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Phase Advance Compensation of Voltage Sags Using Full Bridge Inverter Based DVR

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***Abstract*—Voltage sag is considered as the most expensive power quality problem. With the advent of power electronics, custom power devices are introduced to mitigate the sag issues. Among the custom power devices, Dynamic Voltage Restorer (DVR) is the most cost-effective one. The voltage injected in series by the DVR compensates the load profile during sag events. The compensation techniques such as in-phase, energy minimized and phase advance methods determine the way in which the DVR voltage is injected into the grid. By providing a phase advance to the DVR voltage with respect to the supply voltage gives the merit of reduced active power injection and thereby reduces the rating of energy storage. The disadvantages such as increased DVR voltage magnitude, phase shift, load swings and discontinuity of wave shape are associated with this compensation technique. This method is suitable for magnitude sensitive loads. This paper presents simulation results showing the compensation of both sag and swell using phase advance compensation.**

***Index Terms*—DVR; voltage sag; voltage swell; minimum active power; in-phase compensation; phase advance compensation; ride-through capability**

I. INTRODUCTION

Power Quality (PQ) problems are becoming a serious menace for the smooth running of industries these days. The industrial loads are getting more and more voltage sensitive and this leads to the temporary shut downs, damaged equipment and poor product quality. The common PQ problems are voltage sags, swells, flickers, harmonics, notches etc. [1][2][3].

Voltage sag is the reduction in rms value of the voltage from 0.9p.u to 0.1p.u for a short duration of 0.5 cycles to less than one minute, usually occurring due to faults in transmission and distribution lines and it is the most severe PQ problem [1]. Majority of the PQ problems are due to voltage sags. The economic loss associated with voltage sags in the industries is humongous.

As a solution to the PQ problems, the new power electronic technology is introduced under the name Custom power devices (CUPS). The devices such as DSTATCOM, DVR and UPQC helped to improve the voltage quality of the utility along with the mitigation of PQ problems [4][5]. Among the CUPS, DVR is identified as the most cost effective solution [5].

II. DYNAMIC VOLTAGE RESTORER

Dynamic Voltage Restorer (DVR) is considered as the most economical solution for the mitigation of power quality problems [6]. DVR is a series connected device which injects appropriate voltage to maintain the load profile constant. The

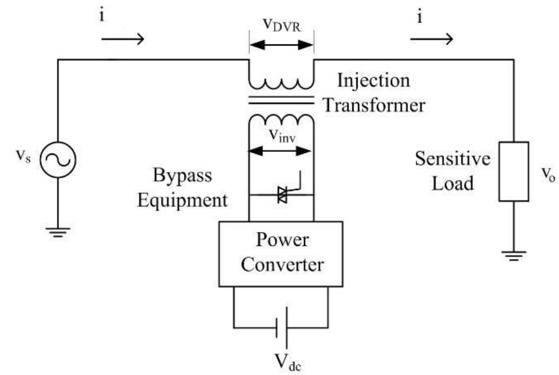

Fig.1 Basic structure of DVR

basic elements of a DVR are *dc*-link and energy storage, converter, filter, injection transformer, bypass equipment and disconnection equipment as shown in Fig.1 [7][8]. Energy storage is the source of real power in the DVR. Battery, Superconducting Magnetic Energy Storage (SMES), supercapacitors, flywheel, fuel cell etc are some of the choices of energy storage in DVR [9]. According to the type of energy storage, the converter type is selected either dc-ac or ac-ac [10].

DVRs are classified depending on the converters used. Voltage Source Inverters (VSI) are the most common converter type used in DVR. Full Bridge (FB) VSI is the most sought after inverter in the DVR technology. They provide independent single phase connections and can be used in high voltage distribution system [11][12]. Even though harmonic content in the inverter output is high, the control of the inverter is comparatively easy.

