International Journal of Science Engineering and Advance Technology

A new interline DVR with displacement factor improvement using fuzzy logic controller for voltage unbalance condition

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***Abstract*— A new interline dvr with displacement factor improvement using fuzzy logic controller for voltage sags and swells condition have been designed. Generally interline dynamic voltage restorer (IDVR) is employed in distribution systems to mitigates voltage sag and swell problems. An IDVR consists of several dynamic voltage restorers (DVRs) sharing a common dc link connecting independent feeders. One of the DVRs compensates for the local voltage sag in its feeder; the other DVRs replenish the common dc-link voltage. For normal voltage levels, the DVRs should be bypassed or un-operated. Generally instead of bypassing the DVRs, this paper proposes a new operating technique to improve the displacement factor (DF) of one of the involved feeders. DF improvement can be achieved via active and reactive power exchange between two different feeders. The fuzzy logic controller improves the performance and reduces the total harmonic distortion. Simulation results can be shown the performance of proposed converter using MATLAB software.**

***Index Terms*— Displacement factor improvement, (IDVR), IVDFC, *PQ* sharing mode, FLC**

I. INTRODUCTION

Several practical techniques are commonly used to improve DF. DF improvement employing capacitor banks with size and location optimization has been introduced in [2]. The optimal location and size of the capacitor bank to be placed in radial distribution feeders to improve their voltage profile and to reduce the total energy loss are presented in [3]. Different techniques are employed in [4] to minimize the power loss in distribution networks. In [5], the feeder reconfiguration concept in distribution systems is introduced to reduce system loss. In [6], a combined system for harmonic suppression and reactive power compensation is proposed not only to improve the DF but also the power factor.

A Statcom can be used as a viable alternative for DF improvement. Suitable adjustment of the phase and magnitude of the STATCOM output voltages enable effective control of active as well as reactive power exchanges between the STATCOM and the distribution system. Such a configuration allows the device to absorb or generate controllable active and reactive powers. A STATCOM has various features, including fast response, low-space requirement, and good stability margins. Recently, it is rapidly replacing the conventional naturally commutated reactive power controllers and static VAR compensators. The reactive power supplied by the STATCOM for DF improvement is capacitive in nature. Intuitively, the higher the STATCOM's reactive power, the higher the dc-link voltage of the STATCOM. The DVR is one of the most common and effective solutions for protecting critical loads against voltage sag.

The DVR is a power electronic device used to inject three-phase voltages in series and in synchronism with the distribution feeder voltages in order to compensate for voltage sags. Moreover, it can be effectively used to enhance the fault ride through capability in wind applications. Detection time is an important factor in the voltage restoration process. Fast detection algorithms and effective control schemes for a DVR are proposed in [16] and [17], respectively. Space vector modulation (SVM) is the recommended modulation scheme in a DVR due to its simple digital realization and improved dc-link utilization.

In distribution systems, load voltage restoration can be achieved by injecting active and/or reactive power into the distribution feeder. Active power capability of the DVR is governed by the capacity of the energy storage element and the employed compensation technique. Several control techniques have been proposed for voltage sag compensation, such as pre-sag, in-phase, and minimal energy control approaches.

If the required power for voltage restoration is obtained from the neighboring feeder(s), the compensating device is technically called interline dynamic voltage restorer (IDVR). The basic concept behind the IDVR is derived from the interline power flow controller (IPFC) proposed by Gyugyi in 1999 to exchange power between parallel transmission lines. The two converters of the IPFC shown in Fig. 1 are used to control the transmitted power in each line ($P1$ and $P2$) and active power transfer between lines ($P12$). With respect to the line current, the injected voltage has two components. The quadrature component provides reactive power compensation for the line, while the in-phase component absorbs or generates the required active power.

The main differences between an IPFC, IDVR, and the proposed system are summarized in Table I. In this table, the IPFC, which is used in transmission applications, is compared with an IDVR and IVDFC, which are considered for distribution systems. It should be noted that the IPFC was the inspiration for proposing the IDVR for distribution networks. The IDVR can be used to mitigate voltage sag, or swell, at critical loads in distribution systems. It consists of several back-to-back voltage source converters with common dc link connecting independent feeders as shown in Fig. 2.

