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Elliptical Restoration Based Single-Phase Dynamic Voltage Restorer for Source Power Factor Correction

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Abstract— The dynamic voltage restorer (DVR) can compensate the load voltage by injecting a series voltage in the distribution line. However, the conventional compensating methods only focus on the load voltage and the DVR itself. The power factor correction (PFC) at the source side has seldom been considered. This paper aims at correcting the power factor (PF) at the source side using an elliptical restoration based voltage compensating method via the single-phase dynamic voltage restorer (DVR). Specifically, the virtual impedance is used to describe the active and reactive components of the DVR injected voltage. The active and reactive voltage components and a centrifugal angle are utilized to formulate an elliptical compensation trajectory. When the centrifugal angle changes from 0° to 90° , the injected voltage will follow the elliptical compensation trajectory. Thus a smooth changeover of the DVR injected voltage can be achieved during the load switching. The source voltage will be in phase with the load current with the proper control of the DVR injected voltage. It means that the PFC at the source side can be achieved using the proposed compensating method. A laboratorial prototype of the single-phase DVR is utilized to validate the proposed control method. The experimental results verify that a unity PF can be maintained at the source side with seamless state transition.

Index Terms—Dynamic voltage restorer (DVR), elliptical restoration, voltage sag compensation, power factor correction (PFC).

I. INTRODUCTION

AS well-known, the critical loads (e.g., chip manufacturing factory, programmable logic controllers, com-

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Fig. 1. Topology of the single-phase DVR system.

puter numerical control equipment, etc.) integrated in the power system are sensitive to the power quality of the supply voltage [1]. The voltage fluctuation may result in the shutdown and damage of the critical loads [2, 3]. Hence, maintaining the load side voltage at a sinusoidal waveform is essential for the safe and efficient operation of the critical loads [4].

The Dynamic Voltage Restorer (DVR) is the most comprehensive and cost-effective device to solve the voltage power quality problems [5, 6]. The basic topology of the single-phase DVR is illustrated in Fig. 1. A typical DVR consists of a voltage source inverter (VSI) to achieve DC/AC conversion, a DC voltage source to supply the DC link of the VSI, a filter to suppress the switching harmonics of the VSI, and a series transformer to obtain the series voltage injection at the distribution line. The basic principle of the DVR is to inject a voltage of specific phase angle and magnitude in series with the distribution line, so that the load voltage can be maintained at the rated sinusoidal waveform [5, 6]. In the literatures, in addition to its basic function, the DVR can provide other benefits. For example, in the pre-sag operation [7-9], the DVR can restore the exact amplitude and phase of the load voltage when the sag and phase jump happens in the source voltage. The magnitude of the injected voltage of the pre-sag compensation method is higher than the required value of the in-phase method. Thus, the pre-sag compensation cannot guarantee a minimized injected voltage. In the in-phase method [10-14], the DVR can inject the minimum amplitude of the compensation voltage. The reason is that the injected voltage is always maintained to be in-phase with the source voltage. However, if a phase jump happens in the source voltage, it will result in a corresponding phase jump in the load voltage. It means that the phase jump in the source voltage cannot be handled by utilizing the in-phase

method. In the self-supported mode [15-20], the DVR does not require external energy storages by utilizing the capacitor connected at the DC link of the VSI. However, the energy stored in the capacitor is limited. In the energy optimized strategy [21-25], the energy handled by the DVR can be optimized. The energy optimized strategy maintains a balanced load voltage in the case of unbalanced large voltage sag with a reduced active power injection. But the phase jump is not considered in the energy optimized strategy. From the works in [5-25], it is noted that the researchers focus on the load side voltage and the DVR itself. The power factor correction (PFC) at the source side has seldom been considered in the control method of the DVR.

