harmonics	3 phase 3 leg VSI	Time Domain Simulation	Two Level Hysteresis Controller	23
Voltage Sag and Harmonic Voltage Distortion	3 phase 2 leg VSI	Filters	--	24
Voltage Sag	3 Phase 12 pulse VSI	PWM	Phase Locked loops	25
Voltage Sag and Voltage Restoration	1 phase 1leg	Boundary control & PLL	Closed loop controller	26
Voltage Compensation and Fault Current Limit	1 phase 3 level two 2leg VSI	Back-Back Converter	Crowbar Thyristor	27
Voltage sag and Disturbances	3 phase half-bridge Inverter	PWM	Current Controlled Inverter	31
Harmonic Distortion and Switching Losses	3-leg and 4-leg VSI's	PWM	Extended Digital Scalar and Symmetrical Component	32
Voltage sag and swell	4-leg VSC	DSP based Digital Controller	Closed Loop Control	33
Voltage Sag	9- Level Inverter	DC-DC converter	--	34

Harmonic Distortion	2 three phase Inverters 3-leg and 6-leg	PWM	Level Shifted carrier or single carrier	35
Total Harmonic Distortion	3 phase VSC	PI controller	Chaotic accelerated PSO algorithm	36
Voltage Sag and Harmonic Distortion	7 level cascade H-Bridge Inverter	DC-DC converter	Active voltage balance algorithm	37
Voltage Sag/Swell Detection	3 single phase H bridge Inverters	PWM	Fuzzy Logic Controller	41
Voltage Sag	3 phase 4 leg Inverter	--	Least Error Squares (LES)	49
Voltage sag	2 cascaded H-Bridge Inverter-7 level	Phase Shifted PWM	Closed Loop Controller	50
Voltage sag	3 Phase VSI	PWM	Phase Locked Loop	52
Weighted Total Harmonic Distortion	3-H Bridge	PWM	Space Vector	54
Voltage Sag	Single phase	PWM	DFT algorithm	55
Voltage sag	Single Phase Inverter-7 level	--	Open and closed loop control	58
Saturation in transformer	Single Phase	PWM	Space vector control	59
Voltage Regulation	Three Phase	PWM	--	60
Voltage sag and short circuit current faults	3 phase 7 level	PWM	Short circuit current limiting mode	62
Voltage Sag	Single phase High Voltage Multi level Inverter	Posicast control	Open loop and Closed loop control	63
Voltage Control	Single Phase Single Leg VSI	DSP processor	Discrete Time Model	72
Voltage Fluctuations	Three phase 3 leg VSI	PWM	double-loop control	73
Transient overshoot, settling time and steady state error	Three phase 4 leg VSI	PID Controller	Closed loop control	75
Voltage regulation	Three phase 2 three leg VSI	PWM	Phase Locked Loop	79
Voltage Sag	Three Phase VSI	DSP based Hardware	Multi Loop Control	82
Voltage protection	Three phase 3-	Synchronous	constant	87

from Unbalanced and Non-Linear Loads	Level H-bridge VSCs	Reference Frame Theory (SRF)	switching frequency hysteresis band controller	
Voltage Harmonics	Single phase and three phase	Resonant Feed back	Phase Locked Loop	90
Voltage Sag	Three Phase	PLL	multiloop control system	92
Voltage Sag	Three Phase 2 level	two degrees of freedom (2DOF)	Closed Loop system	94

5. Classification of Converter Control Techniques of Dynamic Voltage Restorer

5.1. Current limitation by Flux-Charge Model DVR

In this flux charge model as shown in Fig. 16, the protection of DVR components is done by restoring the Point of common contact voltage and fault current limitation. In Distribution feeder, DVR connected in series acts like a Virtual inductance and this can only be done by injecting appropriate voltage controlled by DVR with opposite polarity than in usual. By providing the additional communication between the circuit breaker and DVR over current tripping is possible here. Another functioning of this model is that, point of common contact voltage is protected by limiting downstream fault current. Just by adding the impedance the control of reactive power is achieved [3].

