A Comparative Study of Full-Bridge Inverter based DVR and Semi-Z-Source Inverter based DVR

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***Abstract*— There is always a necessity to protect the voltage sensitive industrial systems from Power Quality (PQ) issues to prevent the loss of product quality and revenue. Generally, custom power devices take the responsibility to mitigate these PQ problems, restore the voltage and thus maintain the PQ standards. Dynamic Voltage Restorer (DVR) is one among the custom power devices which offers an economical compensation of load voltage under abnormal supply voltage conditions. The voltage injected in series by the DVR compensates the load profile during PQ events; appropriate voltage injected by the DVR in series with supply protects the load and restores the voltage to pre-defined values. The required injected voltage is generated by the inverter circuit in the DVR system. The most commonly used DVR inverter is the full-bridge inverter which consists of four switches. The Semi-Z-Source (SZS) inverter based DVR which offers same injection capability with only two- switches is compared with the full-bridge inverter. The in-phase compensation technique is employed in both the DVRs for injecting required voltage into the grid. The efficiency, quality of the injected voltage and load voltage are studied. This paper presents simulation results in MATLAB/Simulink environment to validate thecomparison.**

Keywords—Power Quality (PQ), DVR, voltage sag, Full-bridge (FB) inverter, Semi-Z-Source (SZS) inverter, in-phase compensation, voltage injection capability

I. INTRODUCTION

Nowadays, the industrial loads are becoming voltage sensitive and any deviation from the pre-defined quality of power results in temporary shut downs, equipment damage and deteriorated end products. The Power Quality (PQ) issues such as voltage sag, swell, flicker, harmonics, notches etc causes loss of production and loss of revenue[1]–[4].

With the advent of power electronics, a new class of power electronic based voltage support solutions are offered by CUPS such as Distributed Static Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Unified Power Flow Controller (UPQC) and they bring considerable and measurable improvement in the power quality. The inclusion of these compensating type CUPS in the power line is a prerequisite for profitable operations in the critical industries. During unhealthy supply voltage conditions, these devices help to improve power quality by restoring the load voltage profile [5], [6] .

Among the CUPS, the most economical compensation is provided by the DVR [7]. DVR is a series connected compensating device which maintains the load profile to pre- specified standards by injecting appropriate voltage in series with the supply voltage. The DVR structure consists of *dc*-link and energy storage, converter, filter, injection transformer, bypass equipment and disconnection equipment as shown in Fig.1[8]. The real power source in the DVR is the energy sources such as Battery, SMES (Superconducting magnetic energy storage), super capacitors, flywheel, fuel cell etc [9]. The type of the energy storage determines the type of converter in the DVR circuit [10]. The ac energy source such as flywheel requires ac-ac conversion or ac-dc-ac conversion. If the energy source supplies dc power such as battery, fuel cell etc, the converter type is dc to ac or inverter. The most commonly used inverter in the DVR system is Full Bridge (FB) inverter [11]. The FB inverter based DVR finds application in low voltage to high voltage distribution system. [12],[13].