The power factor (PF) plays a crucial role in the power transmission and distribution systems [4]. The advantages of correcting the PF [26, 27] at the source side can be summarized as follows:

1) Reduce Utility Charges

The electric utility companies generally charge for peak power demand based on the metered apparent power. In the case of a low PF, the metered apparent power is much higher than the active power [26, 27]. Thus, the utility has to increase the power generation to supply the higher apparent power demand. The electric utility companies usually impose a penalty on the customer of a low PF. Therefore, by improving the PF, the power demand charge, as well as the penalty charge, will be reduced.

2) Increase System Capacity

For the same amount of metered apparent power, more active power can be delivered in the situation of a higher PF [26]. Thus, more loads can be supplied when the PF correction devices are installed without upgrading the distribution network.

3) Reduce System Losses

To transfer a certain amount of electrical power, the current magnitude in the transmission line is higher under a lower PF. The transmission losses are increased proportional to the square of the current magnitude [26, 27].

In order to achieve all the aforementioned advantages, we attempt to improve the controller of DVR to provide PFC at the source side. When a resistive load is connected in the system, the PF of the load is unity. The load voltage is in phase with the load current. The PFC is not needed at the source side. When the reactive load is connected to the system, the PF of the load is not unity. In order to achieve the PFC at the source, the load current should be maintained in phase with the source voltage. If the load current is considered as the

reference, a phase shift occurs in the load voltage during the change of load. Thus, the DVR should provide the corresponding phase shift in the load voltage to ensure that the load current is in phase with the source voltage. If the phase shift is not well managed, it will cause a sudden phase jump in the load voltage. The DVR should have the capability of restoring the nominal voltage amplitude and handling the phase jump in the load voltage.

In [28], the virtual impedance concept is proposed to deal with the DVR voltage injection. In the control method, the virtual impedance is utilized to mimic the compensating behaviors of the restorer. The voltage drop on the virtual impedance and the power handled by this impedance can be regulated by controlling the value of this impedance. The authors in [29] use the virtual impedance to describe the active and reactive components of the DVR injected voltage. The two components and a centrifugal angle are utilized to formulate an elliptical compensation trajectory to deal with the phase jump in the source voltage.

In this paper, the DVR is designed to restore the nominal load voltage and realize the PFC at the source. The elliptical restoration method is applied to handle the transition state during the PFC process. Specifically, the DVR injected voltage will follow the formulated elliptical compensation trajectory. Thus, a smooth changeover of the compensation can be obtained. The phase jump in the load voltage can be avoided.

The rest of the paper is arranged as follows. Section II introduces the concept of the PFC with the elliptical restoration. Section III describes the controller design of the DVR. Section IV shows the simulation results. The experimental results are presented in Section V. Section VI concludes this paper.

Fig. 2. Virtual impedance of DVR.

II. CONCEPT OF PFC WITH ELLIPTICAL RESTORATION

A. Basic Elliptical Restoration Concept

Different from the conventional compensating strategy in [5-25], another compensating principle is proposed such that the DVR is regulated to act as virtual impedance [29]. The equivalent circuit diagram is presented in Fig. 2.

Fig. 3. Phasor diagram of the elliptical restoration.

It is noted that the DVR injected voltage can be obtained as

$$\vec{V}_{DVR} = \vec{I}_L \cdot Z \quad (1)$$

$$Z = R + jX \quad (2)$$

where $\vec{I}_L$ is the load current; Z is the virtual impedance; R is the virtual resistance; and X is the virtual reactance. By adjusting the virtual impedance, the load voltage can be compensated as

$$\vec{V}_L = \vec{V}_S + \vec{V}_{DVR} \quad (3a)$$

$$\vec{V}_L = \vec{V}_S + \vec{I}_L \cdot Z \quad (3b)$$

where $\vec{V}_S$ is the source voltage. Substituting (2) into (1), $\vec{V}_{DVR}$ can be given by

$$\vec{V}_{DVR} = \vec{I}_L \cdot (R + jX) = \vec{I}_L \cdot R + \vec{I}_L \cdot jX \quad (4)$$

