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A newly proposed IVCVR controlled IUPQC device for PQ enhancement in multi-feeder distribution networks

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ABSTRACT

Nowadays, the greater relevance of power-quality has being received substantial attention in multi-feeder distribution system due to increased usage of critical non-linear power-electronic loads in many applications. These loads proliferates the quality-power and it can degrade the voltage and current quality in multi-feeder networks from the utility-grid code specifications. Numerous custom-power compensation devices are accessible to mitigate corresponding voltage/current relevant power quality (PQ) concerns, resulting that the multi-feeder networks are maintained as fundamentally strong, sinusoidal wave-shape, essentially balanced, linear/stable in nature. Amid of several custom-power compensation devices, the interline-UPQC is the most significant for enhancing both voltage/current waveforms in utility-grid integrated multi-feeder distribution system by employing suitable control algorithms. It is noted that the newly proposed integrated voltage-current vector reference (IVCVR) control algorithm eliminates the various technical issues in conventional schemes. In this work, a novel IVCVR algorithm controlled IUPQC device has been proposed for PQ enhancement and also maintaining flexible power-flow between the multi-feeders. The operation and performance of newly proposed IVCVR algorithm controlled IUPQC device has been investigated under definite PQ problems by using MATLAB/Simulink software-computing tool. The extracted simulation results are highlighted with feasible interpretations complying with IEEE-519/2022 standards.

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1. INTRODUCTION

These days, power quality (PQ) is the most substantial and notable key specification for delivering the standard and quality power to end-user loads as complying with grid-code guidelines [1]–[5]. The major problem has been identified; the increased usage of such critical non-linear power-electronic devices injects the harmful odd harmonics into the common-coupling point (PCC) of multi-feeder distribution systems [6]–[9]. This serious odd harmonics distorts the PCC/utility-grid current wave-shape, frequency, phase-angle as unbalanced, along with drastic changes in the reactive-power demand, non-ideal power-factor, maximizes the thermal losses which damages the other loads at the PCC level. Moreover, these distortions are influencing the utility-grid voltage by injecting the voltage harmonics, voltage sags-swells, unbalanced voltage which increases the subversive power pollution and deterioration of quality power in entire multi-feeder distribution systems [10]–[13].

In this manner, the mitigation of such serious PQ issues is taken as the main objective by employing suitable custom-power conditioning (CPC) techniques developed by several power-system engineers and researchers are explored in [14]–[18]. The modern CPC devices help to mitigate the relevant voltage-current PQ issues and can transform the utility-grid specifications into a sinusoidal wave shape, fundamentally strong, balanced linear network by using various PQ detection and classification techniques [19]–[22]. Various modern CPC devices are classified based on compensation/integration such as Interline-DVR [23], interline-PFC [24], and interline unified power-quality compensator (IUPQC) [25]. The IUPQC device is the most influential and prominent PQ compensator in a multi-feeder network; it can mitigate both voltage/current relevant PQ issues. Moreover, stable and continuous power has been maintained between the two or adjacent feeders in a multi-feeder network by initiating the active-power regulation through feasible control algorithm.

From several literature studies, these control algorithms are generally used for extraction of reference voltage/current signals to compensate related PQ problems [26], [27]. The regular synchronous reference frame (SRF) control algorithm is availed for extraction of reference voltage signal to series VSC-I, II of IUPQC device, which is explored by the researcher in [28]. The regular instantaneous real-reactive power (IRP) control algorithm is availed for extraction of reference current signals to parallel VSC-III, IV of IUPQC device is explored by Palanisamy *et al.* [29]. The major problems in [28], [29] has been identified based on substantial studies, at present the above-said methods are not recommended because of critical limitations in control algorithm such as sophisticated mathematical calculations and transformations, more transient delays, non-sinusoidal reference signals, non-fundamental switching frequency, high dv/dt switch stress, more switching losses and degrading the compensation efficiency.

The technical problems in aforementioned reference control algorithms have been counteracted by newly proposing integrated voltage-current vector reference (IVCVR) control algorithm. This new IVCVR control algorithm extracts the fundamental current/voltage vector reference signals is used to produce the feasible switching pattern to VSC's of IUPQC device by sensing the distorted voltage/current wave-shapes. In this work, a novel IVCVR algorithm-controlled IUPQC device has been proposed for PQ enhancement and also maintaining flexible power-flow between the multi-feeders. The operation and performance of newly proposed IVCVR controlled IUPQC device has been investigated under definite PQ problems by using MATLAB/Simulink software-computing tool. The extracted simulation results are highlighted with feasible interpretations complying with IEEE-519/2022 standards.