The harmonics in the inverter output voltage are removed using inverter side filtering scheme or line side filtering scheme [13]. The injection transformer provides the series interconnection of the converter and the utility. The leakage reactance of the transformer also acts as filter inductance. It also provides the provision of voltage boosting [2][9].The bypass equipment aids to bring the DVR offline or online. It also shields the DVR from downstream high currents [14].

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III. System Description

The DVR system considered for the simulation study in this paper is based on FB Inverter. IGBT switches are used for realizing the FB inverter. The filter inductor and capacitor values are taken as 2mH and 1μF such that it eliminates the higher order harmonics in the injected voltage . The switching frequency of the DVR control is 50kHz. The transformer isolated DVR is connected in series with the supply and the load. The turns ratio of the transformer is taken as 1:1 since it only provides galvanic isolation. The rms values of the load voltage and the load current for 1kVA load is taken as the base values for p.u calculations. The system parameters used for MATLAB/Simulink simulation is given in Table.I.

TABLE I
System Parameters

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

Simplicity and robustness makes the feed forward control well accepted in the DVR technology. By measuring the supply voltage(v_s) and the required load voltage($v_{o,ref}$), the DVR voltage required to be injected ($v_{DVR,reqd}$) is calculated. The missing voltage thus obtained is scaled down to produce the reference signal for the sinusoidal pulse width modulation (SPWM) technique. The switching pulses generated are givento the inverter to output the appropriate voltage. This voltage when injected in series with the Point of Common Coupling (PCC) voltage maintains the load profile constant.Fig.2 gives the block diagram of feed forward controller [15].

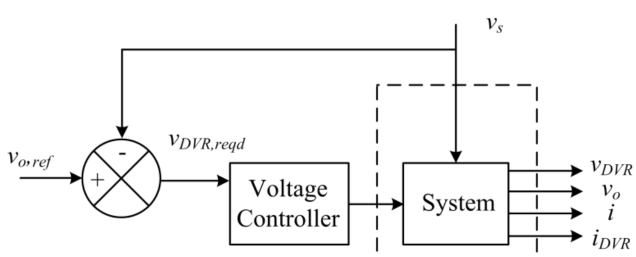

Fig.2 Feed forward controller

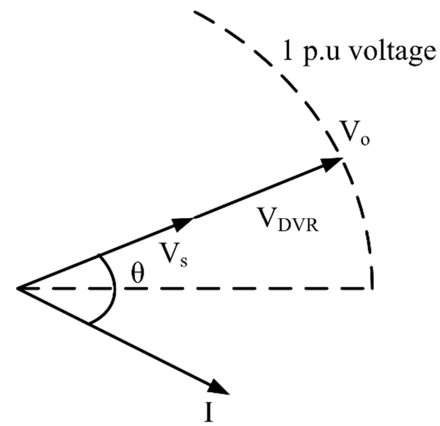

Fig.3 Phasor diagram of in-phase compensation

IV. Compensation Techniques

The way in which the voltage is injected in series with the PCC decides the real and reactive power exchange between the DVR and the distribution network. The existing compensation techniques are in-phase compensation, presag compensation and energy minimized compensation.

A. In-phase compensation

Regardless of the prefault condition, the voltage injection is in-phase with the utility voltage in this compensation technique. When compared to the other existing compensation methods, the magnitude of injected voltage is minimum in the in-phase compensation for the given voltage sag condition. The voltage rating of the dc-link is also less, if the compensation method is in-phase.