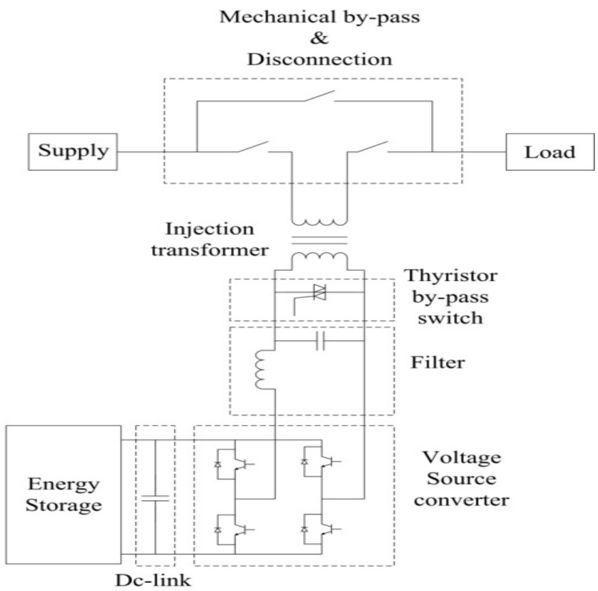

Fig.1 Basic structure of DVR

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The independent single phase connection available makes the FB inverter suitable for both single-phase and three-phase DVR system. The SZS inverter based DVR reported in [14] offers a possibility of replacing the FB inverter based DVR. The SZS inverter based DVR achieve same injection capability as the FB inverter based DVR, with just two semi- conductor switches. The size of the SZS inverter is minimized as the Z-source network is present in the ac-side, compared to the traditional Z-source network. However, there is no shoot- through condition present in the SZS inverter as in the traditional Z-source inverter. The dead-time control of switches is not required in the SZS inverter and it makes the control of the inverter simple. The SZS inverter can output voltage which is completely sinusoidal with proper control. This rule out the aforementioned benefits of the SZS inverter makes the DVR more effective than the FB inverter based DVR. This paper presents a comparison of the FB and SZS inverter based DVRs. The parameters of comparison are the injection voltage quality, distortion caused by the filter in FB inverter based DVR, load voltage THD and the efficiency of the DVR. The description about the FB inverter based DVR and SZS inverter based DVR are presented in next section. The simulations carried out in MATLAB/Simulink software validate the feasibility and practicality of the SZS inverter based DVR.

II. System Description

The FB based DVR is the most commonly used inverter circuit in the DVR systems and is shown in Fig.1. The FB inverter is preferred in high voltage systems over other inverter topologies. It consists of four switches, two each in one leg of the inverter [15] . The switches are operated complementarily in one leg and the anti-parallel switches are turned on and off simultaneously. Sinusoidal pulse width modulation (SPWM) technique is used for generating the switching pulse for the FB inverter switches. The simultaneous turning on and off of switches in same leg brings the risk of short-circuiting of the dc supply voltage or shoot-through condition in the FB based DVR due to the finite turn-on and turn-off time

TABLE I
System Parameters of FB inverter based DVR

Parameters	Values	
Rated Voltage and frequency	230 V and 50 Hz	
Load	800 + j600 VA	
Injection Transformer	1:1,230 V, 1.6 kVA	
Full Bridge Inverter	Dc-link voltage, V_{dc}	200V
	Switching frequency	50kHz
Filter	Capacitor	1µF
	Inductor	2mH

associated with the IGBT switches. However, dead-time control is provided for eliminating the shoot-through Condition and makes the system control complex. The dead-time control introduces fifth and seventh harmonics in the output voltage [16]. This deteriorates the quality of the injected voltage which in turn reflects on the DVR voltage and load voltage. In contrary, the output voltage of the FB inverter is pulsating in nature and requires filter circuit for achieving the sinusoidal output voltage. Normally, second order LC filter follows the FB inverter in inverter-side filtering scheme of the DVR. In line-side filtering, the filter components are present across the secondary winding of the transformer. The filter components affects the magnitude and phase of the injected voltage fundamental component and may even result in control glitches in the DVR[17].

The parameters of the FB based DVR used in the MATLAB/Simulink software simulation is given in the Table
I. The FB inverter is realized using ideal IGBT switches. For obtaining sinusoidal output voltage, the filter capacitor and inductor values are selected as 1µF and 2mH respectively. The switching frequency of the DVR control is 50 kHz. The DVR system considered is isolated type with a transformer of turns ratio 1:1.The load power is taken as 1kVA in all the simulations.

The SZS inverter based DVR is presented in detail in [14] and is given in Fig.2. The SZS inverter proposed by Cao et.al in[18] is in corporate in to the DVR system for the generation of required injected voltage. The steady-state equations governing the SZS inverter and further details are explained in the literature [18]–[20]. The SZS inverter is capable of producing output voltage range same as the FB inverter with only two switches. IGBT and MOSFET are the choices of switches in the SZS inverter. The SZS inverter only occupies less space than the traditional Z-source inverter as the Z-source network is present in the ac-side. It also possess the doubly ground characteristic which makes the SZS inverter popular for solar and fuel cell based DVR.In SZS inverter switches are present in two different legs which eliminate the risk of shoot- through condition and avoid the need for dead-time control.