5.2. Voltage sag compensation by closed loop feedback control system DVR

In this method of closed loop feedback control, for voltage compensation, voltage loop is associated apparently to an internal loop current which is taken from current of filter capacitor of the DVR in order to avoid the drawbacks in open loop feedback control system. This scheme of control is similar to compensate voltage and real power in the system and the only change is that generation of reference signal and its dependency on control mode for real power flow which is generated according to the demand of reactive power requirements [5].

5.3. Voltage restoration by Integrated Higher Order Controller DVR.

In this method, Phase locked loop-PLL is utilised for finding rotating angle so that voltage swell and sag compensation can be done by Ultra Capacitor-DVR without any dependence on grid. The compensation of voltage is done by in phase injection of voltage with the fundamental voltage. Integrated Controller which is at higher level of is operated based on system specifications and produce inputs to DC-DC converter and inverter for controlling process [13].

5.4. Voltage sag mitigation by transformerless self-charging DVR.

In this method two modes exists i.e., voltage restoration and self-charging mode. In voltage restoration mode, the fall of phase voltage V_{phase} is controlled by Inverter 1 with control of series voltage V_{series} [16]. In order perform this action, Inverter 1 is provided with sufficient DC voltage link [59]. In the other mode i.e., self charging mode, the restoration of energy in capacitor has to be done for compensating the further any sags by the DVR when V_s returns to its normal mode of operation [72], [77].

5.5. Fault current Limit Control (FCL) DVR.

According to grid state, the fault current limiting DVR can operate in two modes i.e., Switching Strategy operation mode and detection of fault current method [27]. In this control strategy, a quick response along with the voltage compensation of low steady state error is obtained [62], [74].

5.6. Disturbance Filtering DVR

In this, the control system is operated to attempt for semiconductor switches signals and also adopted inverter with current control which comes with a quick response. The direct control of the voltage across load is performed by this method, which leads to not in calculating the series compensation voltage in prior and in a significant aspect by shortening procedures for circuit design [31].

5.7. Voltage sag/swell detection DVR
In this method V_{abc} parameter are considered for the generation of compensating voltage and activating the PWM generator by generating the pulses. In this control strategy the drawbacks of conventional methods like, transformation process, slow transient response and complexity in mathematical modelling was conquered [41].

5.8. DVR based on Synchronous Reference Frame-SRF theory
This method generates instantaneous reference voltage for compensating by controlling the self sustained SRF basic theory based DVR in order to defend the non-linear and unbalanced loads. In this positive sequence fundamental phase voltages (three phase voltages) are generated by positive sequence fundamental extractor, by suspecting only two distorted and/or unbalanced line voltages. Also, when Nonlinear loads are present the DVR alone itself suppress the voltage spikes without any use of filter capacitor which is shunt connected [57], [87].

5.9. DVR for compensating Voltage Fluctuations
In this instantaneous power theory is adopted for dynamic compensation of voltage and voltage fluctuation detection. The different compensation methods such as pre- sag, minimum energy, In-Phase, and optimized energy techniques have been adopted for generating the reference signal for voltage compensation. In this method super conducting magnetic energy storage based DVR is used for compensating Voltage as well as long tern voltage fluctuations [73].

5.10. Two Degrees of Freedom Resonant Control DVR
In this method unbalanced and balanced voltage sags are compensated by two degree Resonant Control Scheme. This control structure, is based on a scheme with two [$R_1(s)$ and $R_2(s)$] nested controllers which generates 2 degree of freedom for compensation of voltage sag. A number of parameters are defined in this methodology, which are equal to the number of poles, rising to closed loop system [94].

6. Conclusion
This paper presents the comprehensive review and discussion on DVR to enhance power quality at grid and industrial competence. Modern developments and different topologies of DVR have been discussed by focusing on their advantages and advantages. Different control strategies and functioning of compensation methods for power quality enhancement by mitigating the power quality issues using DVR has been discussed. With this review it is been concluded that DVR are beneficial in voltage Sag mitigation and other voltage related power quality issues.

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