Fig.3 gives the phasor diagram of in-phase compensation. The supply voltage, load voltage and the DVR voltage are given by V_s ,Vo and V_{DVR} respectively. The phase angle difference between the supply voltage and supply current is given by Θ. There is exchange of both real and reactive power in this compensation technique. If the dc link is unable to

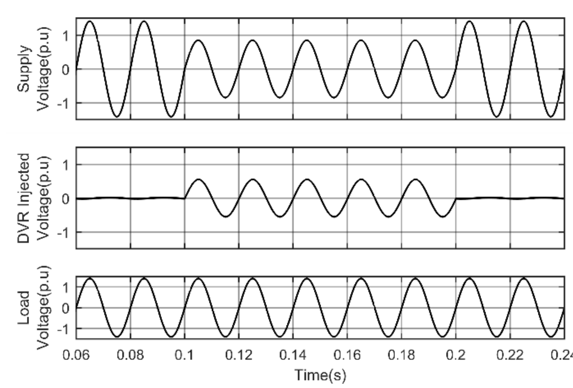

Fig.4 Load voltage restoration during sag using in-phase compensation method.

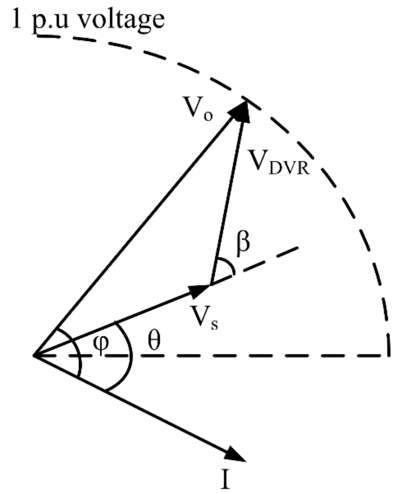

Fig.5 Phasor diagram of phase advance compensation

supply the active power requirement, the dc-link voltage will drop and hence the DVR voltage too will drop[16], [17]. The compensation of load during 40 % voltage sag from time 0.1 s to 0.2 s using the in-phase compensation technique is shown in Fig.4. FB inverter based DVR is used for mitigating the sag condition.

B. Energy minimized compensation

DVR injects incorrect voltage if the active power requirement is not supported by the dc-link. In this case, the load voltage is not compensated during the PQ events. The energy minimized compensation technique puts forward the idea of injecting as much reactive power as possible to compensate the sag.

There is only exchange of reactive power between the DVR and the grid if the DVR voltage is injected perpendicular to the load current[18], [19]. But this compensation has the drawback that it is only applicable to shallow sags.

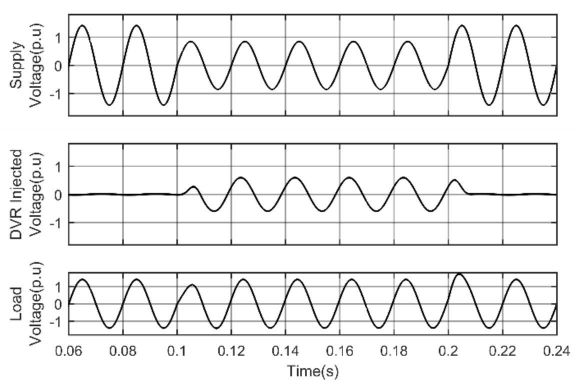

Fig.6 Load voltage restoration during sag using phase advanced compensation method.

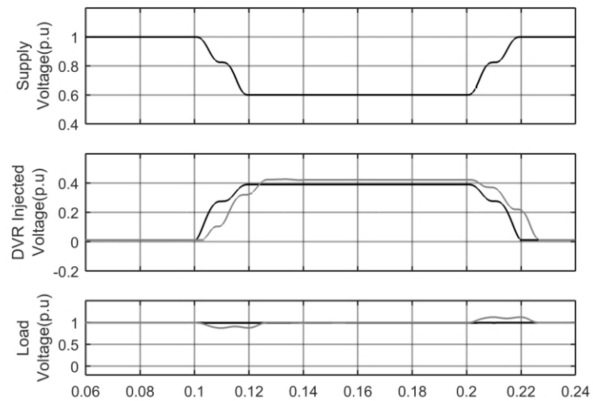

Fig.7 Variation in rms voltage of supply, DVR and load during compensation of sag (black-in-phase compensation, grey-phase advanced compensation).

