Design Strategy for Optimum Rating Selection of Interline DVR

Bhamidipati.Ravikiran[1] ,K.VenuMadhav[2] Associate professor.
Ravikiran[1] *Student of* Sree chaitanya college of Engineering,Karimnagar.
K.VenuMadhav[2] Associate professor Sree chaitanya college of Engineering,Karimnagar.

***Abstract*—This paper is concerned with calculating the optimum rating for two dynamic voltage restorers (DVRs) when used in an interline DVR (IDVR) structure. An IDVR consists of two or more DVRs which have a common dc link and, thus, can exchange ac-tive power. This can increase the compensation range of an IDVR compared with separate but otherwise similar DVRs. The basic op-eration of the DVR and IDVR is briefly explained. The limitations of IDVR operation in terms of active power exchange are explained and, based on that, the expressions governing the steady-state oper-ation of IDVR are derived. The compensation range of an IDVR is compared with that of two separate DVRs. This paper also explores how the limitations in absorbing power from a healthy feeder can narrow the compensation range of an IDVR. After identifying and formulating various limitations in IDVR operation, a design proce-dure is presented to determine the optimum size (or rating) of the DVRs in an IDVR structure. In the proposed approach, all possible scenarios concerning healthy and faulty feeders are taken into con-sideration. Examples along with graphs and tables aid in conveying the proposed approach.**

***Index Terms*—Power distribution reliability, power quality (PQ), voltage control.**

I. Introduction

VOLTAGE variations are one of power-quality (PQ) events that can cause substantial damage to consumers with sensitive loads. These disturbances are normally caused by system faults, load variations, energization of large loads, and poorly designed systems. Traditional methods of combating voltage variations include tap-changing transformers, con-stant voltage transformers, and uninterruptible power supplies (UPS). Furthermore, so-called custom power devices, such as static transfer switches (STS), Distribution-STATCOM or D-STATCOM, unified power-quality conditioner (UPQC), and dynamic voltage restorers (DVRs) are some emerging solu-tions to help alleviate the damaging consequences of voltage variations [1]–[3].

A DVR protects feeder loads against voltage variation by in-jecting a voltage in series with the feeder voltage. This device is usually installed in places where large industrial plants or large groups of sensitive loads are supplied by a distribution feeder. To date, many successful installations of DVRs have been re-ported [3].

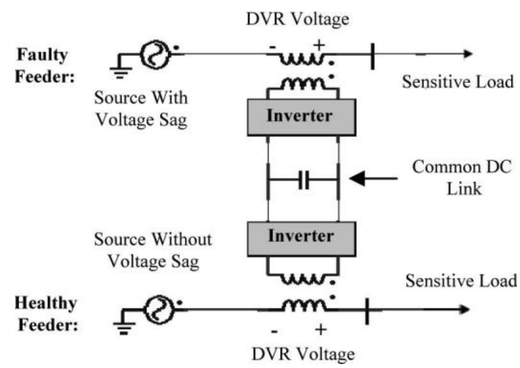

Fig. 1. General structure of an IDVR with two DVRs.

Several strategies have been proposed to control a DVR during voltage variations [4]–[7]. Some of these methods try to minimize the energy exchanged by the DVR during compensation, or even reduce it to zero. Thus, these methods are called minimum-energy (ME) strategies. Other methods are concerned with reducing the rating and size of the DVR, which occurs when the injected voltage aligns with the source voltage. Therefore, these methods are called minimum rating (MR) or inphase (IP) control strategies. MR strategies usually require active power for compensation. This active power has to be supplied from an energy storage device, which adds to the installation and running costs.

In some industrial or commercial areas, loads can be poten-tially supplied by different feeders connected to different sub-stations. As a result, disturbances in existing feeders in the area do not always occur concurrently. In these cases, the reliability of a system can be increased by custom power devices. For ex-ample, by using static transfer switches (STS), the load is sup-plied by a main (or preferred) feeder, and transferred to an alter-native feeder in the case of unacceptable conditions in the main feeder. STS, however, cannot alleviate all PQ problems. Fur-thermore, it completely disconnects the load from the preferred feeder, which may still be able to deliver some power.

If the DVR is to be installed in two or more adjacent feeders, then it is possible to use a common dc bus for several DVRs, as proposed by some studies [8]–[11]. This structure, called in-terline DVR or IDVR (Fig. 1) enables active power exchange between two or more DVRs and, therefore, extends the com-pensating range of separate DVRs. This benefit is achieved at almost no additional cost.

In an IDVR structure, the required active power for any DVR in the faulty feeder(s) can be supplied from other feeder(s) through a common dc link. Thus, it would seem at first glance that the DVRs in an IDVR structure can be designed to operate in inphase mode, since active power is always available and, thus, is of no concern. However, the amount of power supplied by the healthy feeder(s) has certain limitations due to the op-erational characteristics of these feeder(s). On the other hand, the amount of energy required for compensation (in the faulty feeder) is not constant and depends on other parameters, such as the phase and magnitude of injected voltage. Therefore, DVRs in an IDVR structure can neither work with minimum energy nor inphase strategy. The crucial problem is how to select the size of DVRs in an IDVR structure so that all compensating scenarios can be fulfilled while the total rating of the IDVR is minimized. This question is directly related to the amount of active power that can be sourced from healthy feeders and that is required for compensation of voltage variation. Since the parameters involved in this problem are highly inter-related, answering the aforementioned questions calls for a thorough analysis of an IDVR structure, which is the objective of this paper. Specifically, this paper presents a design procedure in which the optimum size of DVRs in an IDVR structure can be determined by taking all possible operational scenarios into consideration.

