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Mitigation of Sags and Power Sharing Through Series Leading Voltage Injection Scheme

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***Abstract*--Dynamic Voltage Restorer (DVR) is a device used to mitigate voltage sags which are a significant power quality issue. This paper involves mathematical calculation for leading series voltage injection for mitigation of sags thereby achieving utility power factor improvement as well as power sharing between DVR and utility as per requirement and available distributed generation. Mathematical derivations have been made for leading voltage injection and simulation results verifying these calculations have been included.**

***Index Terms*-- Power Quality, Distributed Generation, Voltage Sags, Series Injection.**

I. INTRODUCTION

Voltage sag is a momentary reduction in available supply for a short duration below 90% of rated value [1]. The main characteristics of voltage sag are its duration and magnitude of available utility voltage [2].

Voltage sags are very hazardous to control equipment in process industry [3]. Failure of control results in the failure of process and therefore, loss of raw material and production time and even risk to human life. It is therefore, of utmost importance that these be countered.

A Dynamic Voltage Restorer (DVR) is one of the devices employed for this purpose. It is connected in series between the point of common coupling (PCC) and the load bus as shown in figure 1 (which is a one phase equivalent). A DVR can mitigate voltage sags by injecting voltages of appropriate magnitude and phase angle so that the load bus voltage remains within the permissible limits.

There are two main classifications as far as active power contribution from DVR is concerned. In the first type, only reactive power compensation is done by injecting a voltage in quadrature with the load current. This means no active power contribution. In the second case, active power available from any distributed generation resource is utilized to inject a voltage that compensates the load voltage to required level. The phase angle between the injected voltage and load current therefore does not need to be 90°. The reference voltage for the DVR to track (as shown in figure 1) is given by the relationship [4]

$$V_D^* = V_L^* - V_T \quad (1)$$

where

V_D^* = Reference voltage for DVR to track

V_L^* = Desired load voltage

V_T = Utility voltage available at the point of common connection

Phase angle of desired load voltage in equation (1) can theoretically have any value. It is suggested in [5] with an example and without mathematical proof that the phase angle of desired load voltage should lag the phase of the available terminal voltage. Otherwise, reverse power flow through DVR may damage it.

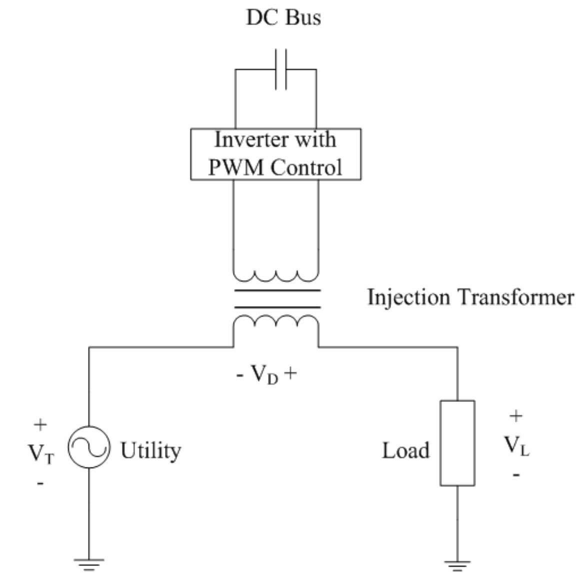

Fig. 1. Conceptual Diagram of one phase of a DVR

This paper evaluates the possibility of leading voltage injection by a DVR with mathematical equations and the same have been validated by results obtained from MATLAB®/SIMULINK® SimPowerSystems™ simulations. The benefits of leading voltage injection are also discussed. A possibility regarding power export using a DVR is also explored with calculations and simulation results validating the same have been presented.