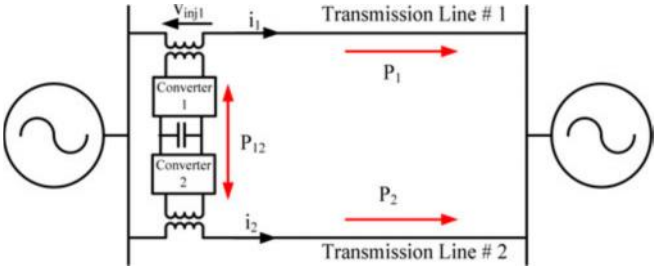


Fig. 1 Single line diagram of an IPFC in transmission system

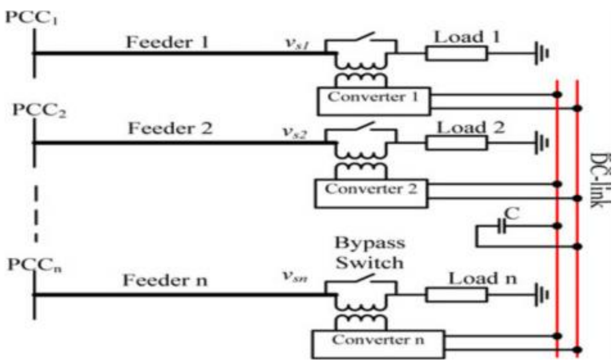


Fig. 2 Single line diagram of multiline IDVR in the distribution system

TABLE I
SALIENT FEATURES OF THE IPFC, IDVR, AND IVDFC

	IPFC	IDVR	IVDFC (Proposed concept)
Function	It is used in transmission systems to control the power flow of parallel transmission lines.	It is used in distribution systems for voltage sag/swell restoration.	It is used in distribution systems for voltage sag/swell restoration and improvement of displacement power factor during normal conditions.
Operation	Employed in normal operation	Employed in abnormal conditions	It can be employed in normal as well as abnormal conditions
In-phase voltage injection	Active power control	When the feeder is switched to power control mode, the in-phase voltage component represents the active power to be pumped/ absorbed by that feeder to/from the DC-link (Active power control).	When the feeder is switched to power control mode or DF improvement mode, the in-phase voltage component represents the active power to be pumped/ absorbed by that feeder to/from the DC-link (Active power control).
Quadrature voltage injection	Line reactive impedance control	When the feeder is switched to power control mode, the quadrature voltage component is used to keep the load voltage magnitude of that feeder constant (load voltage control).	When the feeder is switched to power control mode or DF improvement mode, the quadrature voltage component is used to keep the load voltage magnitude of that feeder constant (load voltage control).

Each converter can be operated in either power control (PC) or voltage control (VC) modes. If one of the feeders is subjected to voltage sag, its converter will operate in VC mode and the required power for voltage restoration will be absorbed from the dc link. In this state, the other converters connected to the healthy feeders should be switched to PC mode to replenish the dc-link voltage; a power-sharing scheme to determine the reference power of each healthy feeder is presented in [24].

The injected voltage in a healthy feeder during PC mode should have two components. The first component is in-phase with line current, which absorbs active power from the supply and provides it to the dc link to support its voltage. The second component is in quadrature with the line current and is used to avoid load voltage magnitude perturbations after voltage injection. In previous work [25], the injected voltage in a healthy feeder is emulated by using the virtual impedance. During normal operating conditions, the DVRs are typically bypassed via bypass switches, or they can be alternatively used for load sharing purposes as presented in [26].

Instead of bypassing the IDVR in normal operation, this paper proposes a new operational mode, namely *PQ* sharing mode, to improve the DF of one of the involved feeders by sharing active and reactive power among different system feeders through the buffering stage (the common dc link). To apply this concept, several constraints are observed throughout the paper. A new inter-line dvr with displacement factor improvement using fuzzy logic controller for voltage sags and swells condition have been designed. The proposed interline dynamic voltage restoring and DF controlling device (IVDFC) is supported using simulation results. The fuzzy logic controller improves the performance and reduces the total harmonic distortion. Simulation results can be shown the performance of proposed converter using MATLAB software.

II. IVDFC SYSTEM IN NORMAL OPERATION

Similar to the IDVR, the two-line IVDFC simply consists of two voltage source converters connected back-to-back with a common dc link, as shown in Fig. 3. For normal voltage levels, achieving active power exchange *P*ex between the feeders requires controlled voltage injection in each feeder by the corresponding converter. This injected voltage should not perturb the load voltage magnitude of both feeders; therefore, both converters are operating under PC mode.