This paper follows the ensuing outline: the nature of voltage variations in utility grids is described and the need for active power in series compensation is explained. A brief description of DVR operation is given with a focus on DVR rating and various control strategies. The basic expressions governing the steady-state operation of IDVR are derived. The operation of IDVR is compared with the case of separate DVRs to show the improvement in the compensation range of an IDVR. The problem of IDVR rating minimization is formulated and a de-sign procedure is presented.

II. Long-Duration Voltage Variation in the Utility Grid and Series Compensation

Voltage variations have been a characteristic of the utility grids since their appearance. Among different types of voltage variations, long-duration variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min [1], [2]. These variations generally are not the result of system faults, but are caused by load variations on the system, system switching operations, and poorly designed or old systems.

A DVR compensates for voltage variations by injecting a voltage in series with the feeder voltage. This action may or may not involve any active power (or energy) exchange, depending on the control strategy of the DVR and the duration of voltage variation. For short-duration events [1], [2], there is usually no need for an energy storage device in a DVR since the electrolyte capacitor in the dc link can supply/absorb enough energy for short durations without a significant change in its voltage. However, when it comes to deep and/or long-duration voltage variations, an energy storage device usually becomes necessary.

Based on the aforementioned discussion, a DVR with active power-exchange capability is particularly attractive for situations where deep and/or long-duration voltage variations are of concern. Similarly, an IDVR is also best suited for these oper-ating conditions.

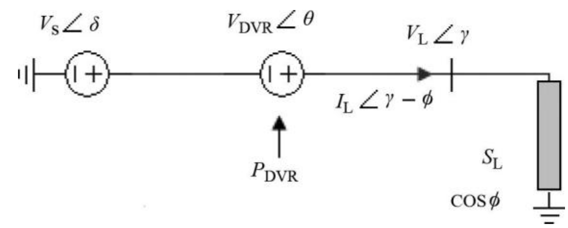

Fig. 2. Single-phase equivalent circuit of a DVR.

III. Review of DVR Operation

As previously stated, an IDVR comprises two or more DVRs connected via a common dc bus. Therefore, a quick review of DVR operation will help in understanding the operation of an IDVR.

A. DVR Equivalent Circuit

In this paper, only balanced voltage variations are considered. Therefore, the single-phase equivalent circuit of the system, as shown in Fig. 2, is adequate for analysis. The DVR in this figure is modeled by an ideal series-controllable voltage source $V_{DVR}\angle\theta$. V_L, γ, S_L, ϕ and I_L represent the load voltage magnitude and angle, load kilo volt-ampere (kVA), load phase angle, and load current magnitude, respectively. Finally, $V_S\angle\delta$ shows the supply or grid voltage. Any voltage variation is modeled by a change in the amplitude and/or phase of this voltage. The analysis is performed in a per-unit basis, with the rated load (or feeder) voltage as the base voltage. The base power and phase reference can be arbitrarily chosen. Also note that line impedances are neglected, resulting in a more comprehensible analysis without introducing significant error.

To characterize voltage variations, a quantity called voltage factor (VF) is defined as

$$\text{VF} = \frac{V_S}{V_{L,\text{rated}}} = \frac{V_S}{1} = V_S \quad \text{(per unit)} \tag{1}$$

where $V_{L,\text{rated}}$ is the rated load (or base) voltage. Under ideal conditions, $VF=1$ corresponds to the normal condition, while $VF<1$ and $VF>1$ signify undervoltage and overvoltage, conditions respectively. However, in almost all practical cases and based on available standards, V_L has a permissible range of variation normally between 0.9 to 1.1 p.u. Therefore, from a practical point of view, $0.9<VF<1.1$ can be considered as a normal condition.

B. DVR Rating

A DVR always appears in series with the load and, thus, the full feeder current flows through it. Therefore, a DVR must have the same current rating as the feeder irrespective of the operating condition, i.e.,

$$I_{\text{DVR,rated}} = I_{\text{L,rated}}. \tag{2}$$

The voltage rating of a DVR is an important design parameter, as it determines many DVR characteristics, such as compensating range, the need to include (and size of) energy storage devices, and overall size. Based on the phasor diagram depicted

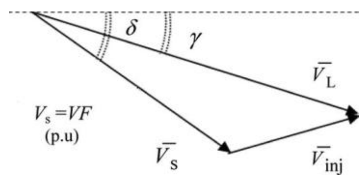

Fig. 3. Simple phasor diagram of the DVR (pertaining to Fig. 2).

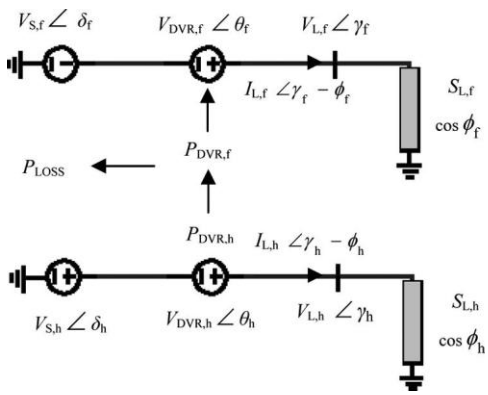

Fig. 4. Single-phase equivalent circuit of the IDVR.

in Fig. 3, the required injecting voltage for a typical operating point is obtained by using the following equation:

$$V_{\text{inj}} = \sqrt{\text{VF}^2 + V_{\text{L}}^2 - 2\text{VFV}_{\text{L}} \cos(\delta - \gamma)}. \quad (3)$$

The voltage rating of a DVR, denoted by $V_{\text{DVR,rated}}$, should be equal to the highest V_{inj} .