II. CALCULATIONS FOR LEADING VOLTAGE INJECTION

The steady-state phasor diagram of a system, where a leading voltage is injected by the DVR is shown in figure 2, where available terminal voltage and DVR injected voltage phasors add up to make load voltage phasor (A similar

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treatment is presented in [6] with limitations on voltage rating of DVR and arbitrary phase angle of utility supply, however, choosing the utility voltage as a reference solves this problem as the reference generation for DVR can track the phase angle of utility and generate reference waveforms accordingly).

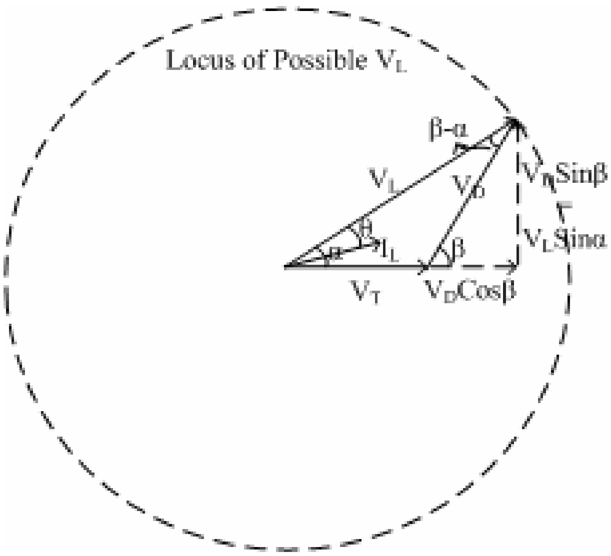

Fig. 2. Phasor Diagram

In phasor notation, the load voltage can be written as:

$$V_L = V_T + V_D \tag{2}$$

Where:

$V_L =$ Load voltage phasor with phase angle α after injection

$V_T =$ Utility voltage available at the point of common connection taken as a reference i.e. phase angle is zero.

$V_D =$ DVR injected voltage with a phase angle β

$I_L =$ Load current which lags the load voltage by an angle θ.

The phase angle between the terminal voltage and load current is thus α-θ and that between DVR injected voltage and load current is β-α+θ.
From figure 2 it is clear that:

$$|V_L|^2 = (|V_T| + |V_D|Cos\beta)^2 + |V_D|^2 Sin^2\beta \tag{3}$$

$$|V_L|Sin\alpha = |V_D|Sin\beta \tag{4}$$

Equation (3) and (4) result into the following equations for magnitude of injection voltage from DVR and phase angle of load voltage:

$$|V_D| = -|V_T|Cos\beta \pm \sqrt{|V_L|^2 - |V_T|^2 Sin^2\beta} \tag{5}$$

Negative sign with 2nd term in equation (5) is discarded as a magnitude should remain positive.

$$\alpha = Sin^{-1}\left(\frac{|V_D|}{|V_L|} Sin\beta\right) \tag{6}$$

As sine is a dual value function in the range 0° to 180°, equation (6) may produce invalid results. Another relationship for α from figure 2 can be obtained as:

$$\alpha = Tan^{-1}\left(\frac{|V_D|Sin\beta}{|V_T| + |V_D|Cos\beta}\right) \tag{7}$$

It is to note here that inverse tangent algorithms catering for sign of numerator and denominator values should be used; otherwise, equation (7) may also produce incorrect results.
Active power equations for terminal (P_T), DVR (P_D) and load (P_L) can be written as under (employing active sign convention for sources and passive sign convention for load, meaning that positive values of active/reactive powers for sources mean supply and negative values mean absorption of active/reactive power):

$$P_T = |V_T||I_L|Cos(-\alpha + \theta) \tag{8}$$

$$Q_T = |V_T||I_L|Sin(-\alpha + \theta) \tag{9}$$

$$P_D = |V_D||I_L|Cos(\beta - \alpha + \theta) \tag{10}$$

$$Q_D = |V_D||I_L|Sin(\beta - \alpha + \theta) \tag{11}$$

$$P_L = |V_L||I_L|Cos(\theta) \tag{12}$$

$$Q_L = |V_L||I_L|Sin(\theta) \tag{13}$$

Equation (10) implies that active power contribution from DVR shall remain positive as long as the cosine term remains positive. Mathematically, this condition can be expressed as:

$$-90 \le \beta - \alpha + \theta \le 90° \tag{14}$$

The equations developed above clearly set out guidelines for dynamic voltage restoration using leading voltage injection.