2. DESIGN AND OPERATION OF IUPQC DEVICE

The design and working of proposed IUQPC device have similar characteristics of basic UPQC, but the IUPQC device consists of four-modules of three-phase-three-level voltage-source converters (3-level VSC's) employed as VSC-I, II, III, IV, respectively. These VSC-I, II, III, IV modules act as common barrier and are integrated as series/parallel and parallel-series to PCC of feeders A and B as back-to-back configuration energized by common DC-link source capacitor ($C_{dc.cs}$). When any voltage deviations such as voltage-sag, voltage-swell, voltage harmonics, voltage unbalance, voltage flickers have occurred, affecting the entire load apparatus in both feeders A and B due to discontinuous power-flow. In this PQ enhancement mode, the voltage relevant PQ issues are mitigated by utilizing VSC-I, II of IUPQC device which are acted as series active filters (SAF) are integrated to PCC of distribution feeders A and B through 1:1 line interfaced transformers-A, B. The series VSC-I, II are operated as in-phase voltage mitigation principle which injects the requisite compensated voltage of $V_{CS\text{-}I.abc}$ (V) and $V_{CS\text{-}II.abc}$ (V) into both feeders A and B. The injected voltage reshapes the critical non-linear load voltage as balanced, fundamental frequency, and sinusoidal in-phase form. Both series VSC-I, II varying the injected voltage based on sensing elements and line-interfaced LCL notch filters, it helps to continuous load voltage regulation in multi-feeder network. The model block diagram of proposed IUPQC device for PQ enhancement in utility-grid powered multi-feeder distribution network is depicted in Figure 1.

Similarly, any current distortions such as current harmonics, load unbalance, load reactive-power demand, non-ideal power-factor has occurred due to usage of critical non-linear diode-bridge-rectifier (NL-DBR) controlled loads. This NL-DBR controlled loads injecting the harmful odd harmonics into PCC of feeders A and B affecting the entire load apparatus due to thermal losses, which damages the other loads in both feeders A and B. In this PQ enhancement mode, the VSC-III, IV of IUPQC device which are acted as shunt/parallel connected active-filters (PAF) for mitigation of all current relevant PQ issues in both feeders A and B, respectively. The parallel VSC-III, IV is operated as in-phase opposition current mitigation principle which injects the requisite compensation current of $I_{CSh\text{-}III.abc}$ (A), $I_{CSh\text{-}IV.abc}$ (A) in to both feeders A and B. The injected current reshapes the source/PCC current of feeders A and B as balanced load, fundamental frequency, ideal-power factor, constant reactive-power support, and sinusoidal in-phase form. Both parallel VSC-III, IV varying the injected current based on sensing elements and line-interfaced second-order low-pass LC notch filters, it helps to continuous source/PCC current regulation in multi-feeder network. It is noted that, as per IEEE/IEC regulations the IUPQC device has been recognized for mitigation of all voltage-current relevant PQ issues in multi-feeder network by employing newly proposed IVCVR control algorithm.