The kilovolt-ampere rating of a DVR is the product of its rated current by its rated voltage, which is equal to the product of rated load kVA by DVR rated voltage in per unit basis, i.e.,

$$\begin{aligned} S_{\text{DVR,rated}}^{(\text{p.u})} &= I_{\text{DVR,rated}}^{(\text{p.u})} \times V_{\text{DVR,rated}}^{(\text{p.u})} \\ &= S_{\text{L,rated}}^{(\text{p.u})} \times V_{\text{DVR,rated}}^{(\text{p.u})} \\ &= S_{\text{L,rated}}^{(\text{p.u})} \times \text{MAX}(V_{\text{inj}}^{(\text{p.u})}) \end{aligned} \quad (4)$$

where $S_{\text{L,rated}}$ is the rated load kVA. Both the voltage and kVA rating of a DVR determine its size and cost and, thus, are of importance.

C. Power Requirements

The phasor diagram in Fig. 3 can also be used to calculate the active power exchange in a DVR. Since undervoltages are only considered in this paper, a DVR always delivers active power to the line for compensation, which can be obtained as

$$P_{\text{DVR}} = S_{\text{L}} \left[\cos(\phi) - \frac{VF}{V_{\text{L}}} \cos(\delta - \gamma + \phi) \right]. \quad (5)$$

Based on (3) and (5), and for a given VF, there are multiple solutions for V_{inj} and P_{DVR}. This is the basis for different control strategies in a DVR as discussed in the literature [4]–[7]. The control strategies are mainly divided into two categories:

1) Some control strategies try to minimize the energy exchange during compensation, or even reduce it to zero [4]–[7]. These strategies are called minimum energy (ME).
2) Some strategies try to reduce the size of converter and injecting transformer by reducing their voltage rating [4]–[7]. This can be accomplished by adjusting the in-serting voltage in phase with the supply voltage. Therefore, these strategies are called inphase (IP) or minimum rating.

IV. IDVR Steady-State Analysis

The steady-state analysis of the IDVR is presented for the case of the system with two DVRs, but can be extended to multi-DVR structures. The single-phase equivalent circuit of a DVR can be extended to an IDVR as shown in Fig. 4. In this figure and the following analysis, subscripts "f" and "h" denote "faulty" and "healthy" feeders, respectively. The active power associated with the faulty and healthy feeders can be, respec-tively, obtained as

$$P_{\text{DVR,f}} = S_{\text{L,f}} \left[\cos(\phi_{\text{f}}) - \frac{VF}{V_{\text{L,f}}} \cos(\delta_{\text{f}} - \gamma_{\text{f}} + \phi_{\text{f}}) \right] \quad (6)$$

$$P_{\text{DVR,h}} = S_{\text{L,h}} \left[\frac{V_{\text{S,h}}}{V_{\text{L,h}}} \cos(\delta_{\text{h}} - \gamma_{\text{h}} + \phi_{\text{h}}) - \cos(\phi_{\text{h}}) \right]. \quad (7)$$

Another important equation which governs the operation of an IDVR is the power balance equation, i.e.,

$$P_{\text{DVR,h}} = P_{\text{DVR,f}} + P_{\text{LOSS}}. \quad (8)$$

P_{LOSS} represents different losses in the intermediate dc link which are neglected in this paper.

V. Comparison Between IDVR and Separate DVRs

A good understanding of the advantages of IDVR can be achieved by comparing the operation of two separate DVRs without energy storage devices and one IDVR consisting of sim-ilar DVRs but with a common dc link.

The compensation range of a DVR without energy storage device can be found from (5) by equating P_{DVR} to 0. Thus, the minimum VF (corresponding to the deepest undervoltage) is obtained as

$$VF_{\text{DVR,min}} = V_{\text{L}} \cos(\phi_{\text{f}}). \quad (9)$$

To find the maximum compensating range of an IDVR, the minimum active power required for compensating an under-voltage must be smaller or equal to the maximum power that can be delivered from the other (healthy) feeder, i.e.,

$$\text{Min}\left(P_{\text{DVR,f}}\right) \leq \text{Max}\left(P_{\text{DVR,h}}\right). \quad (10)$$

Substituting from (6) and (7) in (10) yields

$$S_{\text{L,f}} \left[\cos(\phi_{\text{f}}) - \frac{\text{VF}}{V_{\text{L,f}}} \right] \leq S_{\text{L,h}} \left[\frac{V_{\text{S,h}}}{V_{\text{L,h}}} - \cos(\phi_{\text{h}}) \right]. \quad (11)$$