The choice of β is driven by the active power available at the DVR input and its value can be increased or decreased accordingly.

It is evident that for a similar sag depth, increase in β will result in a higher required injection voltage. However, this will reduce the requirement of active power from DVR and increase the reactive power contribution from DVR. This is a significant result as distributed energy resources like solar and wind are dependant on environment and available active power may vary over a large range, provided enough storage capacity is not provided. The injection voltage phase angle can then be varied to achieve saving on available active power and prevent the collapse of DVR voltage.

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III. POWER EXPORT

If there is sufficient distributed energy capacity present and the load power factor is kept near unity with the help of power factor correction devices (normally employed in industry, meaning θ becomes zero), phase angle of load current will become the same as that of load voltage and the angle difference between injected voltage and load current will be β-α (which is also one of the internal angles of the voltage triangle as indicated in fig. 2), and for it to be 90° or greater, V_T has to be greater than V_L in magnitude which is not a possibility. Hence, for a unity power factor load, no value of β will produce a phase angle difference of 90° or greater, between injected voltage and load current, thereby ensuring a positive power injection every time.

If β is increased, magnitude of V_D increases and α also increases. A point will be reached when α will attain the value of 90° and active power from terminal side will become zero and DVR will be providing all the load active power as well as reactive power to the utility.

If β is further increased such that α becomes greater than 90°, the utility active power will become negative meaning that power is being supplied by the DVR to the utility which is also supplying complete load active power.

Maximum active power supplied to utility by the DVR occurs when both α and β attain the 180° value. At this point, DVR is supplying maximum power, some of which is picked up by the load and the rest is exported to utility.

This is a new concept in its own, as power export to utility is generally characterized by shunt connection to the bus. Another point to emphasize is that current magnitude during varying power export by DVR remains the same; variation in power is obtained by change in voltage magnitude and phase angle. Maximum voltage required during this variation is twice the rated load voltage minus the sag voltage on the terminal side.

This arrangement will also work even if there is no voltage sag and maximum voltage required to inject maximum power in the system will be twice the rated load voltage and maximum power will be twice the rated load power, half of which will be taken up by the load and the other half will be exported to utility.

IV. SIMULATION

A simulation of one phase of a system compensated by DVR was carried out for 85% sag by keeping different injection voltage angles in MATLAB®/SIMULINK® SimPowerSystems™ environment. The system frequency is 50 Hz. The DVR consists of a Pulse Width Modulated IGBT based inverter supplied from a DC bus with a filter connected at the output of inverter. The filter output is connected to the primary winding of a 1:1 transformer whose secondary is connected in series between the point of common connection and load bus. Two different cases have been simulated:

Case I: Here, the load is assumed to be an inductive load with 70.7% lagging power factor. Active power rating of the load is 500 kW and reactive power is also 500 kVAr. The results are graphically presented in figure 3 to 6, where all the concerned quantities are plotted against injection voltage phase angle β.

Case II: In this case, it is assumed that the load is compensated by a power factor correction device and the power factor is 100%. Active power rating of the load is 500 kW. The results are shown in figure 7 to 10, where all the concerned quantities are again plotted against injection voltage phase angle β.

