Power Quality Improvement Using Interline Dynamic Voltage Restorer

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***Abstract*—**Voltage sags describe dynamic variations in the network voltage which may be caused by continuous variations in input power from a fluctuating energy source or by varying loads. The Dynamic Voltage Restorer, a custom power device, has been proposed to protect sensitive loads from the effects of voltage sags on the distribution feeder. The major drawback of a particular dynamic voltage restorer is incapable of compensating long-duration voltage sags (and / or large amount of voltage sags also) since the amount of stored energy within the restorer is small enough. This paper proposes a new concept of Interline Dynamic Voltage Restorer, which is advanced to dynamic voltage restorer, where two or more dynamic voltage restorers in different feeders are connected to a common dc link. While one of the dynamic voltage restorers compensates for voltage sag, the other dynamic voltage restorer connected to a common dc link reloads the energy for dc-link. The detailed simulation has been carried out for a simple 6.6 kV voltage and 22 kV voltage feeders in SIMULINK.

***Index Terms*—**Interline Dynamic Voltage Restorer, power quality, sensitive load, series compensation, voltage sag

1. INTRODUCTION

POWER quality is the term used to describe how closely the electrical power delivered to customers corresponds to the appropriate standards and so operates their end – use equipment correctly. Thus, it is essentially a customer – focused measure although greatly effected by the operation of the distribution and transmission network.

There are a large number of ways in which the electrical supply (i.e. current, voltage or frequency) can deviate from the specified values. These range from transients and short – duration variations (e.g., voltage sags or swells) to long – term waveform distortions (e.g., harmonics or unbalance). Sustained complete interruptions of supply are generally considered an issue of network reliability rather than power quality. The growing importance of power quality is due to the
increasing use of sensitive customers' load equipment including computer – based controllers and power electronic converters as well as the awareness of customers of the commercial consequences of equipment mal'operating due to disturbances originating on the power system.

Now-a-days, the electricity sector is going through deregulation and privatization in the developed world and will go through further deregulation and privatization in the developed world in future. Competition therefore amongst electricity suppliers with the increased use of power electronics in everyday activities has resulted in increased attention to the issue of power quality.

With the wide spread use of electronic equipment, loads are becoming more sensitive and less tolerant to short – term voltage disturbances in the form of voltage sags. Voltage sag is one of the most severe power quality disturbances to be dealt with by the industry sector in recent time. Even a short-duration voltage sag could cause a malfunction or a failure of a continuous process, thereby incurring heavy financial loss. A series-connected converter-based mitigation device, the Dynamic Voltage Restorer (DVR) , is the most economical and technically advanced mitigation device proposed to protect sensitive loads from voltage sags.

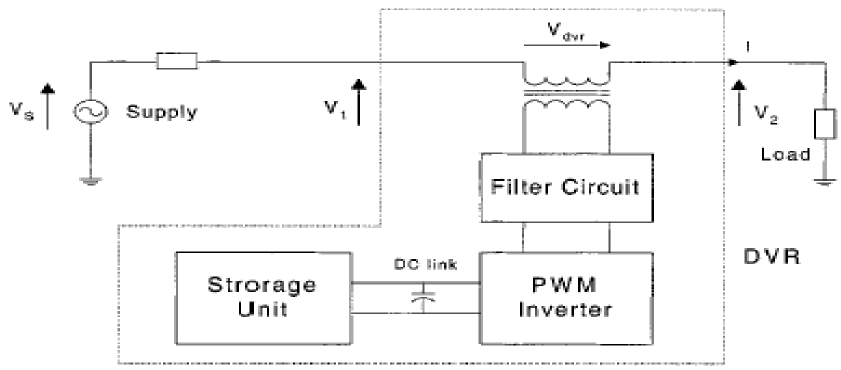

Fig 1. A Typical schematic block diagram of a power system compensated by the DVR

DVR consists of a Voltage Source Converter (VSC), a switching control scheme, a DC energy storage device and a coupling transformer connected in series with AC system, as illustrated in Fig 1. DVR being an example of custom power and it can be designed to have excellent dynamic performance capable of protecting critical and/or sensitive load against short duration voltage sags. Storage unit gives sufficient energy to the inverter through capacitor. In order to prevent the load from harmonics that contain in inverter output, filter is placed in the circuit. Finally, sufficient voltage is injected through transformer. The storage unit may be a fuel cell or a solar cell depending on the level of the voltage to be injected. The fuel cells are nowadays more popular than others. However, it may be either solar cell or fuel cell; once the energy in the any cell is vanishing, charging is to be done in that particular battery must be changed. So, the battery is not coping up with long duration voltage sags, hence the battery should be used in an optimum way. Protection equipment and instrumentation is also part of the DVR.

DVR is suited for solving a variety of power quality and reliability problems including

- Voltage sags and swells
- Voltage unbalances
- Voltage harmonics
- Power factor correction

The DVR injects a set of three – phase AC voltages in series and is synchronized with the distribution feeder voltages of the AC system. The amplitude and phase angle of the injected voltages are variable thereby allowing control of the active and reactive power exchanges between the DVR and the AC system within predetermined positive power supply, and negative power absorption limits.