With the assumption as follows:

$$\vec{V}_{mi} = \vec{I}_L \cdot R \quad (5a)$$

$$\vec{V}_{ma} = -j \cdot \vec{I}_L \cdot X \quad (5b)$$

Equation (4) can be rewritten as

$$\vec{V}_{DVR} = \vec{V}_{mi} + \vec{V}_{ma} \quad (6)$$

From (6), it can be seen that the DVR injected voltage $\vec{V}_{DVR}$ consists of two components, i.e., $\vec{V}_{mi}$ and $\vec{V}_{ma}$. As illustrated in Fig. 3, $\vec{V}_{mi}$ is in phase with the load current $\vec{I}_L$, which is utilized to describe the active power handled by the DVR. $\vec{V}_{ma}$ is perpendicular to $\vec{I}_L$, which is utilized to describe the reactive power handled by the DVR.

B. Schematic Formulation of Voltage Ellipse Parameters

In Fig. 3, $\vec{I}_L$ is chosen as the 0° phase angle reference. The vector AB represents the load voltage $\vec{V}_L$, which has a PF angle shift (φ) with respect to $\vec{I}_L$. The vector AC is the source voltage $\vec{V}_s$, which has a phase angle shift (δ) with respect to $\vec{V}_L$. Vector CB represents the DVR injection voltage $\vec{V}_{DVR}$, which satisfies the relationship described in (3a). The two voltage components of $\vec{V}_{DVR}$, i.e., $\vec{V}_{mi}$ and $\vec{V}_{ma}$, are also illustrated in the phasor diagram.

In order to introduce the elliptical restoration, two auxiliary lines (l_1 and l_2) are drawn in Fig. 3. l_1 is parallel to $\vec{V}_{mi}$ and goes through point B . l_2 is parallel to $\vec{V}_{ma}$ via point C . The two lines l_1 and l_2 cross each other at point O . Then two circles with radius V_{mi} and V_{ma} can be drawn, respectively, centered at point O . They are denoted by two dashed blue circles in Fig. 3. Based on the concentric-circle method, the two concentric circles can be used to draw an ellipse whose semi major axis and semi minor axis are V_{ma} and V_{mi} , respectively. The generated ellipse is denoted by the solid green ellipse in Fig. 3. It is observed that the line segment CB is a chord in the ellipse. It means that by calculating the length of the chord CB , the magnitude of the DVR injected voltage can be obtained.

The generated ellipse is presented in the xy coordinates as illustrated in Fig. 4. The three parameters of the ellipse are semi major axis V_{ma} , semi minor axis V_{mi} , and centrifugal angle ϕ . Considering one point on the elliptical trajectory, e.g., point i , the coordinates of the point i can be obtained in (7a) and (7b) according to the concentric-circle method:

$$x_i = V_{mi} \cdot \sin \phi \quad (7a)$$

$$y_i = -V_{ma} \cdot \cos \phi \quad (7b)$$

C. Mathematical Formulation of the Elliptical Restoration

Firstly, the source voltage ratio will be calculated as

$$k = V_s / V_L \quad (8)$$

where V_s is the measured root mean square (RMS) value of the source voltage, and V_L is the nominal load voltage.

Fig. 4. Graphical representation of the voltage ellipse parameters.

The PF angle φ can be obtained by utilizing two phase-locked loop (PLL) controllers [29]. After giving the instantaneous load voltage phase angle θ_{VL} and the load current phase angle θ_{IL} via the PLL controllers, φ can be computed as

$$\varphi = \theta_{VL} - \theta_{IL} \quad (9)$$

The load active power can be calculated as

$$P_L = V_L \cdot I_L \cdot \cos \varphi \quad (10)$$

The source active power can be obtained as

$$P_S = V_S \cdot I_L \cdot \cos(\varphi - \delta) \quad (11)$$

As the power losses during the operation are negligible, the active power handled by the DVR can be derived as

$$P_{DVR} = P_L - P_S \quad (12)$$

Thus, using (8)-(12), the virtual resistance can be computed as follows:

$$R = P_{DVR} / I_L^2 = [V_L \cdot \cos \varphi - V_S \cdot \cos(\varphi - \delta)] / I_L = V_L / I_L \cdot [\cos \varphi - k \cdot \cos(\varphi - \delta)] \quad (13)$$