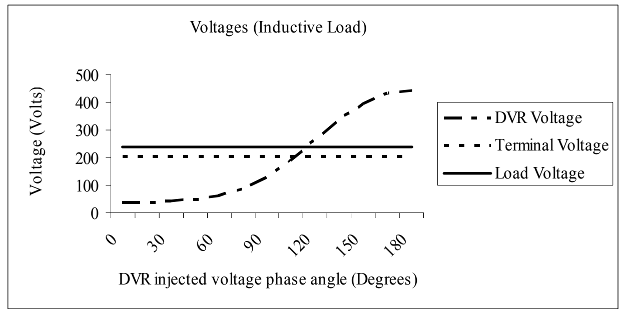

Fig. 3. Voltage variation with injected voltage phase angle (Case I).

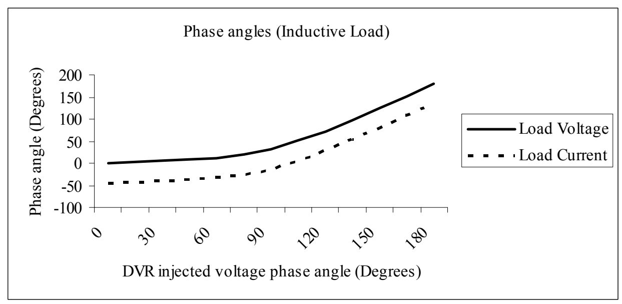

Fig. 4. Phase angle variation of load voltage and current with injected voltage phase angle (Case I).

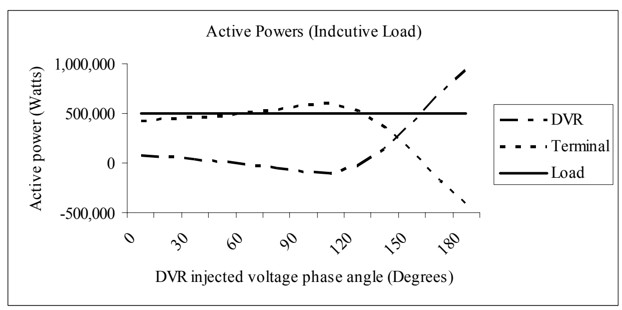

Fig. 5. Active Power variation with injected voltage phase angle (Case I).

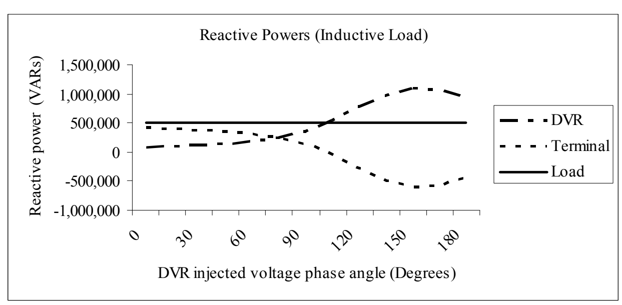

Fig. 6. Reactive Power variation with injected voltage phase angle (Case I).

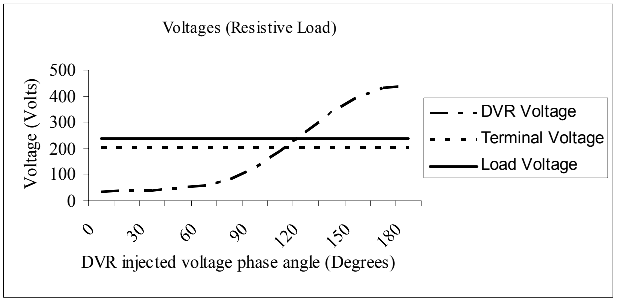

Fig. 7. Voltage variation with injected voltage phase angle (Case II).

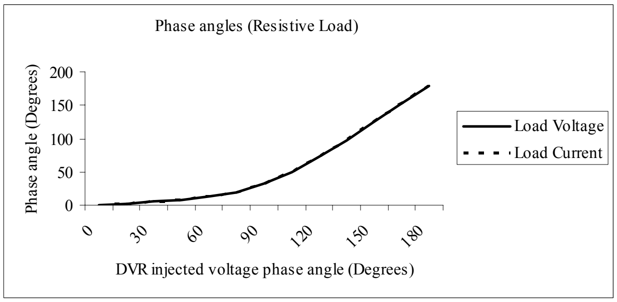

Fig. 8. Phase angle variation of load voltage and current with injected voltage phase angle (Case II).