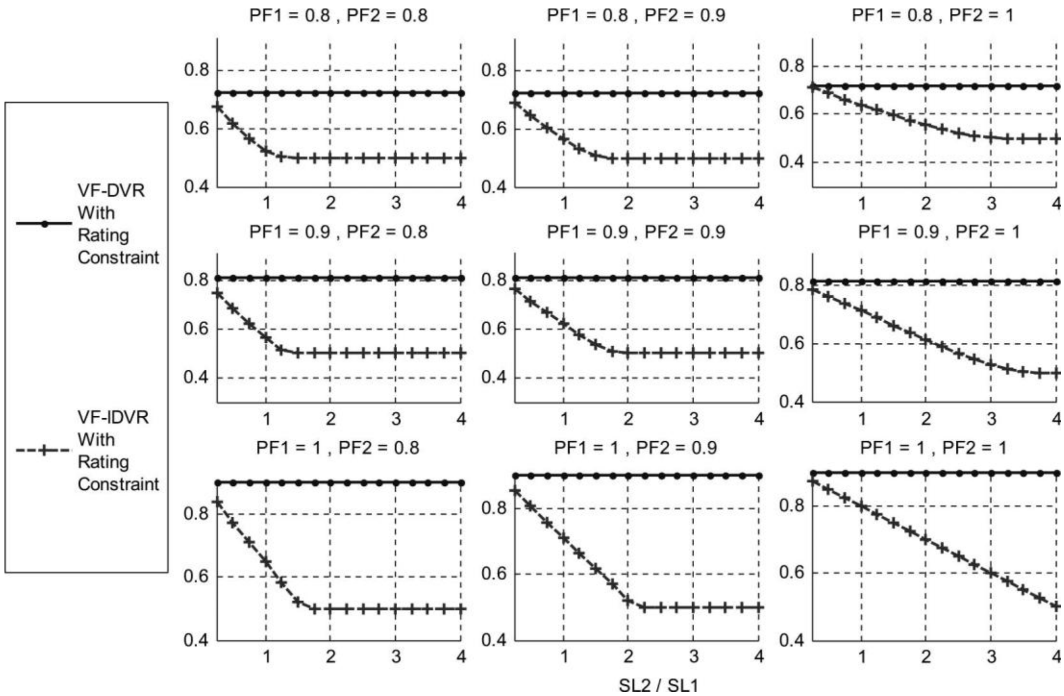

Fig. 5. Comparison between the compensating range of the IDVR with similar separated DVRs when the voltage rating is limited to 0.4 p.u. The horizontal axis is the L2L1 ratio, and the vertical axis is .

The worst limiting case can be obtained by substituting $S_{L,rated}$ in (11), hence

$$\mathrm{VF}_{\mathrm{IDVR,min}} = V_{\mathrm{L,f}}\left[\cos(\phi_{\mathrm{f}}) + \frac{S_{\mathrm{L,rated,h}}}{S_{\mathrm{L,rated,f}}}\left(\cos(\phi_{\mathrm{h}}) - \frac{V_{\mathrm{S,h}}}{V_{\mathrm{L,h}}}\right)\right]. \quad (12)$$

As stated in Section III-A, in practice, V_L has a permissible range normally between 0.9 to 1.1 p.u. Thus, to obtain the minimum VF, $V_{L,h}$ and $V_{L,f}$ must be properly substituted, i.e.,

$$VF_{\mathrm{IDVR,min}} = 0.9\left[\cos(\phi_{\mathrm{f}}) + \frac{S_{\mathrm{L,rated,h}}}{S_{\mathrm{L,rated,f}}}\left(\cos(\phi_{\mathrm{h}}) - \frac{V_{\mathrm{S,h}}}{0.9}\right)\right]. \quad (13)$$

For example, based on (13), when two similar feeders are supplying their rated loads at the $\mathrm{PF} = 0.85$ lag, an IDVR can compensate undervoltages as deep as $\mathrm{VF}_{\mathrm{IDVR,min}} = 0.53 (0.9 \times [0.85 + 1 \times (0.85 - 1/0.9)] = 0.53)$. For separate DVRs and based on (9), $\mathrm{VF}_{\mathrm{DVR,min}}$ is $0.765 (0.9 \times 0.85 = 0.765)$.

Fig. 5 shows the variation of $VF_{\mathrm{DVR,min}}$ and $\mathrm{VF}_{\mathrm{IDVR,min}}$ versus $(S_{\mathrm{L,rated,h}}/S_{\mathrm{L,rated,f}})$ for various load power factors. It is assumed in these figures that the voltage rating of each DVR (both in separate DVRs and IDVR structure) is 0.4 p.u. As the figure demonstrates, the lower the DVR voltage rating is, the smaller the compensating range will be. The minimum load voltage in both feeders is assumed to be 0.9 p.u.

Fig. 5 clearly shows that the compensating range of IDVR is larger than that of separate DVRs with similar ratings. Further-more, the following observations can be made based on these figures:

- Higher power factor load reduces the compensation range of DVR and IDVR.
- When the rating of the healthy feeder is higher than that of the faulty feeder, the compensation range in the IDVR structure increases.

In all figures, the minimum VF is always 0.5 regardless of other operating conditions. This value corresponds to an IP strategy which provides the maximum compensation with minimum injecting voltage (i.e., minimum rating).

Based on the aforementioned analysis, it can be seen that an IDVR can provide a larger compensating range than that with similar, separate DVRs without a common dc link, while the size and cost remain fairly consistent.

The aforementioned feature can be exploited in different ways in the design stage of an IDVR. For example, think of using an IDVR for a given compensation scenario and with the objective of reducing the total rating and size of the system. This objective is well justified since the total system cost is dependent on the rating and size of the system. This subject is discussed in the following section.

VI. IDVR Optimum Design

The size and cost of solid-state converters (and associated magnetic components, such as transformers) are approximately proportional to their kVA rating. Therefore, it is usually desir-able to minimize the kVA rating of these systems without com-promising their performance. In the case of the IDVR, which is a system consisting of two (or more) sets of converters and in-jecting transformers, minimizing the total kVA of the system is the same as minimizing the sum of the kVA ratings of individual DVRs.