The load active power can also be expressed as

$$P_L = I_L^2 \cdot R_L \quad (14)$$

where R_L is the equivalent load resistance. From (10) and (14), it can be derived as

$$R_L = V_L \cdot \cos \varphi / I_L \quad (15)$$

When the load condition remains unchanged, φ and R_L will not change. R_L can be calculated by the RMS values of the measured transition load voltage and current (V_L^t and I_L^t) as

$$R_L = V_L^t \cdot \cos \varphi / I_L^t \quad (16)$$

Therefore, (13) can be rewritten as

$$R = R_L \cdot [1 - k \cdot \cos(\varphi - \delta) / \cos \varphi] \quad (17)$$

Using (5a) and (15), the active component of the injected voltage can be denoted as

$$V_{mi} = R \cdot I_L = R \cdot V_L \cdot \cos \varphi / R_L \quad (18)$$

Based on the geometrical relationship in Fig. 3, using the cosine formula, the magnitude of the injected voltage can be expressed as

$$V_{DVR} = \sqrt{V_S^2 + V_L^2 - 2V_S \cdot V_L \cdot \cos \delta} = V_L \cdot \sqrt{1 + k^2 - 2k \cdot \cos \delta} \quad (19)$$

From (1), the modulus of the virtual impedance is given by

$$|Z| = V_{DVR} / I_L = (R_L / \cos \varphi) \cdot \sqrt{1 + k^2 - 2k \cdot \cos \delta} \quad (20)$$

From (2), (17), and (20), the virtual reactance is derived as

$$X = \sqrt{|Z|^2 - R^2} \quad (21)$$

The reactive component of the injected voltage can be calculated as

$$V_{ma} = X \cdot I_L = X \cdot V_L \cdot \cos \varphi / R_L \quad (22)$$

In Fig. 3, the operating point D will start at point C , go along the arc CB of the ellipse during the transition state of the DVR compensation, and terminate at point B . The corresponding chord CD starts at zero and terminates at chord CB , which is the final state of the DVR compensation. Therefore, the length of chord CD represents the magnitude of the DVR injection voltage during the transition state. In Fig. 3, the red auxiliary lines are utilized to calculate the coordinates of point D as follows:

$$x_D = |AC| \cdot \cos(\varphi - \delta) + |ED| = |AC| \cdot \cos(\varphi - \delta) + |OF| = V_S \cdot \cos(\varphi - \delta) + V_{mi} \cdot \sin \phi_i \quad (23a)$$

$$y_D = |AB| \cdot \sin \varphi - |DF| = |AB| \cdot \sin \varphi - |EO| = V_L \cdot \sin \varphi - V_{ma} \cdot \cos \phi_t \quad (23b)$$

where ϕ_t is the centrifugal angle of point D . The coordinates of point C can also be obtained as

$$x_C = |AC| \cdot \cos(\varphi - \delta) = V_s \cdot \cos(\varphi - \delta) \quad (24a)$$

$$y_C = |AB| \cdot \sin \varphi - |CO| = V_L \cdot \sin \varphi - V_{ma} \quad (24b)$$

The magnitude of the DVR injection voltage during transition state, i.e., the length of chord CD can be computed as

$$V_{DVR}^t = \sqrt{(x_D - x_C)^2 + (y_D - y_C)^2} \quad (25)$$

Using (23a), (23b), (24a), and (24b), V_{DVR}^t can also be formulated as

$$V_{DVR}^t = \sqrt{(V_{mi} \cdot \sin \phi_t)^2 + (V_{ma} - V_{ma} \cdot \cos \phi_t)^2} = \sqrt{4V_{ma}^2 \cdot \sin^4(\phi_t/2) + V_{mi}^2 \cdot \sin^2 \phi_t} \quad (26)$$