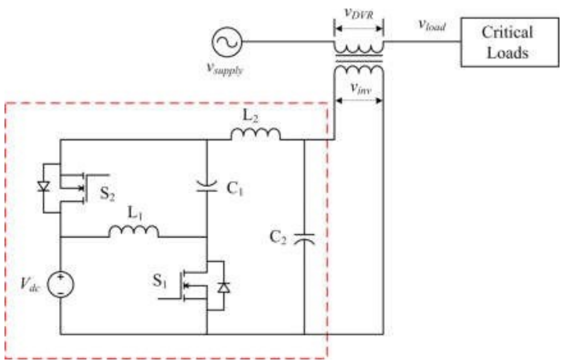

Fig.2 DVR topology with SZS inverter

The simple control is required to turn-on and turn-off the switch complementarily. The voltage gain of the SZS inverter is given by equation (1). The non-linear voltage gain demands a non-linear reference for the modulation technique. A revised modulation strategy termed as Modified Sinusoidal Pulse Width Modulation(MSPWM) is employed for the SZSinverter [19], [21],[22]

$$V_o/V_{dc} = 1\text{-}2D/1\text{-}D \quad (1)$$

The same output range of the SZS as that of FB inverter for same input voltage leads to the comparison of the two topologies of DVR. The existing in-phase compensation technique is utilized for the injection of the voltage. There are different controls associated with the DVR. In this paper feed forward control mechanism is used to maintain the load profile constant and is shown in Fig.3[21]. The simulation parameters of the SZS inverter are given in Table II. In FB inverter based DVR and SZS inverter based DVR, the dc supply voltage is selected such that the DVRs give 50% injection capability. The dc supply voltage of both inverters are designed such that it is enough for the 50% compensation capability and does not allow reverse power flow through the anti-parallel diodes in the IGBT or MOSFET. The supply voltage, transformer and load specifications are the same as in Table I for the SZS inverter based DVR simulation. The switching frequency of the two DVR systems is also kept the same. The SZS network is designed with these parameters and the detailed design is given in[18]–[20].

III. DVR CONTROL SYSTEM

The control of the DVR consists of the following steps- voltage disturbance detection, reference voltage generation, inverter control, modulation and switching pulse generation constitutes the DVR control system [21].

TABLE II
System Parameters of SZS inverter based DVR

Parameters	Values	
SZS Inverter	Dc-link voltage, V_{dc}	200V
	Switching frequency, f_{sw}	50kHz
	Capacitor C_1 and C_2	3.9μF
	Inductor $L_1$and L_2	320 μH

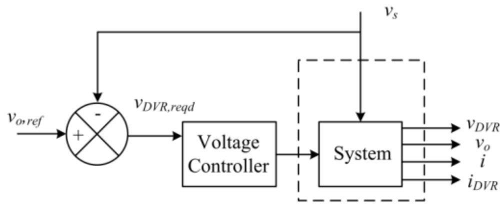

Fig.4 Feed forward controller

The amount of supply voltage deviation from pre-defined standards is the prime factor that decides whether the DVR should operate or not. The DVR continues to stay in the standby mode under healthy supply conditions. The DVR shifts to its active mode of compensation whenever the detection unit detects a voltage disturbances as sag, swell or harmonics.

The reference voltage generation unit generates the DVR reference voltage (v_{DVR}^*) for restoring the load profile under the detected voltage quality problems. The DVR should be operated in such a way that it generates an alternating voltage that completely tracks the DVR reference voltage. The DVR operation is successful only when the DVR actual voltage equals the DVR reference voltage in terms of magnitude,
phase and frequency, given the compensation strategy in- phase method.