The IP or minimum rating control strategy may be employed in an IDVR for size and kVA reduction. However, as indicated by (7), there is always a limitation in absorbing energy from a healthy feeder in an IDVR. Therefore, not all voltage varia-tion events can be compensated for by IP strategy in IDVR. In other words, when the maximum attainable active power from a healthy feeder [given in (7)] is reached, the control strategy should be adjusted so that the transferred active power is con-stant but the compensation is still accomplished. A numerical example will help to clarify this concept.

Assuming that two feeders in an IDVR structure are similar and operate with rated load and PF= 0.85 lag. Based on (7), the maximum power which can be taken from either feeder is 0.261 p.u., assuming the load voltage is not to fall below 0.9 p.u. Now, based on (6) and equating $\delta_f = \gamma_f$, an undervoltage in the faulty feeder with VF= 0.7 needs 0.189-p.u. active power for compensation, which can be taken from the healthy feeder. In this case, the DVR in the faulty feeder may or may not work with under IP (or minimum rating) control strategy, depending on operational parameters. On the other hand, if VF= 0.6, the required power for compensation is 0.283 p.u., which cannot be delivered from the healthy feeder because its voltage drops below the permissible level. In this situation, the control strategy of the DVR in the faulty feeder must adopt an operating point so that it can compensate for the undervoltage with the imposed power transfer limitation. Both DVRs in an IDVR structure must be designed and selected in order to cope with these operational conditions. This selection must be accomplished in the design stage.

The aformentioned example demonstrates that selecting the rating of the individual DVRs in an IDVR structure depends on many parameters. Specifically, if the maximum attainable power from the healthy feeder is reached, the DVR in the faulty feeder cannot operate with the minimum rating strategy. This limitation will affect the rating of the individual DVRs in the IDVR structure which must be taken into consideration at the design stage. This section is concerned with the calculation of the optimum rating for individual DVRs which minimizes the total rating of the IDVR structure.

Problem formulation is an important stage of this optimiza-tion, which will be considered next. The solution of the problem along with the results is given thereafter.

A. Problem Formulation

The basic idea in the formulation of the problem is to identify and understand different limiting factors in IDVR operation. In doing so, assumptions are made as follows.

- Only two feeders are taken into consideration.
- Only balanced operation is considered.
- Only undervoltage events are considered.
- In all conditions, the load voltage is allowed to be between 0.9 and 1.1 p.u.

As discussed in Section III-C, there are multiple solutions (operating points) when a DVR is compensating a given under-voltage. Each specific solution corresponds to a specific value of power and injecting voltage. Let us assume that the power required for the compensation of any specific undervoltage is denoted by P_{uv}. This power lies between two limits, i.e.,

$$P_{\mathrm{uv,min}} \leq P_{\mathrm{uv}} \leq P_{\mathrm{uv,max}} \quad (14)$$

where $P_{uv,min}$ is the minimum power required for the compen-sation of a specific undervoltage in a faulty feeder, which corre-sponds to the ME strategy and can be obtained from (5) as

$$P_{\mathrm{uv,min}} = S_{\mathrm{L,rated,f}} \left[\cos(\phi_{\mathrm{f}}) - \frac{VF}{V_{\mathrm{L,f,min}}} \right] \quad (15)$$

where subscript f denotes the parameters corresponding to the faulty feeder. Note that this power can even be zero for shallow undervoltages. On the other hand, $P_{uv,max}$ in (14) is determined by the parameters of the other (presumably healthy) feeder and is the maximum deliverable power from that feeder in the worst case. This can be obtained from (7) as

$$P_{\mathrm{uv,max}} = S_{\mathrm{L,rated,h}} \left[\frac{1}{V_{\mathrm{L,h,min}}} - \cos(\phi_{\mathrm{h}}) \right] \quad (16)$$

where subscript h denotes the parameters corresponding to the healthy feeder. Note that $P_{uv,min}$ and $P_{uv,max}$ are fixed param-eters and can be calculated during the design stage based on the compensating range (given by VF) and other nominal pa-rameters of both feeders. It is also worth noting that in deter-mining (15) and (16), parameters must be substituted so that the worst-case scenario is taken into consideration.

Any value of power in (14) corresponds to a voltage magni-tude which must be injected to the faulty feeder for the required compensation. This voltage, which is a function of P_{uv}, can be obtained from (3) and (6) as

$$V_{\mathrm{inj,f}}(P_{\mathrm{uv}}) = \sqrt{a + bP_{\mathrm{uv}} + c\sqrt{d + eP_{\mathrm{uv}} + fP_{\mathrm{uv}}^2}} \quad (17)$$

where $a,\dots,f$ are fixed parameters and are given in the ap-pendix. With similar reasoning, for any value of power in (14), there is a corresponding voltage magnitude across the DVR in the other (healthy) feeder. This voltage is a function of P_{uv} and V_{Lh}, and can be obtained from (3) and (7) as

$$V_{\mathrm{inj,h}}(P_{\mathrm{uv}}, V_{\mathrm{L,h}}) = \sqrt{1 + V_{\mathrm{L,h}}^2 \left(g - eP_{\mathrm{uv}} + h\sqrt{\frac{1}{V_{\mathrm{L,h}}^2} + m - eP_{\mathrm{uv}} + fP_{\mathrm{uv}}^2} \right)} \quad (18)$$

where $g,\dots,f$ are fixed parameters and are given in the Ap-pendix.