This paper presents a concept of Interline Dynamic Voltage Restoration (IDVR) where two or more voltage restorers are connected such that they share a common dc link. This is in a way similar to the Interline Power Flow Controller (IPFC) concept which is still under research for the compensation and effective power flow management of multiline transmission system[5]. In its general form, the IPFC employs a number of inverters with a common dc link to provide series compensation for a selected line of the transmission system. In a similar way, the IDVR system is formed by using several DVRs protecting sensitive loads in different distribution lines to share a common dc-link energy storage.

For an example, two different sensitive loads fed from two different feeders with different voltage levels can be protected from voltage sags by two DVRs employed in an individual feeder. However, dc links of these two DVRs could be connected to a common dc link to form an IDVR system. This would cut down on the cost of the custom power device, as sharing a common dc link reduces the dc-link storage capacity significantly compared to that of a system whose loads are protected by clusters of DVRs with separate energy storages.

II BASIC OPERATING PRINCIPLES OF IDVR SYSTEM

A simple radial system may not be considered suitable for certain concentrated loads as it has the least reliability. The distribution systems such as secondary selective systems are common nowadays in industrial plants and institutions where the customer load is generally divided between two buses and are fed from two different substations.

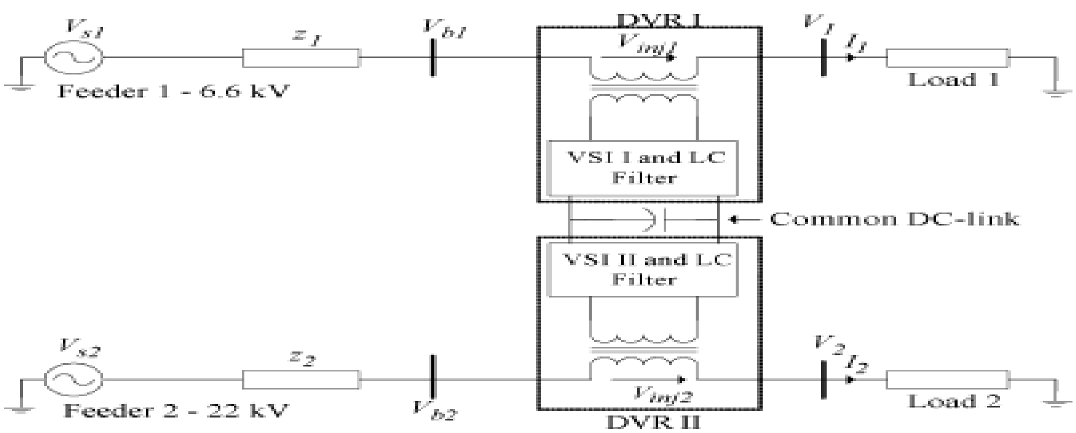

Fig.2. A block diagram depicting a simplistic IDVR system with two DVRs connected to dc link.

The IDVR system proposed in this paper employs two or more DVRs connected to a common dc link. A possible location for an IDVR scheme is an industrial park where several industrial loads are fed electrical power from different feeders emanating from different grid substations, perhaps at different voltage levels. A general schematic block diagram of such an IDVR system with two independent feeders with two different voltage levels is shown in Fig. 2. Due to these factors and, as the two feeders of the IDVR system in Fig. 2 are connected to two different grid substations, it is reasonable to assume that the voltage sag in Feeder 1 would have a lesser impact on Feeder 2. Therefore, the upstream generation–transmission system to the two feeders can be considered as two independent sources. Once the electrical coupling is neglected, two feeders can be considered as two isolated sources V_{s1} and V_{s2} with their source impedances Z_1 and Z_2 based on fault level at the Point of Common Coupling (PCC) in the respective feeders. Therefore, when a fault occurs in one of the lines, the DVR in that line acts to compensate the voltage sag taking real power from the common dc link while the compensator in the other line injects real power to common dc-link energy storage to maintain the dc-link voltage. In order to establish the power exchange between the two systems, it is assumed that DVR1 is mitigating voltage sag appearing in that line and DVR2 is controlled to provide real power to the dc-link energy storage. As line 2 is operating at its normal condition, the load voltage of line 2 should be equal to the load bus voltage. Thus, the inverter of DVR2 should be controlled to meet this condition while it is providing real power to the dc-link energy storage. The real power which should be supplied by DVR2 to maintain the dc-link voltage is equal to the real power needed to compensate voltage sag in line 1 and the system power losses including the converter switching losses. The phasor diagram shown in Fig. 3 illustrates magnitude and the direction of the injected voltage of inverter 2 to transfer real power from line 2 while keeping the load voltage of line 2 at a specified value. It is clear that voltage V_2 is equal to V_{b2} and in phase with the bus voltage V_{b2} under normal operating conditions. Hence, it is necessary to advance the phase angle of the load voltage V_2 appropriately whenever a replenishment of the common dc-link energy storage is required.