The phase angle of the injected voltage with respect to the reference can be calculated as

$$\lambda_{DVR}^t = \cos^{-1} \left(\frac{|ED|}{|CD|} \right) = \cos^{-1} \left(\frac{|OF|}{|CD|} \right) = \cos^{-1} \left(\frac{V_{mi} \cdot \sin \phi_t}{V_{DVR}^t} \right) \quad (27)$$

From (26) and (27), it can be seen that by controlling the transition centrifugal angle ϕ_t , the DVR injected voltage can be regulated. In order to maintain a smooth changeover during the operation, a transition ramp [29] is utilized. As the centrifugal angle starts from 0° and terminates at 90° , it can be given by

$$\phi_t = \frac{90^\circ}{\Delta T} \cdot t \quad (28)$$

where ΔT regulates the slope of the DVR injected voltage during the transition state and is chosen as 60 ms. When ϕ_t terminates at 90° , the smooth changeover of the DVR injected voltage is accomplished and the desired load voltage is also achieved. The next step is to determine the compensation criterion that the load voltage can be restored, and the source PFC can also be realized.

D. Determination of the Compensation Criterion

In order to correct the source PF, the DVR should support all the load reactive power demand. Using the derived virtual reactance in (21), the reactive power handled by the DVR can be calculated as follows:

$$Q_{DVR} = I_L^2 \cdot X = I_L^2 \cdot \sqrt{|Z|^2 - R^2} \quad (29)$$

Using (15), (17), and (20), the expression can be rewritten as

Fig. 5. Flowchart of the voltage elliptical restoration algorithm for PFC.

$$Q_{DVR} = V_L \cdot I_L \cdot \sqrt{\sin^2 \varphi + k^2 \cdot \sin^2 (\varphi - \delta) - 2k \cdot \cos \delta + 2k \cdot \cos \varphi \cdot \cos (\varphi - \delta)} \quad (30)$$

The load reactive power demand is computed as

$$Q_L = V_L \cdot I_L \cdot \sin \varphi \quad (31)$$

By equalizing (30) and (31), the PFC criterion can be obtained as

$$\delta = \varphi \quad (32)$$

It means when $\delta = \varphi$, the DVR can support all the load reactive power demand, thus the source PFC is achieved.

E. Voltage Elliptical Restoration Algorithm for PFC

The detailed flowchart of the voltage elliptical restoration algorithm for PFC is illustrated in Fig. 5. In order to implement the voltage elliptical restoration for the PFC, the required signals are the computed PF angle φ , the source voltage ratio k , the equivalent load resistance R_L , and the nominal load voltage V_L . According to the DVR compensation criterion described in Section II-D, δ is set equal to φ . Equations (17), (20), and (21) are used to calculate the virtual resistance R , virtual impedance Z , and virtual reactance X . Then, the

Fig. 6. Phasor representation of the DVR elliptical restoration.

three ellipse parameters, i.e., semi minor axis V_{mi} , semi major axis V_{ma} , and transition centrifugal angle ϕ_t , can be obtained by (18), (22), and (28). The magnitude and the phase angle (V_{DVR}^t and λ_{DVR}^t) of the transition DVR injected voltage are calculated by (26) and (27). When ϕ_t finishes the process of starting from 0° and terminating at 90° , the smooth changeover of the DVR injection voltage is accomplished and the desired load voltage is also achieved. The phasor representation of the smooth changeover is presented in Fig. 6.

III. DVR CONTROLLER DESIGN

The signal flow graph of the DVR controller is illustrated in Fig. 7. The measured signals in the control process are source voltage (v_s), load voltage (v_L), load current (i_L), and DVR injected voltage (v_{DVR}).