In this paper, feed forward control of the DVR is adopted. In feed forward control, the DVR reference voltage from the reference generation unit is scaled down by a factor equal to dc-link voltage to provide the modulating signal for the PWM technique which is succeeded by the modulation and switching pulse generation unit The comparison between the modulating wave and the carrier wave produces the switching pulses for the DVR inverter. The switches of the inverter are operated with these switching pulses and the voltage generated is injected in series to the supply voltage to mitigate the unhealthy condition from affecting the sensitive loads.

IV. COMPENSATION OF VOLTAGE SAG

The FB inverter based DVR and SZS inverter based DVR efficiently restore the load voltage under PQ events. The simulation results in Fig.4 and Fig.5 respectively show the compensation of load voltage by FB inverter based DVR and SZS inverter based DVR under voltages condition. The load compensation for 40 % voltage sag from time 0.1 s to 0.2 s is presented in the simulation results .In both the DVR topologies, the actual DVR voltage tries to follow the reference voltage. In FB inverter based DVR, there is a phase-shift and magnitude difference in the fundamental component of the DVR voltage compared to the reference DVR voltage as shown in Fig.6. This deviation from the reference DVR voltage is due to the filter components .The phase-shift compensation can be carried out using the lag/lead compensators[22].

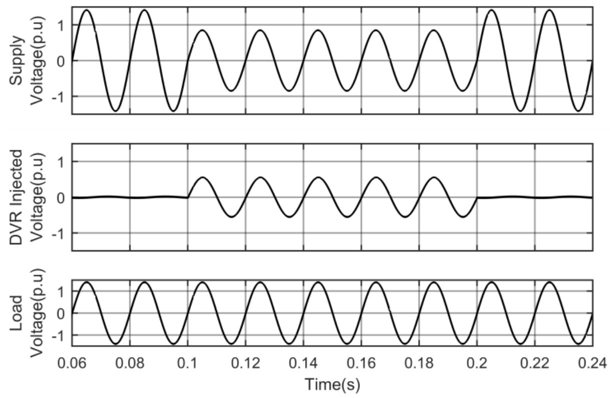

Fig.4 Load voltage restoration during sag using in-phase compensation method by FB inverter based DVR.

However, adaptive lag/lead compensation is required as the Equivalent Series Resistance (ESR) of the filter components are temperature dependent. The higer harmonic content penetration to the injected voltage in line-side filtering scheme of DVR rules out that option too [17]. In SZS inverter based DVR, the reference voltage and actual DVR voltage coincide as shown in Fig.7 The exact tracking of the reference voltage makes the performance of the SZS inverter based DVR better than the FB inverter based DVR. The elimination of filter avoids the possible control glitches, error in compensation and bulkiness of the DVR inverter.

V.COMPARISONOF THE DVR TOPOLOGIES BASEDONFB INVERTERAND SZS INVERTER

In FB inverter based DVR and SZS inverter based DVR, the voltage injection is in-phase with the utility voltage. The in-phase compensation technique gives effective compensation with minimum injected voltage.

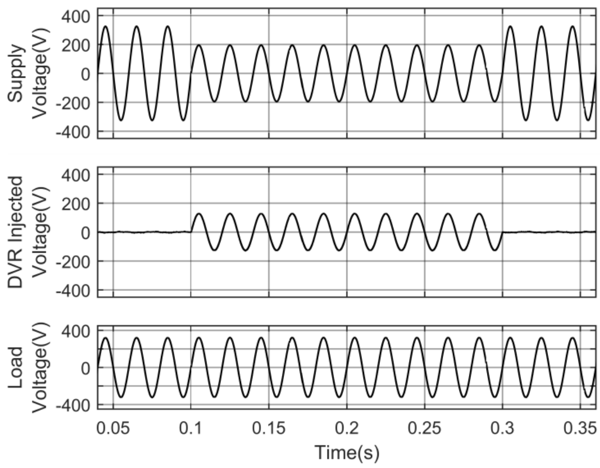

Fig.5 Load voltage restoration during sag using in-phase compensation method by SZS inverter based DVR.