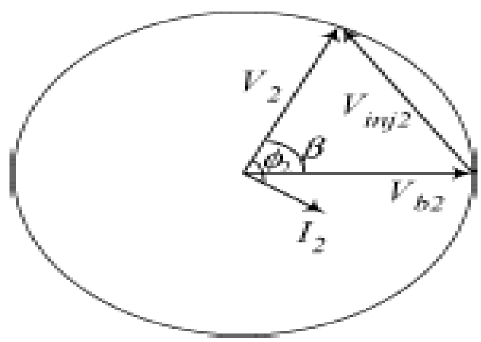

Fig.3. Vector diagram of DVR2 operating for real power exchange.

III POWER FLOW ANALYSIS

It is clear from Fig. 3 that the real power transferred to the dc-link energy storage depends on the advance angle β. The real power exchanged between line 2 and the dc-link energy storage can be written as follows:

$$P_{ex} = 3V_{b2}I_2\text{Cos}(\phi_2 - \beta) - 3V_2I_2\text{Cos}(\phi_2) \quad \text{Eq.... (1)}$$

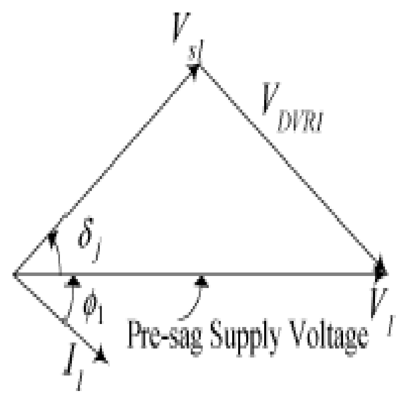

Fig.4. Vector diagram for pre-sag supply voltage boosting.

where I_2, V_{b2}, V_2, Φ_2, and β are load current, load bus voltage, load voltage, load power factor (PF) angle, and load voltage advance angle of line 2, respectively.

As the magnitude of the load voltage should be equal to the load bus voltage V_{b2}, (1) can be written in terms of load apparent power as in (2)

$$P_{ex} = S_2\left(\mathrm{Cos}(\phi_2 - \beta) - \mathrm{pf2}\right)$$ ………… Eq…. (2)

Where $S_2=3V_2I_2$ is line 2 load apparent power and $Pf_2$is line 2 load PF.
P_{ex} can also be written in terms of real power P_{DVR1} , required by DVR1 and the system power losses P_{losses} as in (3)

$$P_{ex} = P_{DVR1} + P_{losses}.$$ ……… Eq…. (3)

From (2) and (3), the advance angle β can be written as in (4)

$$\beta = \phi_2 - \mathrm{Cos}^{-1}\left[\frac{(P_{DVR1} + P_{losses})}{S_2} + \mathrm{pf2}\right].$$ …… Eq…. (4)

The parameters V_2 and I_2, hence, S_2 and Φ_2 in (2) are fixed to their specified values. Therefore, the only variable in (2) which can be varied to inject real power to the dc-link energy storage is the phase advance angle β. Hence, the maximum real power that line 2 can provide to the dc-link energy storage is given by (5). Therefore, real power transfer from line 2 to dc-link energy storage can be maximized when β is advanced such that it is
equal to the line 2 PF angle Φ_2 (i.e., $\beta_{max} = \Phi_2$)

$$P_{exmax} = S_2 (1- Pf2)$$ …… Eq…. (5)

It is clear from (4) that the angle β depends on the real power required by DVR1. The real power requirement of DVR1 depends on the adopted voltage compensation technique, i.e., in-phase boosting technique, pre-sag supply voltage boosting technique, and energy optimum boosting technique. The following sections will address the depth of the voltage sag in line 1 that line 2 can support to mitigate depending on the compensation technique adopted by DVR1.

A. *Dvr1 Operating In Pre-sag supply voltage boosting technique*

In this compensation mode the load voltage is compensated to the pre-sag supply voltage as shown in Fig. 3. The real power delivered by DVR1 to load 1 can be written as in (6)

$$P_{DVR1pr} = V_1 I_1 [3pf1 - M Cos(\phi_1 + \theta)]$$ Eq…. (6)

where $S_1=3V_1I_1$, $a_j=V_{s1j}/V_1$, $X=\Sigma_{j=1}^{3} a_j \cos(\delta_j)$, $Y=\Sigma_{j=1}^{3} a_j \sin(\delta_j)$, $M=\sqrt{X^2+Y^2}$
$\theta = \tan^{-1}[Y/X]$, P_{DVR1pr} is the real power supplied by DVR1, a_j is the sag factor, δ_j is the phase angle jump, Φ_2 is line 1 PF angle, is line 1 load current, V_1 is the load voltage of line 1, and V_{s1} is the supply voltage of line 1.
Assuming a balanced voltage sag with sag factor a and phase angle jump δ and P_{DVR1} substituting for in (4), (7) can be obtained

$$\beta=\phi_2-Cos^{-1}\left[\frac{(S_1[pf1-a*Cos(\phi_1+\delta)]+1P_{losses})}{S_2}+pf2\right].$$