In Fig. 7, the measured RMS value (V_S) of v_s and the nominal load voltage (V_L) are used to compute the source voltage ratio (k) via (8). The instantaneous load voltage phase angle θ_{V_L} and the load current phase angle θ_{I_L} are obtained by the PLL controllers, and they are utilized to calculate the PF angle (φ) using (9). Then, φ and the measured RMS values of v_L and i_L are applied to compute the equivalent load resistance (R_L) via (16). Based on k , V_L , R_L , and φ , the magnitude and phase angle of the DVR injected voltage (V_{DVR} and λ_{DVR}) for each iteration are determined following the flowchart in Fig. 6. Next, ωt , V_{DVR} , and λ_{DVR} are used to

Fig. 7. Signal flow graph of the DVR controller.

TABLE I
DVR SYSTEM PARAMETERS IN SIMULATION

Source nominal voltage and frequency	$V_S = 100 \text{ V}$ $f_S = 50 \text{ Hz}$
DC source voltage	$V_{dc} = 200 \text{ V}$
Load 1: resistance	$R_1 = 200 \Omega$
Load 2: series connected resistance and inductance	$R_2 = 40 \Omega$ $L_2 = 200 \text{ mH}$
Voltage ratio of the series transformer	$n = 1$
Filter inductance	$L_f = 6.3 \text{ mH}$
Filter capacitance	$C_f = 50 \mu\text{F}$
Sampling time	$T_s = 20 \mu\text{s}$

generate the time varying reference signal v_{DVR}^* . The error between v_{DVR}^* and v_{DVR} are sent to the PWM controller to generate the switching signals (G1 and G2 in Fig. 1) for the switches of the VSI (S1 and S2 in Fig. 1).

IV. SIMULATION RESULTS

In order to validate the PFC of the DVR, the simulation is conducted on the MATLAB Simulink platform. The system parameters in the simulation are listed in Table I. The simulation scenarios are arranged as follows: The system is operating under the voltage sag condition ($V_S = 60 \text{ V}$). Before $t = 0.04 \text{ s}$, only Load 1 is connected at the load side, while the DVR is not involved in the system. At $t = 0.04 \text{ s}$, Load 2 is connected in parallel with Load 1, while the DVR is activated to realize the voltage compensation and the PFC. The in-phase operation and PFC without the elliptical restoration are also conducted for the comparison.

Fig. 8. Simulation results of the in-phase operation of the DVR: (a) source voltage, (b) load voltage, (c) DVR injected voltage, (d) DVR supported power, (e) load power demand, (f) source supported power, (g) load PF, and (h) source PF.

A. In-Phase Operation

The simulation results of the in-phase operation of the DVR are presented in Fig. 8. It can be observed from Fig. 8(a) that the source voltage is in 40% sag condition ($V_{s,max} = 85$ V). From Fig. 8(c), (d), and (g), it is noted that the load PF is changing from unity to 0.75 from 0.04 s onwards, then the DVR starts to inject the compensation voltage, as well as the corresponding active and reactive power, into the system. The load voltage is restored to the nominal value at $t = 0.04$ s, which is presented in Fig. 8(b). However, from Fig. 8(h), the source PF is following the load PF, as the in-phase operation of the DVR does not provide the PFC ability. In Fig. 8(f), it is noted that the source still needs to inject reactive power into the system.

Fig. 9. Simulation results of the PF correction without the elliptical restoration of the DVR: (a) source voltage, (b) load voltage, (c) DVR injected voltage, (d) DVR supported power, (e) load power demand, (f) source supported power, (g) load PF, and (h) source PF.

B. PFC without Elliptical Restoration

Fig. 9 demonstrates the simulation results of the PFC without the elliptical restoration. The source voltage is still in 40% sag condition ($V_{s,max} = 85$ V) as presented in Fig. 9(a). In Fig. 9(g), the load PF is changing from unity to 0.75 from 0.04 s onwards. From Fig. 9(c) and (d), it is observed that the DVR immediately injects the compensation voltage, as well as all the load reactive power demand. In Fig. 9(f) and (h), the reactive power supplied by the source is reduced to 0, and the source PF is corrected. However, from Fig. 9(b), the phase jump happens in the load voltage at $t = 0.04$ s, as the transition state is not seamless during the PFC process. From Fig. 9(c), it can be observed that a phase difference is directly injected into the system by the compensating voltage.