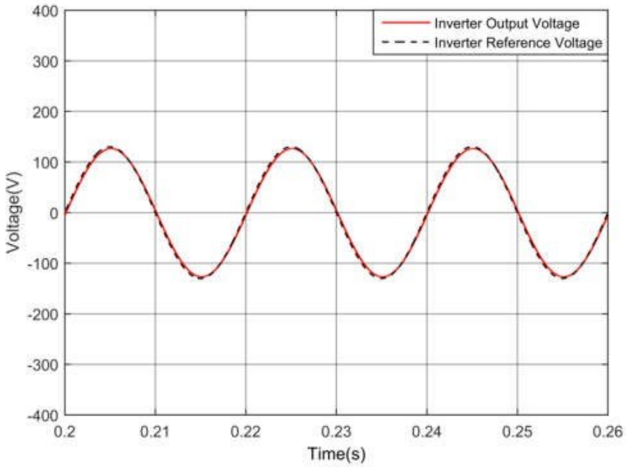

Fig.6 Reference and actual DVR voltage of FB inverter based DVR

It also gives the advantage of reduced dc-link voltage rating. The pharos diagram of in-phase technique used in the DVR topologies based on FB inverter and SZS inverter is given in Fig.8. The notations V_s, Vo and V_{DVR} gives the voltages of source, load and DVR respectively. The input supply voltage and current are phase shifted by Θ. The in- phase compensation exchanges both real and reactive power [14], [23]. As the FB inverter and SZS inverter restores the load voltage using in-phase compensation, the injected voltage magnitude is same in both the DVR topologies. However, the quality of the injected voltage varies with the type of inverter used. The sag depth is varied from 0.1 to 0.5 and the injected voltage THD of the DVR topologies based on FB inverter and SZS inverter is plotted in theFig.9.

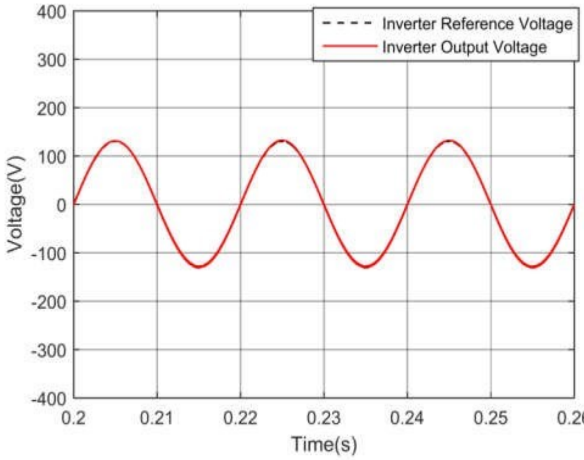

Fig.7 Reference and actual DVR voltage of SZS inverter based DVR.

The THD of FB inverter side voltage is more than permissible. However, with the aid of transformer winding

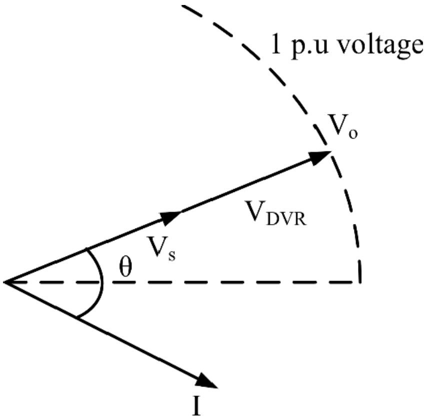

Fig.8 Phasor diagram of in-phase compensation

Inductance the THD is within the permissible limits when injected. The SZS inverter gives less than 5% THD even without filter circuit and transformer inductance.

The quality of the load voltage during the compensating mode of DVR is another aspect of comparison. The FB inverter outputs a sinusoidal voltage with the aid of filter circuit whereas the SZS inverter gives a sinusoidal voltage without filter circuit. The THD of the load voltage for the two DVR topologies are compared in Fig.10 for different sag depth [6]. It can be observed from Fig.10 that the load voltage THD is less for the SZS inverter based DVR compared to the FB inverter based DVR. The SZS inverter offsets the FB inverter based DVR as the filter circuit is absent in the former and the THD of the latter is more.