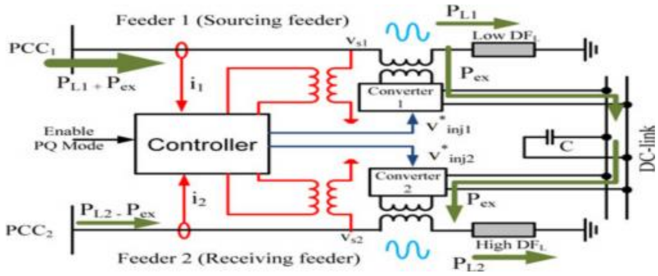


Fig. 3 Principle of IVDFC system operation during normal conditions (*PQ* sharing mode)

A. Sourcing Feeder

The converter in the sourcing feeder is responsible for feeding energy into the dc link via injecting a controlled voltage through the series coupled transformer allowing for power exchange. In this paper, in order to emulate the effect of voltage injection on the feeder DF, the injected voltage is emulated using a voltage drop across series virtual impedance. The resistive component of this virtual impedance absorbs active power (*P*ex) from the source, while the function of the capacitive reactance component is to maintain a constant load voltage magnitude. After voltage injection, the supply's active power increases while it's reactive power decreases due to the virtual injected capacitive reactance, hence, the sourcing feeder DF eventually increases. Assuming a three-phase balanced load is connected to the feeder; the per-phase equivalent circuit of the feeder with series virtual impedance injection. For a given transferred active power *P*ex (through dc link), the load power is given by

$$P_{L1} = 3I_1V_1\mathrm{DF}_{L1} = 3I_1V_1\cos\varphi_1. \qquad (1)$$

As indicated in the phasor diagram, the supplied power is given by

$$P_{s1} = P_{L1} + P_{ex} = 3I_1V_1\cos(\varphi_1 - \beta_1) \qquad (2)$$

Where P_{ex} is the power absorbed from the source and pumped into the dc link. From (2), the angle β_1 can be obtained as follows:

$$\beta_1 = \varphi_1 \quad \cos^{-1}\left(\frac{P_{L1} + P_{ex}}{3I_1V_1}\right) \qquad (3)$$

The maximum allowable P_{ex} corresponds to unity input DF. For a given load DF, the maximum P_{ex} is given by

$$P_{exmax} = 3I_1V_1\,(1 - \mathrm{DF}_{L1})\,. \qquad (4)$$

The virtual injected resistance r_1, which represents absorbed active power from sourcing feeder, is given by

$$r_1 = \frac{P_{ex}}{3I_1^2}. \qquad (5)$$

From the phasor diagram, the virtual injected capacitive reactance x_1 is given by

$$x_1 = r_1\tan\left(-\varphi_1 + \frac{\pi + \beta_1}{2}\right). \qquad (6)$$

For any amount of desired exchanged active power (P_{ex}) and load-side parameters (I_1, V_1 , and DF_{L1}), the voltage source converter at the sourcing feeder injects this power to the dc link without affecting load voltage magnitude by supplying a voltage of magnitude $2V_1 \sin(\beta_1/2)$. This voltage's phase angle lags the supply voltage phase angle by $(\pi - \beta_1)/2$.

B. Receiving Feeder

The converter in the receiving feeder is responsible for absorbing the transmitted power from the sourcing feeder via voltage injection; hence, the power controller has a power command of $-P_{ex}$. The injected voltage in this case is equivalent to injecting a virtual negative resistance $-r_2$ in series with an inductive reactance x_2, as shown in Fig. 4(a). From the equivalent circuit and the phasor diagram shown in Fig. 4(a) and (b), the angle β_2 is given by

$$\beta_2 = -\varphi_2 + \cos^{-1}\left(\frac{P_{L2} \quad P_{ex}}{3I_2V_2}\right). \qquad (7)$$