C. Phase Advance Compensation

The phase advance compensation is another solution for minimizing the active power injection from the DVR. In this method , the DVR voltage is injected with a phase advance angle 'β' with respect to the sag voltage [20]. The phasor diagram in Fig.5 shows the phase advance compensation technique. The angles φ and β denotes the load power angle and phase advance angle respectively.

In this compensation, the active power is reduced at an expense of increased injection voltage magnitude. Compared to the in-phase compensation, the magnitude of DVR voltage required in this method is more [21]. The injected voltage for the phase advance method for given β is determined using the equation (1).

$$V_{DVR} = \frac{V_o \sin[\beta - \sin^{-1}(V_S(\sin\beta)/V_o]}{\sin\beta} \qquad (1)$$

Fig.6 gives the phase advance compensation of load during 40 % voltage sag from time 0.1 s to 0.2 s. The phase advance angle is chosen to be 30^o. The active power is obtained as 0.250 p.u. over 0.313 p.u. in case of in-phase compensation.

Fig.7 gives the variation in the RMS voltage of supply, DVR and load for in-phase and phase advance compensation for 40% sag from 0.1 to 0.2. From the Fig.7, it is clear that the DVR voltage required for compensating the given sag is more in the case of phase advance compensation method. The load experiences a time delay to restore the voltage using the phase advance compensation technique in DVR operation. The THD of the load voltage is more for phase advance compensation. But the reduced active power given by the DVR is the merit of this phase advance method.

The load voltage is compensated and maintained as per the standards using both in-phase and phase advance compensation techniques. Fig.8 shows the compensated load

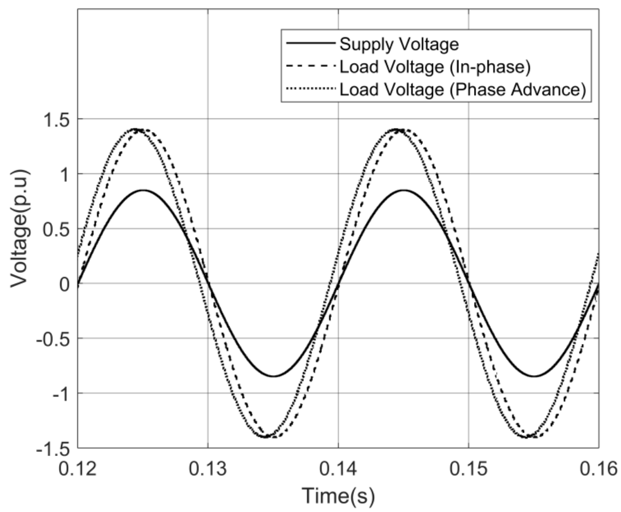

Fig.8 Load voltage compensated using in-phase and phase advance compensation

voltage using both in-phase and phase advance compensation for 40% sag depth in supply voltage from time 0.12 s to 0.16 s.

In-phase compensation compensates the load profile without any waveform discontinuity by injecting DVR rms voltage of 0.4 p.u (as seen in Fig.3 and Fig.8). But in case of phase advance compensation with DVR rms voltage injection of 0.42 p.u and $\beta=30^o$, there exists a waveform discontinuity and phase shift in the load voltage when compared to supply voltage (as seen in Fig.6 and Fig.8).

A comparison study of load compensation using FB inverter based DVR with in-phase and the phase advance compensation is carried out. The angle 'β' is varied from -50^o to 50^o in steps of 20^o. The in-phase compensation takes $\beta = 0^o$. Fig.9 gives the p.u.magnitude variation of the DVR voltage for sag depths from 0.1 to 0.5. The load voltage and current are taken as 1 p.u with a load power factor equal to 0.8 lagging. Fig.10 gives the p.u. active power injection from the DVR for sag depths 0.1 to 0.5.