………… Eq…. (7)

Thus, for maximum real power transfer,

$$a=\frac{S_1 pf1 + P_{losses} - S_2(1-pf2)}{S_1 Cos(\phi_1+\delta)}.$$

…………… Eq…. (8)

For an example, let us assume that the two lines carry the same load with equal PF and 3% system losses with respect to the apparent power of the load (S_2) in line 2. The sag factor which line 2 can support by providing real power can be expressed as in (9)

$$a=\frac{[2*pf-0.97]}{Cos(\phi_1+\delta)}.$$

……… Eq…. (9)

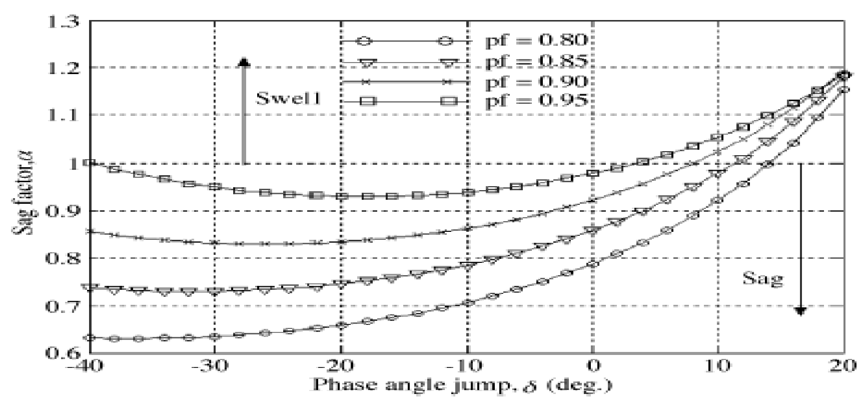

Fig.5. Variation of sag factor with phase-angle jump in line I for which line II DVR has the ability to supply power.

Fig. 5 represents the variation of sag factor with phase angle jump for a given PF. It is clear from this figure that the depth of the sag that line 2 can support to mitigate depends not only on the PF of the load but also on the phase-angle jump. For an example, the sag factor is about 0.86 for

0.85 PF load with δ = 0.0º. This means that line 2 can supply real power to maintain the dc-link voltage only for voltage sag of 14% appearing at the load bus of line 1. However, for δ= +8º, the sag factor has increased to 0.95, which means that line 2 can support a voltage sag of 5% with phase jump of 8º . The sag factor decreases thereby increasing the capability of mitigating sags with large depth when the phase angle jump is negative. For δ = - 20º and 0.8 PF load, the sag factor is about 0.66.

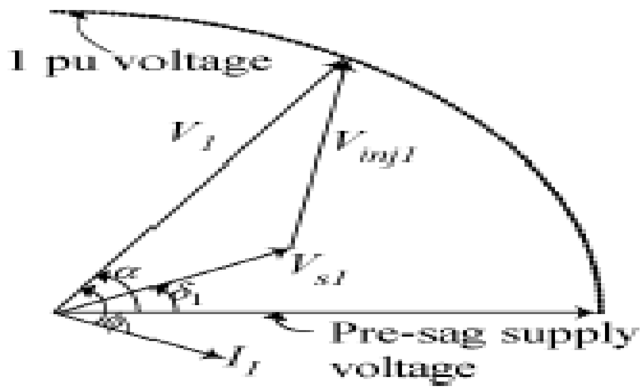

Fig.6. Vector diagram of phase advance technique.

Therefore, the depth of the sag that can be mitigated using energy from line 2 is 34%. As sag factor depends on the phase-angle (δ) jumps and is not controllable, DVR1 operating in pre-sag supply voltage boosting technique generally requires a significant number of lines to be connected to the common dc link in order to mitigate sags with large depths.

B. *Dvr1 Operating In Energy Optimum Technique*

In this technique the load voltage angle is advanced progressively by a certain angle α which will minimize the real power injected to the load from the dc-link energy storage. The complete theoretical analysis for the derivation of necessary phase advance angle for a generalized sag situation is given in [3]. Fig. 6 illustrates the vector diagram for phase-angle advance technique. The optimum real power given by DVR1 under the condition P_{DVR1}>0can be written as in (10)

$$P_{\mathrm{DVR1opt}} = S_1\left[\mathrm{pf1} - \frac{M}{3}\right]$$

…………… Eq…. (10)

where $\alpha_{opt}=\Phi_1+\theta$.