It must be emphasized again that the voltage given by (17) is the voltage across the DVR in the faulty feeder, and the voltage given by (18) is the voltage across the healthy feeder. In an IDVR, any individual DVR must be able to develop adequate voltage during its own fault or the fault in the other feeder. Therefore, the worst case must be taken into consideration

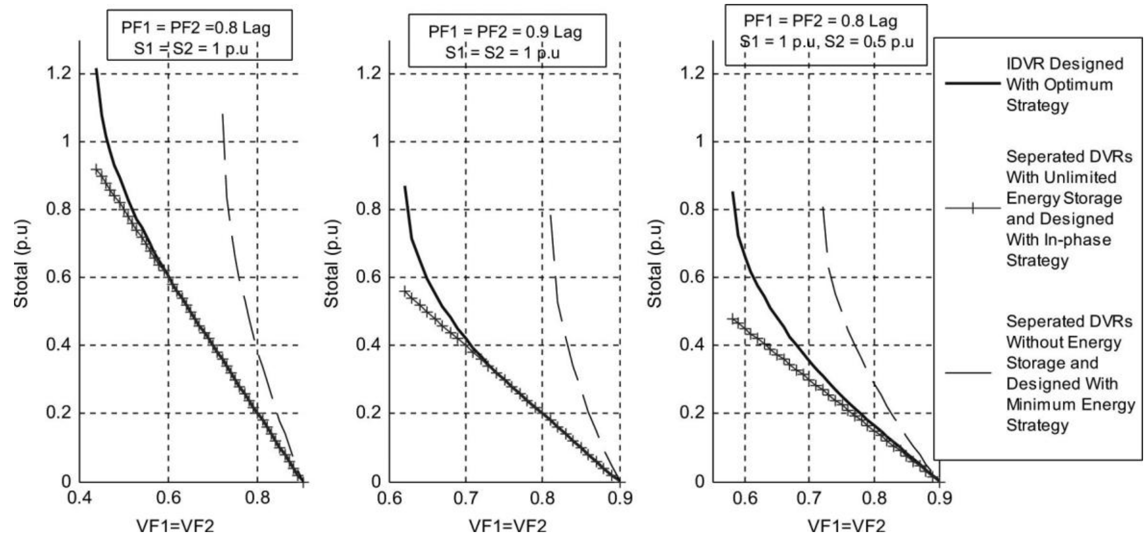

Fig. 6. Total required kVA versus 12 for similar feeders when different strategies are used.

during voltage rating selection in the design stage. In mathematical form

$$V_{\mathrm{DVR,i}} = \mathrm{Max}\left[V_{\mathrm{inj,f,i}}(P_{\mathrm{uv,i}}), V_{\mathrm{inj,h,i}}(P_{\mathrm{uv,j}}, V_{\mathrm{Lh,i}})\right] \quad i = 1,2 \tag{19}$$

where i is the feeder number, $V_{\mathrm{inj,f,i}}$ is the injecting voltage in feeder i when it is facing an undervoltage, and $V_{\mathrm{inj,h,i}}$ is the injecting voltage in feeder i when it is healthy and potentially supplying power to feeder j (faulty feeder). If the voltage rating of any DVR is not to exceed a limit given by $V_{\max}$, it can be included as an additional constraint

$$V_{\mathrm{DVR,i}} \le V_{\mathrm{max,i}} \quad i = 1,2. \tag{20}$$

Now based on the discussion presented in Section III-B, the kVA rating of a DVR in per unit is the product of its voltage rating by the load rated kVA. Therefore, the total kVA rating of an IDVR can be expressed as

$$S_{\mathrm{total}}^{(\mathrm{p.u})} = \sum_{i=1,2} S_{\mathrm{L,rated,i}}{}^{(\mathrm{p.u})} \times V_{\mathrm{DVR,rated,i}}^{(\mathrm{p.u})} \tag{21}$$

where $S_{\mathrm{L,rated,i}}$ is given.

VII. Design Procedure

The step-by-step design procedure of an IDVR with an optimum voltage rating for each DVR can now be presented as follows.

Step 1) For any pair of feeders, the compensation requirements are obtained and expressed in terms of the voltage factor, defined in (1). Note that VF is a design parameter.

Step 2) The parameters of each feeder, including rated kVA, the range of load power factor, and the permissible range of load variation are obtained.

Step 3) $P_{\mathrm{uv,min}}$ and $P_{\mathrm{uv,max}}$, along with coefficients a to m given in (17) and (18), are calculated for each feeder based on Steps 1) and 2).

Step 4) The objective function given by (21) is minimized with constraints for each feeder given by (14) and (17)–(20).

Step 5) The obtained $V_{\mathrm{DVR,rated,i}}$ is the optimized rating for each DVR which minimizes the total kVA of the IDVR structure while fulfilling all compensation requirements.

The optimization problem stated in Step 4) can be solved using different methods. A discussion of these methods, however, is outside the scope of this paper.

VIII. Results

In this section, the approach presented in Section VII is examined with the help of various figures and tables.

Fig. 6 shows the variation of S_{total} versus $VF_1 = VF_2$ when $S_{\mathrm{Lrated1}} = S_{\mathrm{Lrated2}}$ and $PF_1 = PF_2$ (i.e., two iden-tical feeders with the same compensation requirements). S_{total} was obtained based on the procedure described in Section VII. Also shown in this figure are the variation of $S_{\mathrm{total,ME}}$ (corresponding to separate DVRs on the same feeders controlled by minimum energy strategy without energy storage) and $S_{\mathrm{total,IP}}$ (corresponding to separate DVRs on the same feeders controlled by an inphase strategy with unlimited energy storage) versus $VF_1 = VF_2$. Observations can be made from these curves as follows.