Fig. 10. Simulation results of the PF correction with the elliptical restoration of the DVR: (a) source voltage, (b) load voltage, (c) DVR injected voltage, (d) DVR supported power, (e) load power demand, (f) source supported power, (g) load PF, and (h) source PF.

C. PFC with Elliptical Restoration

The performance of the PFC with the elliptical restoration is presented in Fig. 10. The source voltage is in 40% sag condition ($V_{S,max} = 85$ V) as presented in Fig. 10(a). From Fig. 10(c) and (d), it is noted that the compensation voltage, as well as the DVR supplied power, is gradually increased. The reason is that the DVR injected voltage is following the elliptical trajectory presented in Section II. In Fig. 10(b), the load voltage is gradually restored to the nominal value at $t = 0.1$ s. Hence, the phase jump is avoided in the load voltage. From Fig. 10(f) and (h), it is observed that the source supplied reactive power is eventually reduced to 0 and the source PF is restored to unity at $t = 0.1$ s. The whole process of the source PFC takes 60 ms.

Fig. 11. Schematic of the laboratorial prototype of the DVR (1) HEWLETT PACKARD 6834B programmable AC power source, (2) SEMIKRON IGBT based inverter, (3) Chroma 62012P-600-8 programmable DC power source, (4) filter, (5) injection transformer, (6) resistor bank and inductor bank, (7) dSPACE 2102, (8) host PC, and (9) LeCroy oscilloscope.

TABLE II
PARAMETERS OF THE DVR HARDWARE SETUP

HEWLETT PACKARD 6834B programmable AC power source nominal phase voltage and frequency	$V_s = 100\text{ V}$ $f_s = 50\text{ Hz}$
SEMIKRON IGBT based inverter	IGBT module: SKM75GB12T4
Chroma 62012P-600-8 programmable DC power source supply voltage	$V_{dc} = 100\text{ V}$
Load 1: resistance	$R_1 = 200\ \Omega$
Load 2: series connected resistance and inductance	$R_2 = 40\ \Omega$ $L_2 = 200\text{ mH}$
Voltage ratio of the series transformer	$n = 1:2$
Filter inductance	$L_f = 6.3\text{ mH}$
Filter capacitance	$C_f = 50\ \mu\text{F}$
dSPACE 2102 sampling time	$T_s = 50\ \mu\text{s}$

V. EXPERIMENTAL RESULTS

A laboratorial prototype of the DVR is built to verify the proposed PFC ability, as well as the voltage compensation ability. The schematic of the laboratorial prototype is demonstrated in Fig. 11. The parameters of the prototype are summarized in Table II. In the hardware setup, The HEWLETT PACKARD 6834B programmable AC power source is utilized to generate voltage sag for the system. The SEMIKRON IGBT based inverter is used as the VSI of the DVR. The DC link of the VSI is supported by the Chroma 62012P-600-8 programmable DC power source. The filter can mitigate the high frequency harmonics from the IGBT based VSI. The transformer is able to inject the DVR voltage in series with the distribution line. The resistor and inductor banks are connected at the load side of the system. The dSPACE 2102 controller is utilized as the digital signal processor to realize the control of the VSI. The host PC is used to operate the

Fig. 12. Experimental results of the in-phase operation of the DVR: source voltage v_S (100 V/div), load voltage v_L (100 V/div), DVR injected voltage v_{DVR} (100 V/div), and load current i_L (2 A/div).

dSPACE 2102 device. The LeCroy oscilloscope can capture the experimental results. The experimental results are presented in Figs. 12-14.