For a balanced three-phase voltage sag with sag factor and phase-angle jump δ, M=3a, hence, the angle β can be written as in (11)

$$\beta = \phi_2 - \mathrm{Cos}^{-1}\left[\frac{(S_1[\mathrm{pf1} - a] + P_{\mathrm{losses}})}{S_2} + \mathrm{pf2}\right].$$

……… Eq…. (11)

Thus, for maximum real power transfer,

$$a = \frac{S_1\mathrm{pf1} + P_{\mathrm{losses}} - S_2(1 - \mathrm{pf2})}{S_1}.$$

……… Eq…. (12)

For an example, let us assume a two-line IDVR system with equal load and PF and 3% system losses with repsect to apparent power of the loads. Then, the sag factor is given by

$$a = (2 * \mathrm{pf1} - 0.97). \quad \text{……… Eq…. (13)}$$

It is clear from Eq (13) that the sag factor is now independent of the phase-angle jump . The sag factor is about 0.73 for 0.85 PF load and it is about 0.63 for 0.8 PF load. This means that line 2 can transfer real power to mitigate 27% and 37% voltage sags for 0.85 and 0.8 PF load, respectively. Therefore, it is clear that DVR1 should operate in energy-optimum mode to mitigate sags with large depth and long duration. Furthermore, if more lines are connected to the common dc link, the IDVR would be able to compensate even deeper voltage sags.

IV. RESULTS

Fig 7 represents two transmission line model, one (Line-1) is normal circuit and the other is sag creation circuit. In normal circuit (i.e. without voltage sag), current, voltage and real, reactive powers are normal (i.e. there are no fluctuations in these parameters). These waveforms shown in Fig 8 and Fig 9.

In sag creation circuit (Line-2), the second load is switched in a certain time instant. After switching the second load in this circuit, voltage sag is created (see Fig 10). Since the first load (in the sag creation circuit), is in parallel with the second load, same voltage appear in the first load also. The corresponding real and reactive powers in sag creation circuit are shown in Fig11. In Fig 11, there is a change in real and reactive power in the sag creation circuit after switching the second load.

Fig 12 represents two transmission line model consists of normal circuit and sag creation circuit with an IDVR system. The normal circuit (Line-1) can give real power to the DC link through the converter (rectifier) present in the IDVR system. From the DC link, in sag creation period, the sag creation circuit (Line-2) can absorb real power from DC link through converter (inverter). The real power needed by the sag creation circuit to mitigate the sag is exactly equal to the real power delivered by the normal circuit (Line-1) which includes both line losses and converter switching losses.

Fig 13 shows IDVR model which consists of two converters with common DC link. Fig 14 shows IDVR output which compensates for voltage sag. Fig 15 shows the voltage sag in Line-2 (in both the loads). By observing the Fig 15, that there is some time elapsed between occurrence of sag and IDVR compensation. The drawback of this circuit is that the real power transfer depends on the load power factor. This drawback is overcome in next case (i.e. closed loop circuit).

Fig 16 shows closed loop compensation. In the feedback, there is reference signal, and triangular wave generator. PWM pulses are generated for inverter using reference signal and triangular wave. Since, the real power transfer depends on the load power factor. The feedback adjusts the real power such that it compensates the load power factor. Fig 17 shows the output of line 1 and line 2 with closed loop sag compensation.

Case1: Sag creation circuit:

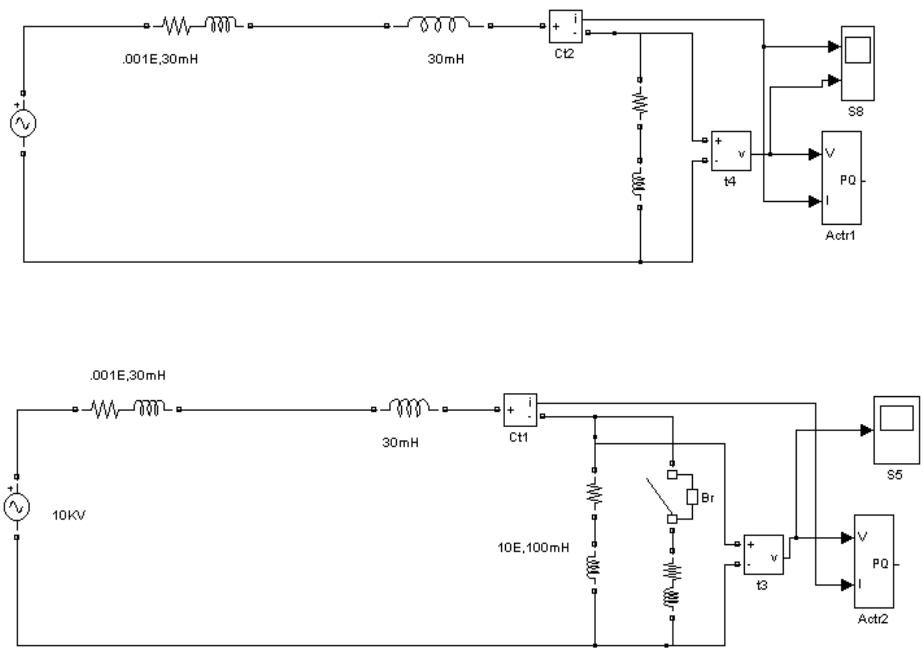

Fig 7. Two transmission line model

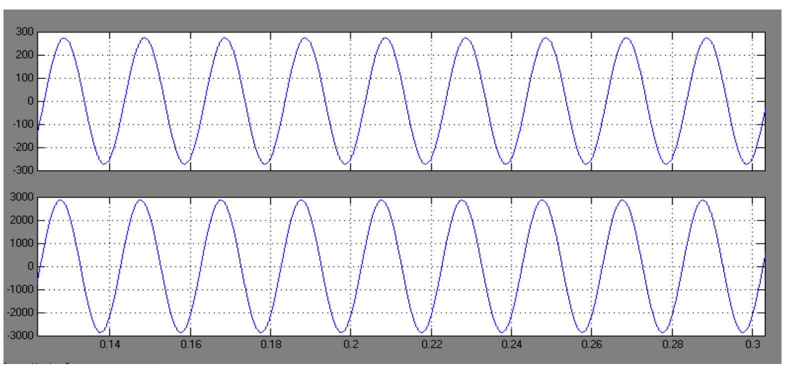

Fig 8. Line-1 Current and voltage output

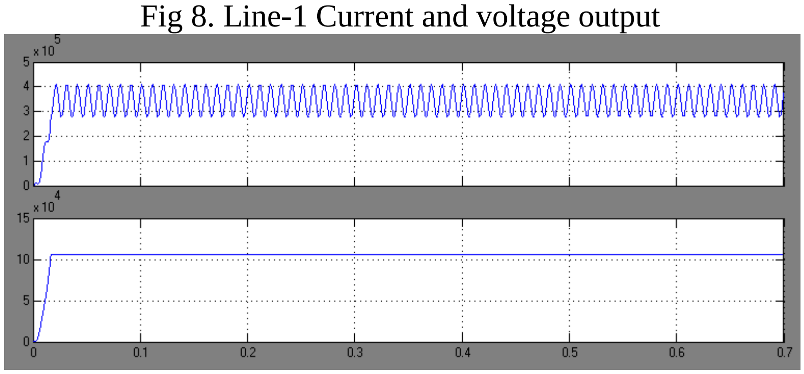

Fig 9. Line-1 real power and reactive power

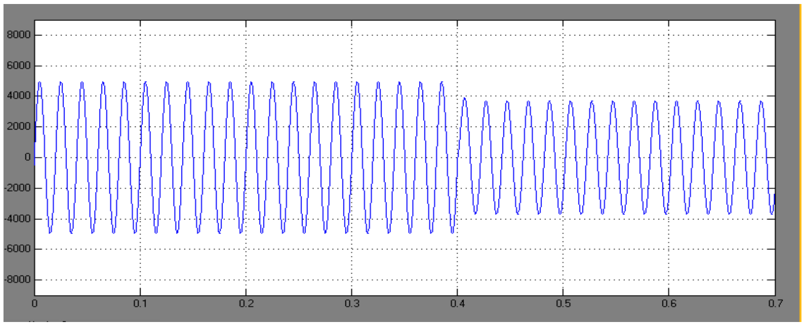

Fig 10. Line-2 voltage output with voltage sag

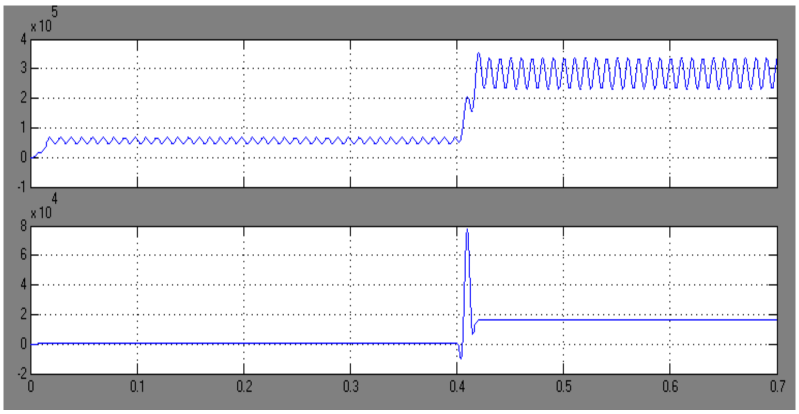

Fig 11. Line-2 real and reactive power

Case 2: Voltage sag compensation with IDVR

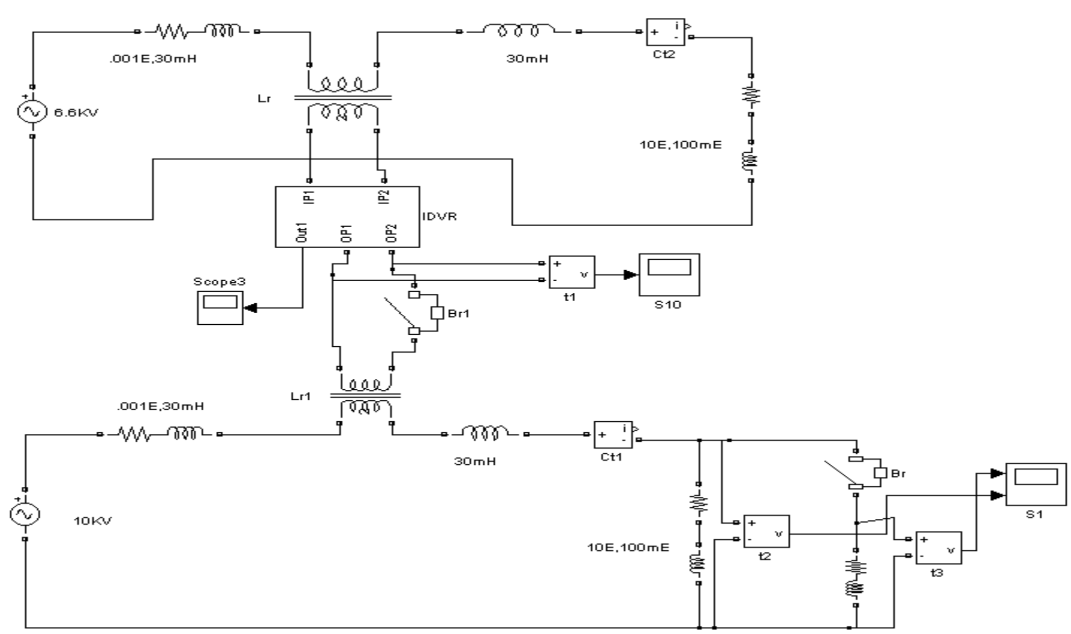

Fig 12. Normal circuit diagram

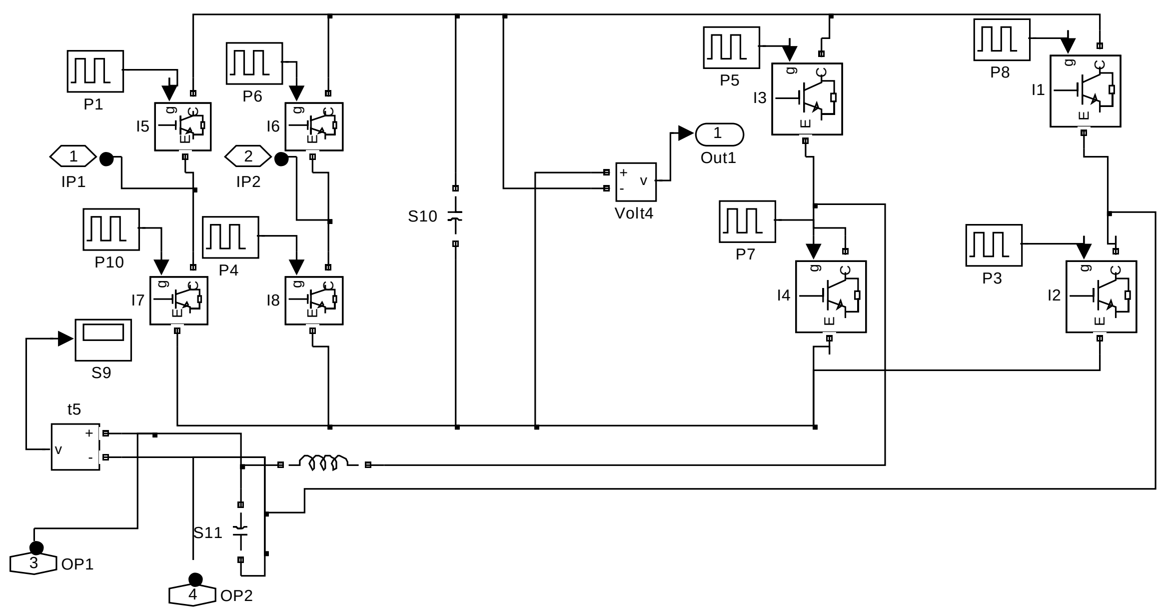

Fig 13. IDVR Model