DVR and SZS inverter based DVR for different modulation index of the inverter [14].The modulation index(M) of the inverters depends on the sag depth. The modulation index assumes a constant value depending on the sag depth and the inverter operates to give the required sinusoidal output voltage for series injection.

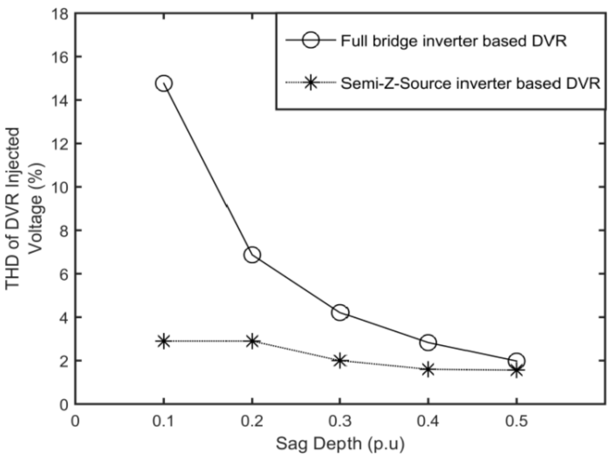

Fig.9 THD of DVR injected voltage

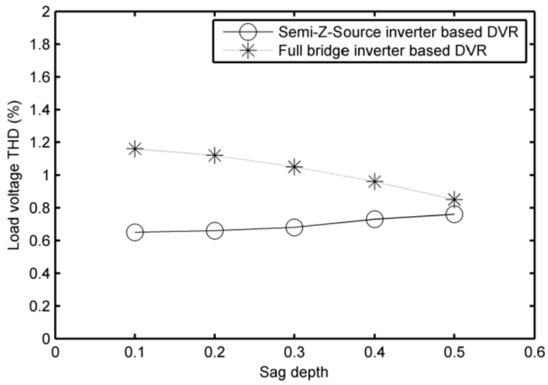

Fig.10 Load voltage THD vs sag depth

Fig. 11 gives the comparison of the efficiency of FB inverter

VI. CONCLUSION

A comparative study of SZS inverter based DVR with the conventional FB inverter based DVR is carried out in this paper. The injection capability of the DVR topologies based on FB inverter and the semi-Z- source inverter remains same for the given input dc energy source as the output voltage range of both the inverters are same. However, the semi-Z- source inverter achieves the required sinusoidal output voltage with only two switches. The control of the switches is simple with uncomplicated steps. The non- linearity of the voltage gain demands a non-linear reference waveform in the semi-Z- source inverter compared to the SPWM used in FB inverter. There is no risk of short circuiting of the dc supply and problems created by filter components in the semi-Z-source.

Inverter based DVR. The harmonics in the injected voltage and load voltage are less for the SZS inverter based DVR .The efficiency associated with both the DVR topologies are comparable. Considering the aspect of quality of voltage injected, size of the inverter, filter circuit, efficiency and number of switches, the SZS inverter based DVR is an effective replacement for the conventional FB inverter based DVR.

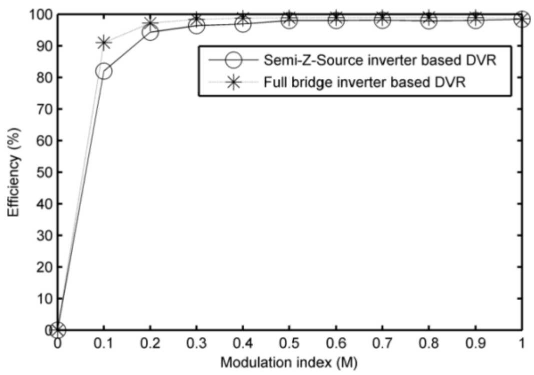

Fig.11Efficiencycurve

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