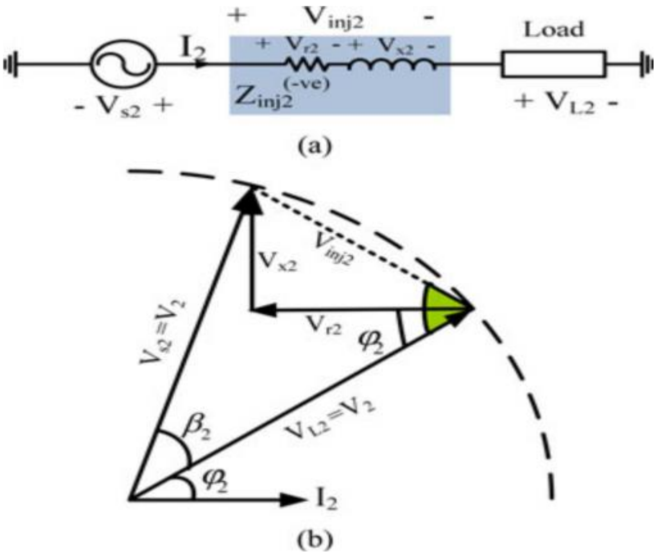


Fig. 4 receiving feeder: (a) per-phase circuit with virtual impedance injection and (b) corresponding phasor diagram

To absorb this amount of transferred active power without affecting the load voltage magnitude, the injected voltage in the receiving feeder should have a magnitude of $2V_2 \sin(\beta_2/2)$, and its phase angle leads the supply voltage phase angle by $(\pi - \beta_2)/2$. It is worth noting that the supply's active power decreases while its reactive power increases due to the virtual injected inductive reactance, i.e., the receiving feeder DF eventually decreases.

C. PQ Sharing Mode for DF Improvement during Normal Operation

The operating mode presented in this subsection will be illustrated using a two-line IVDFC, where feeder 1 is feeding a load with a low lagging DF DF_{L1}, while feeder 2 is feeding a load with a high lagging DF DF_{L2}. Since feeder 1 DF is lower than feeder 2 DF, it will be the sourcing feeder, while feeder 2 will be the receiving feeder. When applying the proposed *PQ* sharing mode, the sourcing feeder DF will be improved, while the receiving feeder DF decreases. As a general constraint, the new receiving feeder DF should be greater than a certain acceptable limit DF_a imposed by the utility company to avoid additional fees.

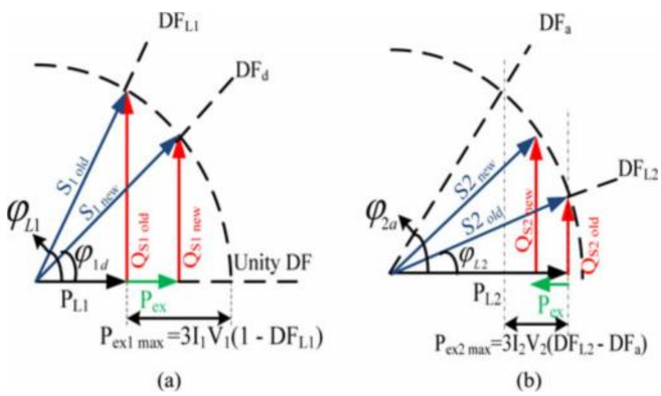


Fig. 5 Effect of *PQ* sharing mode on (a) feeder1 and (b) feeder 2

A typical limit of 0.95 is usually employed in distribution networks. Fig. 5 is used to explain the proposed sharing mode. With *PQ* sharing mode disabled, the DF at the PCC for each feeder is equal its load DF. If a certain amount of active power P_{ex} is transferred from feeder 1 to feeder 2, such that its DF reaches a certain desired value DF_d , as shown in Fig. 7(a), the DF of feeder 2 will be reduced, as depicted by Fig. 7(b). The sourcing feeder DF can be improved to DF_d , if and only if, the needed active power P_{ex} to achieve this condition is less than the needed power to decrease the receiving feeder's DF to the accepted DF limit DF_a . If this condition is not satisfied, the DF of the sourcing feeder will be improved, but it will not reach the desired level, and the receiving feeder DF will be limited to its acceptable level. Hence, the reference active power (P_{ex}) during *PQ* sharing mode is given by

$$P_{ex} = \min\left[3I_1V_1\,(\mathrm{DF_d} - \mathrm{DF}_{L1})\,,\,3I_2V_2\,(\mathrm{DF}_{L2} - \mathrm{DF}_a)\right]. \qquad (8)$$

This rule is defined as the minimum of two terms; the first term gives the needed increment in sourcing feeder supplied active power to improve its DF to a desired level DF*d* , while the second term gives the needed decrement in receiving feeder supplied active power to reduce its DF to the accepted value DFa. If the receiving feeder's active power is higher than that of the sourcing feeder, a slight variation in its DF introduces a noticeable improvement in sourcing feeder DF. Generally, the DF improvement will reduce the magnitude of currents in the up-stream branches of the grid, i.e., decrease grid losses.