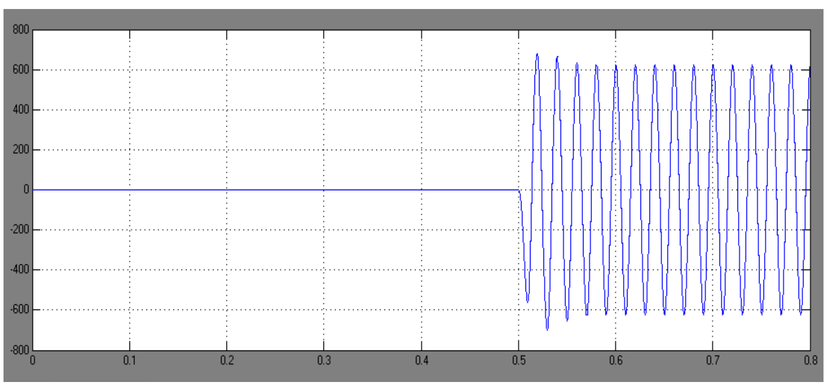

Fig 14. IDVR output

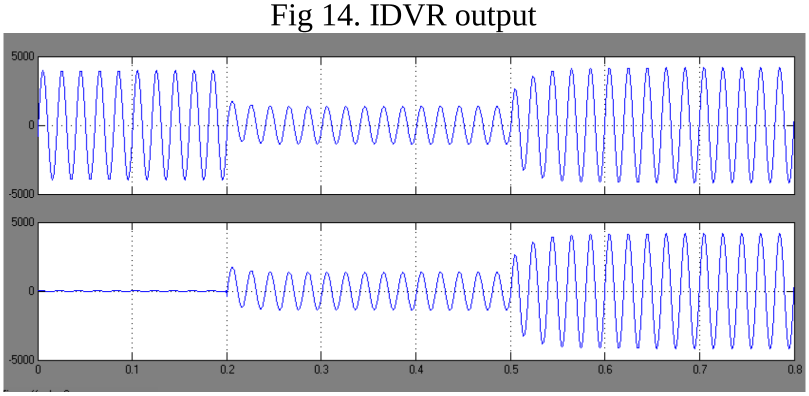

Fig 15. Voltage across load-1 and load-2(line-2)

Case 3: Sag compensation with IDVR (with feedback)

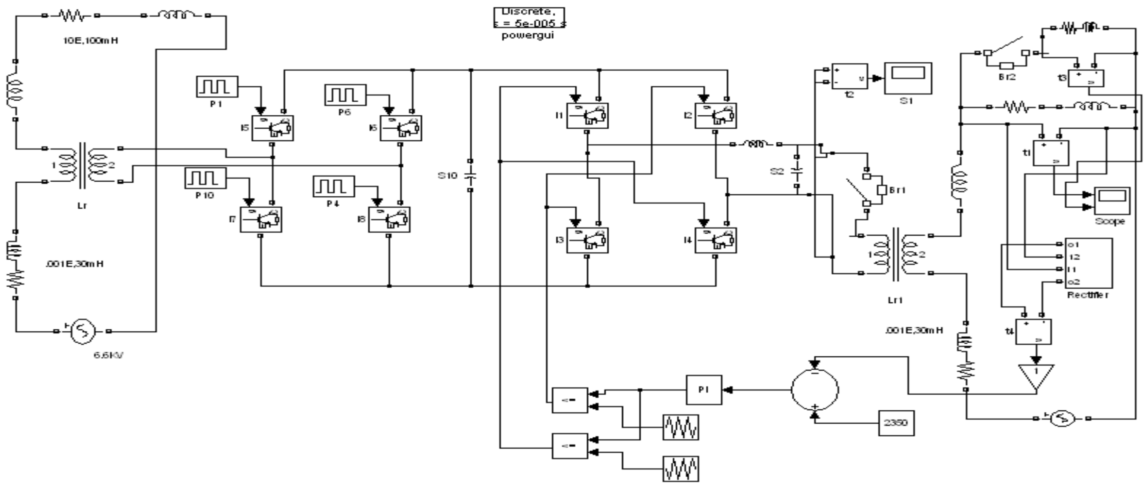

Fig 16. Closed loop circuit diagram

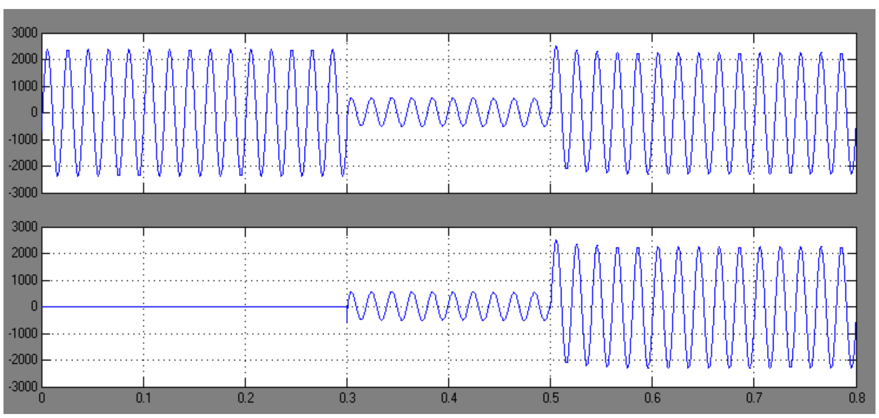

Fig 17. Voltage across load-1 and load-2(line-2)

V. CONCLUSION

The circuit model for four bus (Line 1 sending end, receiving end & Line 2 sending end, receiving end) IDVR is developed using MATLAB/SIMULINK. It is used for simulating the four bus and corresponding results are presented. The real power flows from a bus with higher angle to a bus with lower angle (here angle is δ, angle of advance). The reactive power is found to flow from higher potential to lower potential. The real power can be varied by varying the firing angle of the inverter. The reactive power can be varied by varying the firing angle of the rectifier. In closed loop circuit, the feedback adjusts the real power such that it compensates the load power factor since the real power transfer depends on the load power factor.

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