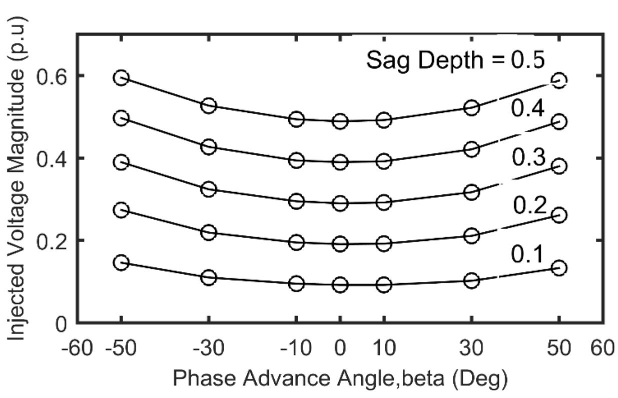

Fig.9 Injected voltage magnitude versus phase advance angle,β.

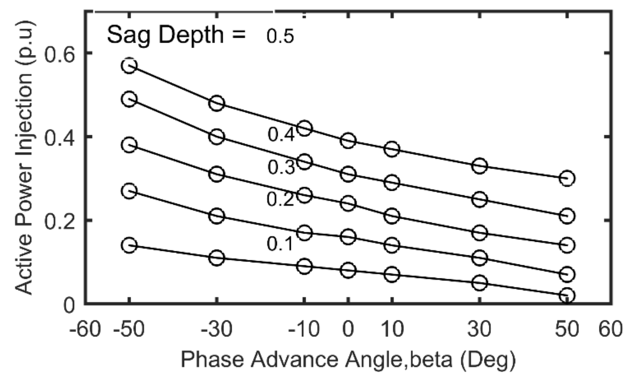

Fig.10 Active power versus phase advance angle,β.

The magnitude of the phase advance DVR voltage is same for both the positive and negative angles. The active power from the DVR is derived from Fig.5 as

$$P_{DVR} = V_{DVR} I \cos(\beta + \theta) \quad (2)$$

Thus from equation (2), it is clear that as the phase advance angle β increases, the active power exchange from the DVR decreases. It requires less active power for a DVR to compensate the load during voltage sags using phase advance compensation technique when compared to in-phase compensation technique.

Since the DVR voltage injection is not in phase with the supply voltage, the phase advance method requires more voltage for non erroneous compensation of any particular sag compared to in-phase compensation [20]. The load voltage magnitude is restored correctly in phase advance compensation method when the dc-link voltage is sufficient enough to cater the peak value of the DVR voltage. The advantage of minimum active power from the DVR makes this method of compensation more suitable for magnitude sensitive loads.

The p.u active power injection of the DVR for the sag condition shown in Fig 3 is calculated (0.313 p.u) and is denoted by P_1. Similarly, the p.u active power injection for Fig 6 is calculated (0.250 p.u) and is given by P_2. The ratio P_1/P_2 denotes how much more power is required to compensate the 40% voltage sag using in-phase method when compared to phase advance method.

The ride-through capability of the DVR is improved by using the phase advance compensation. The above mentioned ratio can also be interpreted as how much more time the phase advance compensation can restore the load voltage for the given 40% sag if it persists when compared to in-phase method. The FB inverter based DVR is capable of compensating voltage swell also. The in-phase compensation

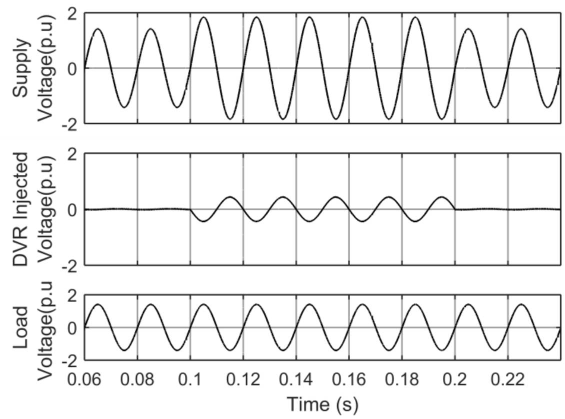

Fig.11 Load voltage restoration during swell using in-phase compensation method.

and phase advance compensation can be utilized for restoring the load profile during swell also. The same DVR topology is used for compensating the voltage swell of 30% from 0.1s to 0.2s.