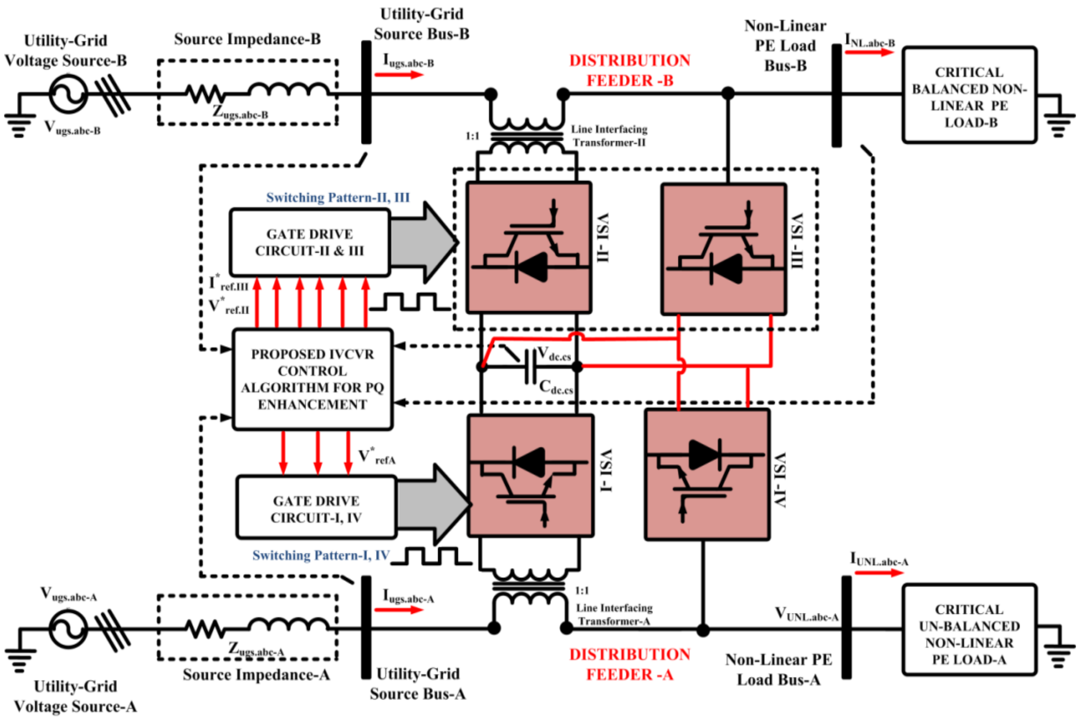

Figure 1. Model block diagram of proposed IUPQC device for PQ enhancement in utility-grid powered multi-feeder distribution network

3. PROPOSED IVCVR CONTROL ALGORITHM

The robust operation and superlative performance of the proposed IUPQC device depends on the viable reference control algorithm over the traditional algorithms [28], [29]. The occurrence of PQ issue has been identified through sensing elements; it measures the rate of change in the amplitude/phase angle of utility-grid source/PCC currents and critical NL-DBR load voltages of both feeders A and B. The sensed load voltages/source current signals are evaluated to attain synchronized vector notations, which are rotated with an angle of (θ_s) through phase-locked loop (PLL) gate-drive circuitry. The sensed load voltages/source current signals in feeders A and B are stated as in (1) and (2).

$$\begin{aligned} V_{NL.a-A,B} &= V_{ugs.a-A,B} \sin(\theta_s) \\ V_{NL.b-A,B} &= V_{ugs.b-A,B} \sin\left(\theta_s - {}^{2\pi}/_{3}\right) \\ V_{NL.c-A,B} &= V_{ugs.c-A,B} \sin\left(\theta_s + {}^{2\pi}/_{3}\right) \end{aligned} \tag{1}$$

$$\begin{aligned} i_{ugs.a-A,B} &= \sum I_{sa.n-A,B} \sin\left(n(\omega t) - \theta_{a-n}\right) \\ i_{ugs.b-A,B} &= \sum I_{sb.n-A,B} \sin\left(n\left(\omega t - \tfrac{2\pi}{3}\right) - \theta_{b-n}\right) \\ i_{ugs.c-A,B} &= \sum I_{sc.n-A,B} \sin\left(n\left(\omega t + \tfrac{2\pi}{3}\right) - \theta_{c-n}\right) \end{aligned} \tag{2}$$

The above-stated utility-grid source/PCC currents and critical NL-DBR load voltages of both feeders A and B are multiplied and summated each other for calculating the averaged-power in both feeders A and B $(P_{Lavg.ugs-A,B})$ in a certain time period 't' is defined as (3).

$$P_{Lavg.ugs-A,B} = \frac{1}{T}\int_{t-T}^{T}\left(V_{ugs.a-A,B} \times i_{ugs.a-A,B} + V_{ugs.b-A,B} \times i_{ugs.b-A,B} + V_{ugs.c-A,B} \times i_{ugs.c-A,B}\right)dt \tag{3}$$