1) A minimum energy strategy is not able to compensate deep undervoltages regardless of how large the rating of the DVRs is selected. This is due to an inherent limitation of the ME strategy which fails to provide a solution for deep undervoltages. Even for shallow undervoltages, the total rating of the DVRs is higher under the ME strategy than it is for other strategies.
2) The proposed design strategy provides a solution similar to the IP strategy down to a certain VF. Within this range, the healthy feeder can deliver enough energy to the faulty feeder to enable operation with the IP strategy. However, when the required VF begins to decrease (i.e., a larger compensating range is required), the IP strategy cannot be

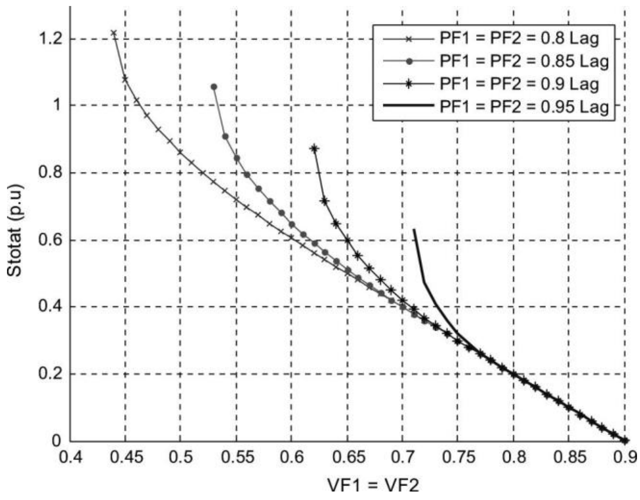

Fig. 7. Variation of the total IDVR rating versus VF for two similar feeders for different power factors.

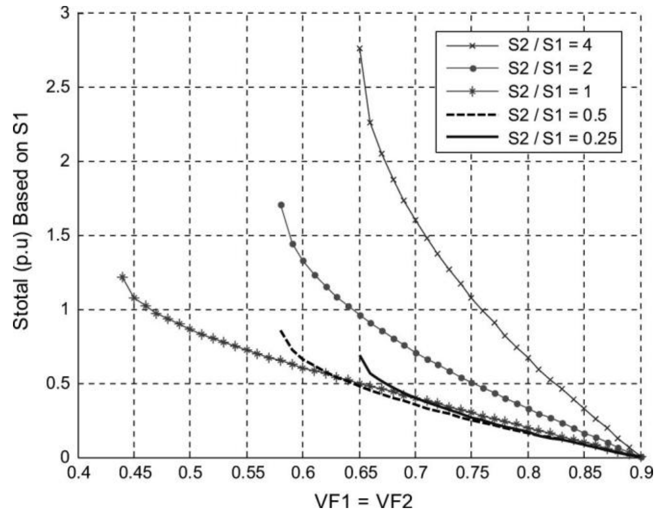

Fig. 8. Variation of the total IDVR rating versus VF for different L,rated,2 L,rated,1 .

employed by IDVR any longer since the supplied energy from the healthy feeder is limited. The proposed strategy is particularly useful in this operating range and provides the minimum rating solution for the whole system. Note that the higher compensating range of separate DVRs with the IP strategy is possible only at the expense of unlimited energy storage devices.

3) Similar to the IP strategy, IDVR fails to compensate deep undervoltages due to the limitation of attainable power from the healthy feeder.

Fig. 7 shows the variation of S_{total} versus VF for two similar feeders with the same compensation requirements (i.e., $S_{Lrated1}=S_{Lrated2}$ and $VF_1=VF_2$). Plots are shown for different $PF_1=PF_2$. When the rated power factor is smaller, the required total rating is also smaller. This figure demonstrates again that the range of IDVR operation is dependent on the nominal power factor of the feeders.

Fig. 8 shows the variation of S_{total} versus $VF_1=VF_2$ for $PF_1=PF_2=$ 0.8 lag and different $S_{Lrated2}/S_{Lrated1}$. Here, S_{total} is normalized with respect to $S_{Lrated1}$. As expected, when the rating of feeder two is larger than that of feeder one, the required total rating increases if the same compensation (same VF) is required. Furthermore, in this case, the compensating range of IDVR is also reduced since the feeder with the lower rating is not able to supply sufficient power for the other feeder.

Tables I–V show the ratings of two DVRs in an IDVR struc-ture for different scenarios when the proposed design strategy has been used. All of the results are in per unit. It is also as-sumed that the rating of each DVR is not to exceed 0.5 p.u. These results demonstrate that IDVR structure can compensate fairly deep undervoltages without any need for an additional energy storage system.

IX. Conclusion

In this paper, we demonstrated that the compensating range of DVRs can be improved by using the IDVR structure (i.e., by connecting the dc bus of several DVRs). A complete steady-state analysis of the IDVR was given, and the impact of active power on the compensating range of DVRs and IDVRs was explained. Various limitations in the operation of IDVR in terms of power exchange between different feeders were addressed. The

TABLE I
DVR RATINGS FOR 1 2 0.8, L2 L1 1.