Fig 11 shows the load voltage restoration when the compensation method is in-phase. For the same swell, phase advance compensation requires more voltage as shown in Fig.12. The phase advance angle is taken as 30^o. The p.u. active power for in-phase and phase advance compensation is 0.239 and 0.083 respectively. The in-phase compensation method makes the DVR to exchange more active power or the ride-through capability of the DVR is improved in the case of phase advance method of load compensation under swell condition. Fig.13 gives the variation of the rms voltages of supply, DVR and the load for the compensation of the above mentioned swell using in-phase and phase advance compensation.

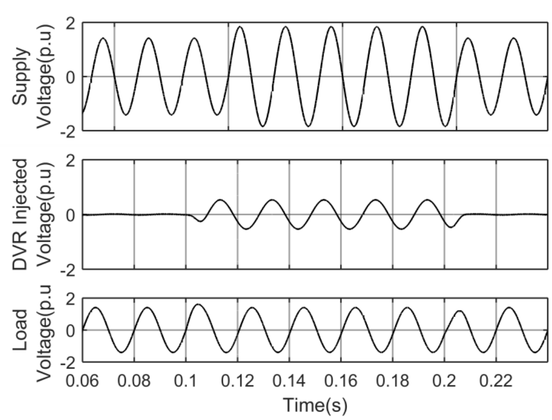

Fig.12 Load voltage restoration during swell using phase advance compensation method.

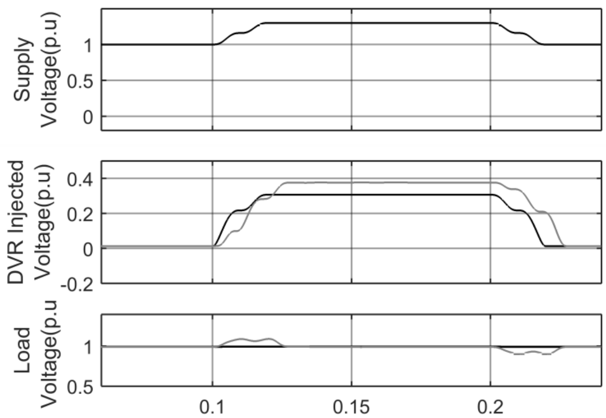

Fig.13 Variation in rms voltage of supply, DVR and load during compensation of swell (black-in-phase compensation, grey-phase advanced compensation).

Even though the phase advance method is associated with the disadvantages such as increased DVR voltage magnitude, load power swings, phase shift and discontinuity in wave shape, the reduction in the active power makes this method popular among the magnitude sensitive loads. The energy storage capacity is reduced in DVR using phase advance compensation. The capital cost of the DVR is reduced using the phase advance compensation technique.

V. Conclusion

This paper presents the simulation of FB inverter based DVR compensating both voltage sag and swell using phase advance compensation method. The phase advance compensation method is compared with the in-phase compensation method for the same topology of DVR. The injected active power from the DVR is reduced considerably in the phase advance method. The introduction of phase advance angle β in the DVR voltage injection reduces the demand for active power compared to the in-phase compensation. The magnitude of the DVR voltage is more in this compensation technique over in-phase compensation. The DVR topology designed with in-phase compensation can compensate the sags and swells for longer time if phase advance compensation method is implemented. Even though this method has the demerits of load swings, phase shift and discontinuity in wave shape, the load voltage magnitude is met correctly. This feature of the phase advance compensation method makes it suitable for magnitude sensitive loads. Extended ride-through capability or reduced energy storage are the attributes obtained by bringing phase advance compensation method in to DVR technology.

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