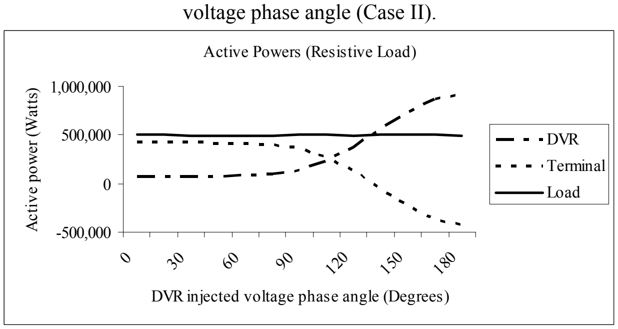

Fig. 9. Active Power variation with injected voltage phase angle (Case II).

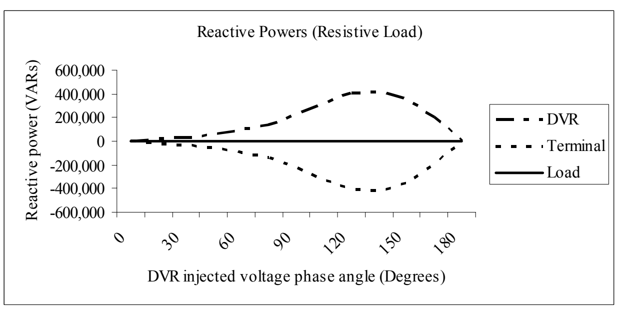

Fig. 10. Reactive Power variation with injected voltage phase angle (Case II).

Figure 3 shows the magnitude variation of required DVR voltage, and its effect on load voltage magnitude which is held almost constant at the required level of 240 V while terminal voltage value is also indicated. Figure 7 shows the same quantities for case II.

Figure 4 and 8 indicate the phase angle of load voltage and current against varying injection voltage phase angle for case I and case II, respectively. Plots of load voltage and current phase angles coincide in figure 8 as these are in-phase for a compensated load.

Figure 5 and 9 show the active power plots for different DVR voltage phase angles for case I and II respectively. It is evident from figure 5, that at a specific phase angle of injected voltage, DVR power becomes negative; this is the same interval during which terminal power becomes greater than load power. This is the point where reverse power flow occurs through the inverter causing damage to it. In contrast to this, analysis of figure 9 shows that DVR power never becomes negative and at a specific angle and beyond, it supplies active power to the terminal, whose power becomes negative.

Figure 6 and 10 indicate the reactive power contribution from all elements for case I and II respectively. Figure 6 indicates that increase in injection voltage will increase the reactive power contribution from DVR side till a specific angle, but further increase will again bring about a reduction in the same. Figure 10 indicates reactive power exchange between DVR and terminal as the load reactive power is being compensated by power factor correction. DVR will always supply reactive power in the angle interval of interest; however, this will start to decrease after a certain angle has been achieved.

V. CONCLUSIONS

It is evident from the calculations and simulations that DVR can contribute towards mitigation of sags as well as share power in a manner which suits a specific customer. In case of abundant availability of own power, maximum power can be shared while in case of scarcity, minimum power sag mitigation can be managed.

In addition, a new concept of power export through a series generator is presented, whose power export capability is managed by injected voltage magnitude and phase angle instead of the current. The current always remains constant in magnitude and is equal to the load current. This may act as a useful tool when there is generation of power at consumer premises without adequate storage and the consumer may get the benefit of price obtained therein. In the context of developing counties, where there is always shortage of power on the grid, electric utilities may benefit from injection of power from consumer side.

However, revolutionary it may seem, this concept needs to be further evaluated for applicability in a practical environment.

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