It has to be noted that, in the proposed method, the DF is improved by reducing the difference between supply voltage and current phase angles assuming a constant volt-ampere condition. As a result, the employment of *PQ* sharing mode will not affect the feeder losses since the current magnitudes are kept constant, but converters losses will be added to the feeder losses to represent the total losses of the system.

III. SYSTEM CONTROLLER

Fig. 6 shows the proposed controller for a two-line IVDFC, which is able to manage the power transfer through the dc-link in normal as well as abnormal operating conditions. As a general controller, voltage sag/swell and DF improvement problems are merged into one control circuit. Referring to Fig. 6, each converter may be switched to one of four possible modes.

The PCC voltages are continuously monitored by a logic unit that is responsible for choosing the appropriate mode of operation for each converter based on the voltage levels. The following section will show how different modes of operation are handled individually in the proposed controller. A set of scenarios can be envisioned for the system. The main cases are summarized in Table II and in the following subsections. For all other cases, the converters will be switched to the off position.

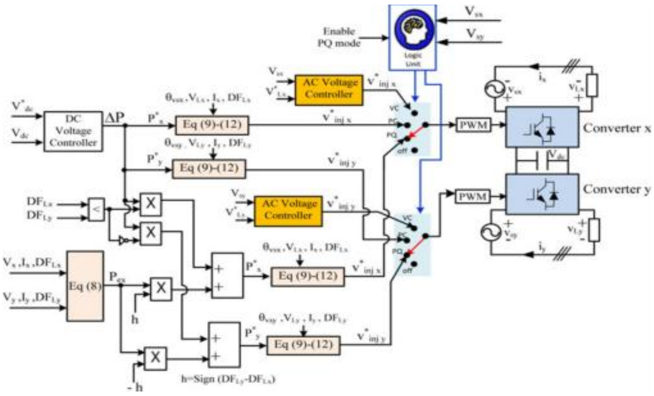


Fig. 6 Proposed controller

A. Normal–Normal (PQ Sharing Mode is disabled)

In this case, the logic unit selects the off positions for both converters.

B. Normal–Normal (PQ Sharing Mode is enabled)

In this case, the logic unit selects the *PQ* positions for both converters after verifying all constraints that accompany this mode. Based on the DFs of the loads connected to the involved feeders (DFLx and DFLy), the direction of active power flow will be defined. The feeder with a lower load DF will be the sourcing feeder with a positive active power reference, and the other feeder will be the receiving feeder with a negative active power reference. In Fig. 6, the sign of the variable *h*, which represents the difference between the two DFs, is used to determine the sign of the different reference powers. To maintain a constant dc-link voltage during the *PQ* sharing mode, the output of the dc link voltage controller, Δ*P* is added to the reference active power of the sourcing feeder.

To achieve that, the two DFs (DFLx, and DFLy) are compared to decide the sourcing and receiving feeders. The comparator output is used to add Δ*P* to the reference active power of the sourcing feeder only as shown in Fig. 6.

TABLE II
PROPOSED CONTROLLER COMBINATIONS

Logic unit decision / Cases	Converter *x*				Converter *y*			
	VC	PC	PQ	off	VC	PC	PQ	off
v_{sx} is normal and sag/swell at v_{sy}	0	1	0	0	1	0	0	0
v_{sy} is normal and sag/swell at v_{sx}	1	0	0	0	0	1	0	0
Normal condition, *PQ* is enabled	0	0	1	0	0	0	1	0
Normal condition, *PQ* is disabled	0	0	0	1	0	0	0	1