Prospective VF	$V_{DVR,rated1}$	$V_{DVR,rated2}$	S_{total}
$VF_1 = 0.5$, $VF_2 = 0.5$	0.431	0.431	0.862
$VF_1 = 0.5$, $VF_2 = 0.6$	0.479	0.339	0.818
$VF_1 = 0.6$, $VF_2 = 0.6$	0.302	0.302	0.604

TABLE II
DVR RATINGS FOR 1 0.9, 2 0.8, L2L1 1

Prospective VF	$V_{DVR,rated1}$	$V_{DVR,rated2}$	S_{total}
$VF_1 = 0.55$, $VF_2 = 0.55$	0.417	0.450	0.867
$VF_1 = 0.6$, $VF_2 = 0.55$	0.303	0.476	0.779
$VF_1 = 0.6$, $VF_2 = 0.6$	0.328	0.329	0.657

TABLE III
DVR RATINGS FOR 12 0.8, L1 1, L2 0.5

Prospective VF	$V_{DVR,rated1}$	$V_{DVR,rated2}$	S_{total}
$VF_1 = 0.6$, $VF_2 = 0.4$	0.424	0.500	0.674
$VF_1 = 0.6$, $VF_2 = 0.5$	0.446	0.436	0.664
$VF_1 = 0.6$, $VF_2 = 0.6$	0.446	0.436	0.664

TABLE IV
DVR RATINGS FOR 1 0.9, 2 0.8, L1 1, L2 0.5

Prospective VF	$V_{DVR,rated1}$	$V_{DVR,rated2}$	S_{total}
$VF_1 = 0.7$, $VF_2 = 0.45$	0.254	0.454	0.481
$VF_1 = 0.7$, $VF_2 = 0.5$	0.270	0.404	0.472
$VF_1 = 0.7$, $VF_2 = 0.6$	0.277	0.390	0.472

TABLE V
DVR RATINGS FOR $_1$ 0.8, $_2$ 0.9, $_{L1}$ 1, $_{L2}$ 0.5

Prospective VF	$V_{DVR,rated1}$	$V_{DVR,rated2}$	S_{total}
$VF_1 = 0.65$, $VF_2 = 0.4$	0.376	0.500	0.626
$VF_1 = 0.65$, $VF_2 = 0.5$	0.376	0.400	0.576
$VF_1 = 0.65$, $VF_2 = 0.6$	0.391	0.307	0.545

problem of calculating optimum rating for DVRs in an IDVR structure was formulated based on different design and operating parameters, and a design strategy was proposed to minimize the total rating of the DVRs used in an IDVR.

APPENDIX

For feeder (i): i= 1,2

$$a_i = VF_i^2 - V_{L\,min,i}^2 \cos(2\phi_i)$$
$$b_i = \frac{2V_{L\,min,i}^2}{S_{L,i}} \cos(\phi_i)$$
$$c_i = -2V_{L\,min,i}^2 \sin(\phi_i)$$
$$d_i = \left(\frac{VF_i}{V_{L\,min,i}}\right)^2 - \cos^2(\phi_i)$$
$$e_i = \frac{2\cos(\phi_i)}{S_{L,i}}$$
$$f_i = -\frac{1}{S_{L,i}^2}$$
$$g_i = -\cos(2\phi_i)$$
$$h_i = -2\sin(\phi_i)$$
$$m_i = -\cos^2(\phi_i).$$

REFERENCES

[1] R. C. Dugan and M. F. Mc Granghan, *Electrical Power System Quality*, 2nd ed. New York: Mc Graw-Hill, 2004.

[2] M. H. J. Bollen, *Understanding Power Quality Problems: Voltage Sag and Interruptions*. New York: Wiley, 1999.

[3] A. Ghosh and G. Ledwich, *Power Quality Enhancement Using Custom Power Devices*. Norwell, MA: Kluwer, 2002.

[4] J. G. Nielsen, F. Blaabjerg, and N. Mohan, "Control Strategies for Dy-namic Voltage Restorer Compensating Voltage Sags With Phase Jump," in *Proc. Applied Power Electronics Conf. Expo.*, Anaheim, CA, 2001, vol. 2, pp. 1267–1273.

[5] M. Banaei, S. H. Hosseini, S. Khanmohammadi, and G. B. Ghareh-petian, "Verification of a new control strategy for dynamic voltage re-storer by simulation," *Simul. Model. Practice Theory*, vol. 14, no. 2, pp. 112–125, Feb. 2006.

[6] S. S. Choi, J. D. Li, and D. M. Vilathgamuwa, "A generalized voltage compensation strategy for mitigating the impacts of voltage sags/swells," *IEEE Trans. Power Del.*, vol. 20, no. 3, pp. 2289–2297, Jul. 2005.

[7] D. M. Vilathgamuwa and R. Perera, "Voltage sag compensation with energy optimized dynamic voltage restorer," *IEEE Trans. Power Del.*, vol. 18, no. 3, pp. 928–936, Jul. 2003.

[8] D. M. Vilathgamuwa, H. M. Vijekoon, and S. S. Choi, "A novel tech-nique to compensate voltage sags in multi-line distribution system-The interline dynamic voltage restorer," *IEEE Trans. Power Electron.*, vol. 53, no. 5, pp. 1603–1611, Oct. 2006.

[9] H. M. Vijekoon, D. M. Vilathgamuwa, and S. S. Choi, "Interline dy-namic voltage restorer: an economical way to improve interline power quality," *Proc. Inst. Elect. Eng., Gen., Transm. Distrib.*, vol. 150, no. 5, pp. 513–520, Sep. 2003.

[10] D. M. Vilathgamuwa, H. M. Vijekoon, and S. S. Choi, "Interline dy-namic voltage restorer: A novel and economical approach for multi-line power quality compensation," *IEEE Trans. Ind. Appl.*, vol. 40, no. 6, pp. 1678–1685, Nov./Dec. 2004.

[11] M. R. Banaei, S. H. Hosseini, and G. B. Gharehpetian, "Inter-line dy-namic voltage restorer control using a novel optimum energy consump-tion strategy," *Simulation Modeling Practice and Theory*, vol. 14, no. 7, pp. 989–999, Oct. 2006.