A. In-Phase Operation

In Fig. 12, it is noted that the source is operating under a sag voltage condition ($V_{S,max} = 85$ V). Before $t = t_1$, only resistance Load 1 (R_1) is connected in the system, while the DVR is not activated. After $t = t_1$, the series connected resistance and inductance Load 2 ($R_2 + j\omega L_2$) is parallelly connected with R_1 , so that the DVR is activated to compensate the voltage sag. The transition state is zoomed to illustrate the phase change, which is presented at the bottom half of Fig. 12. It is observed that, at $t = t_2$, the load voltage is immediately restored to the nominal value, and the load voltage is leading the load current by 41.8° , which means the PF at the load side is 0.75 ($\cos 41.8^\circ = 0.75$). As the DVR is operating under the in-phase compensation mode, the load voltage is always in phase with the source voltage. The source voltage is also leading the load current by

Fig. 13. Experimental results of the PF correction without the elliptical restoration of the DVR: source voltage v_S (100 V/div), load voltage v_L (100 V/div), DVR injected voltage v_{DVR} (100 V/div), and load current i_L (2 A/div).

41.8° , thus the source PF is also 0.75. As a result, the PFC at the source side cannot be achieved during the in-phase operation of the DVR.

B. PFC without Elliptical Restoration

The experimental results of the PF correction without the elliptical restoration are presented in Fig. 13. The source is still operating under the sag voltage condition, and the same load step change is generated at $t = t_1$. The DVR is activated to compensate the voltage sag and correct the source PF. In Fig. 13, at $t = t_1$, it can be observed that the DVR immediately injects the compensation voltage with the specific magnitude and phase angle, which can restore the load voltage and correct the source PF. Thus, at $t = t_2$, the load voltage is at the nominal magnitude and leading the source voltage by 41.8° , while the load current is in phase with the source voltage. In this case, the PFC is achieved at the source side. However, it is noted that the phase jump happens in the load voltage, as the transition state is not seamless during the DVR compensation.

Fig. 14. Experimental results of the PF correction with the elliptical restoration of the DVR: source voltage v_S (100 V/div), load voltage v_L (100 V/div), DVR injected voltage v_{DVR} (100 V/div), and load current i_L (2 A/div).

C. PFC with Elliptical Restoration

Fig. 14 shows the experimental results of the PFC with the elliptical restoration. The same voltage sag condition and load step change are set to validate the proposed PFC of the DVR. At the bottom half of Fig. 14, after $t = t_1$, the DVR starts to inject the compensation voltage by following the elliptical restoration trajectory. It can be observed that the DVR gradually increases the magnitude and phase angle of the injected voltage to the desired values. Correspondingly, the load voltage gradually restores to the nominal value and has a PF angle shift. The phasor representation of the aforementioned elliptical restoration has been presented in Fig. 6. At $t = t_2$, the load voltage is still in phase with the source voltage, and the source voltage is leading the load current by 41.8° . The PF of the source is 0.75 ($\cos 41.8^\circ = 0.75$), as the elliptical restoration process has just started. At $t = t_3$, the elliptical restoration is accomplished. Thus the load voltage is restored to the nominal value and leading the source voltage by 41.8° . The load current is in phase with the source voltage, which

means that the source PFC is achieved at $t = t_3$, and the seamless transition of the DVR compensation can be guaranteed.

VI. CONCLUSION

In this paper, an elliptical restoration algorithm for PFC is applied to the single-phase DVR. By applying the elliptical restoration based controller, the DVR can restore the load voltage and correct the source PF simultaneously and seamlessly. In the proposed control method, the virtual impedance is used to describe the active and reactive components of the DVR injected voltage. The active and reactive voltage components and a centrifugal angle are utilized to formulate an elliptical compensation trajectory. When the DVR injected voltage follows the formulated elliptical trajectory, a smooth changeover of the compensation voltage can be achieved during the transition state, and thus the phase jump in the load voltage can be avoided during the load switching. The source voltage will eventually be in phase with the load current, when the DVR injected voltage has finished following the elliptical trajectory. A laboratorial prototype of the single-phase DVR is utilized to validate the proposed control method. The experimental results demonstrate that (1) the conventional in-phase operation of the DVR cannot provide the source side PFC; (2) the source PFC without the elliptical restoration will result in a phase jump in the load voltage; and (3) the source PFC with the elliptical restoration can avoid the phase jump in the load voltage.

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