For example, if DFLx is less than DFLy, the comparator output will be high; therefore, Δ*P* will be added to *P*ex. The voltage reference of each converter is then determined based on the corresponding active power references (P^*_x and P^*_y) as given by (9)–(12), where $i = x$ or y

$$\varphi_i = \cos^{-1}\left(\mathrm{DF}_{Li}\right) \tag{9}$$

$$\beta_i = \left(\varphi_i - \cos^{-1}\left(\frac{3I_iV_i\mathrm{DF}_{Li} + P_i^*}{3I_iV_i}\right)\right) \times \mathrm{sign}\left(P_i^*\right) \tag{10}$$

$$\left|v^*_{\mathrm{inj}i}\right| = 2V_i \sin\left(\frac{\beta_i}{2}\right) \tag{11}$$

$$\angle v^*_{\mathrm{inj}i} = \theta_{vsi} - \left(\mathrm{sign}\left(P_i^*\right)\left(\frac{\pi - \beta_i}{2}\right)\right). \tag{12}$$

C. Normal–Voltage Sag

If one feeder exhibits voltage sag, the logic unit has to switch its series converter to VC position to regulate the load voltage, and the required power for restoration will be absorbed from the dc link. The converter of the healthy feeder will be switched to its PC position to replenish the dc-link voltage. The needed power to restore the dc link voltage will be the output of the dc voltage controller. This power is used to estimate the corresponding converter reference voltage.

D. Normal–Voltage Swell

If one feeder exhibits voltage swell, the logic unit switches its series converter to the VC position to regulate the load voltage. Additional power is then fed to the dc link. The converter of the healthy feeder will be switched to its PC position, to avoid increasing the dc-link voltage. The amount of power, which should be absorbed by the healthy feeder, will be the output of the dc voltage controller.

TABLE II
PROPOSED CONTROLLER RULES

ch.E\E	NB	NS	ZE	PS	PB
NB	PB	PB	PS	NB	NB
NS	PS	PS	ZE	NS	NS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	ZE	PS	PS
PB	NB	NB	NS	PB	PB

IV. SIMULATION RESULTS

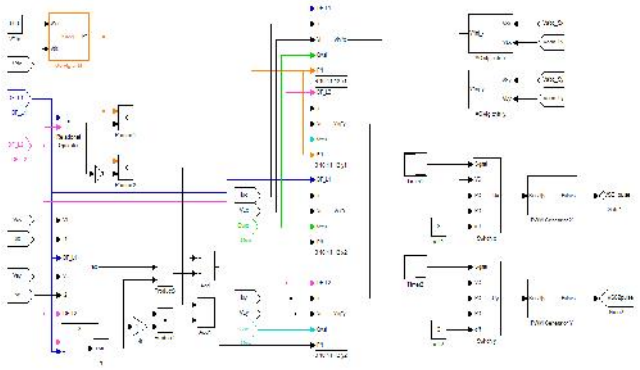


Fig. 7 Proposed fuzzy logic controller

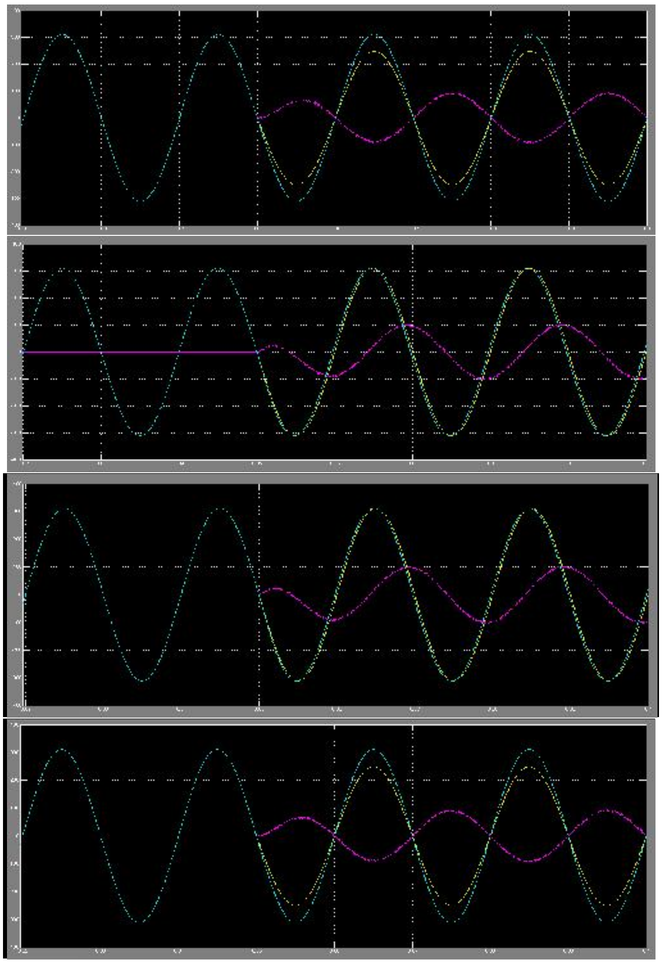
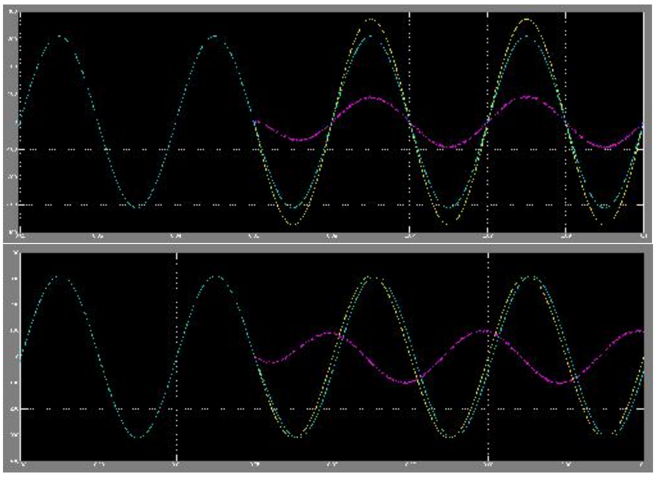


Fig. 8 Per-phase simulation results for voltage sag case using fuzzy logic controller: (a) and (b) at feeder 1 and (c) and (d) at feeder 2



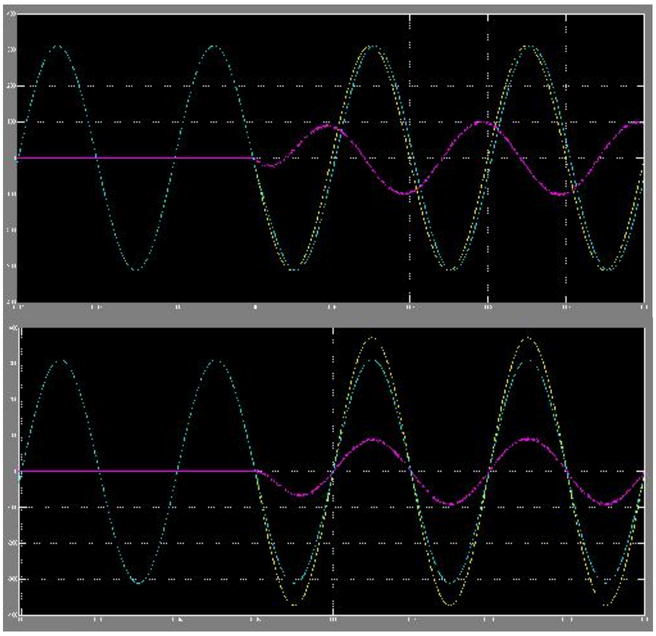


Fig. 15 Per-phase experimental results and corresponding simulation results for voltage swell case at: (a) and (b) feeder 1 and (c) and (d) at feeder 2

V. CONCLUSION

A new interline DVR with displacement factor improvement using fuzzy logic controller for voltage sags and swells condition have been designed. Generally interline dynamic voltage restorer (IDVR) is employed in distribution systems to mitigates voltage sag and swell problems. In this mode, the DF of one of the feeders is improved via active and reactive power exchange between feeders through the common dc link. The same system can also be used under abnormal conditions for voltage sag/swell mitigation. Under *PQ* sharing mode, the injected voltage in any feeder does not affect its load voltage/current magnitude, however, it affects the DFs of both sourcing and receiving feeders.

The DF of the sourcing feeder increases while the DF of the receiving feeder decreases. The fuzzy logic controller improves the performance and reduces the total harmonic distortion. Simulation results can be shown the performance of proposed converter. The proposed mode is highly beneficial if the active power rating of the receiving feeder is higher than the sourcing feeder. In this case, the DF of the sourcing feeder will have a notable improvement with only a slight variation in DF of the receiving feeder.

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