The block diagram of the proposed IVCVR control algorithm is presented in Figure 2 (see Appendix). The calculated averaged power of both feeders A and B ($P_{Lavg.ugs-A,B}$) is approximated with the second-order low-pass filter (SO-LPF) for allowing the low-order frequency signals such as sinusoidal wave-shaped and fundamental frequency allied reference signals. On other side, the common DC-link capacitor voltage of VSC's has been maintained as constant with a rated reference value, which helps to regulate the circulation current flow between the VSC's. The DC voltage has been regulated by using proportional-integral (PI) regulator with significant tuning of ($K_{p.dc}, K_{i.dc}$) gain values using Ziegler-Nicholas (ZN) method. The tuned PI regulator minimizes the error components while differentiating the measured common DC-link voltage ($V_{dc.cs}$) with reference DC-link voltage ($V^*_{dc.cr}$), the resultant outcome is considered as active-loss value ($P_{loss.dc}$) at nth notation is stated in (5).

$$V_{dcs.er} = V^*_{dc.cr} - V_{dc.cs} \tag{4}$$

$$P_{loss.dc} = K_{p.dc} * \left(V_{dcs.er(n)} - V_{dcs.er(n-1)}\right) + K_{i.dc} * \left(V_{dcs.er(n)}\right) \tag{5}$$

From (3) and (5), the averaged power of feeders A and B ($P_{Lavg.ugs-A,B}$) and active-loss value ($P_{loss.dc}$) are summated for generation of the final reference current signals for both parallel VSC's-III, IV of IUPQC device.

The final fundamental reference current signals ($i^*_{ref.abc-III,IV}$) in positive sequence for both parallel VSC's-III, IV of the IUPQC device is represented as (6).

$$\begin{aligned}
i^*_{ref.a-III,IV} &= \frac{V^+_{ugs.a-A,B}}{\Delta V^+_{ugs.abc-A,B}}\left(P_{Lavg.ugs-A,B} + P_{loss.dc}\right)\\
i^*_{ref.b-III,IV} &= \frac{V^+_{ugs.b-A,B}}{\Delta V^+_{ugs.abc-A,B}}\left(P_{Lavg.ugs-A,B} + P_{loss.dc}\right)\\
i^*_{ref.c-III,IV} &= \frac{V^+_{ugs.c}{-A,B}}{\Delta V^+_{ugs.abc-A,B}}\left(P_{Lavg.ugs-A,B} + P_{loss.dc}\right)
\end{aligned} \tag{6}$$

Whereas, ($\Delta V^+_{ugs.abc-A,B}$) is defined as non-complex sequence generated from the unit-vector template is stated as (7).

$$\Delta V^+_{ugs.abc-A,B} = \left\{\frac{2}{3}\left(V^2_{ugs.a-A,B} + V^2_{ugs.b-A,B} + V^2_{ugs.c-A,B}\right)\right\}^{1/2} \tag{7}$$

The resultant unit-vector template produces the non-complex vector sequence for extraction of voltage-phase representation as (8).

$$\begin{aligned}
UV_{ugs.a-A,B} &= \frac{V_{NLr.a}}{\Delta V^+_{ugs.abc-A,B}} = sin\theta s\\
UV_{ugs.b-A,B} &= \frac{V_{NLr.b}}{\Delta V^+_{ugs.abc-A,B}} = sin\left(\theta s - {2\pi}/{3}\right)\\
UV_{ugs.c-A,B} &= \frac{V_{NLr.c}}{\Delta V^+_{ugs.abc-A,B}} = sin\left(\theta s + {2\pi}/{3}\right)
\end{aligned} \tag{8}$$

From the extracted unit-vector phase sequence of feeders A and B ($UV_{ugs.abc-A,B}$) and the reference magnitude component ($V_{ref.m}$) are multiplied for generation of the final reference voltage signals for both series VSC's-I, II of IUPQC device. The final reference voltage signal ($V^*_{ref.abc-I,II}$) is described as (9).

$$\begin{aligned}
V^*_{ref.a-I,II} &= UV_{ugs.a-A,B} * V_{ref.m}\\
V^*_{ref.b-I,II} &= UV_{ugs.b-A,B} * V_{ref.m}\\
V^*_{ref.c-I,II} &= UV_{ugs.c-A,B} * V_{ref.m}
\end{aligned} \tag{9}$$

The final fundamental voltage reference signal ($V^*_{ref.abc-I,II}$) is produced by proposed IVCVR control algorithm, which is summated with actual utility-voltage waveform ($V_{ugs.abc-A,B}$) of feeders A and B for generation of feasible switching pattern to both series VSC's-I, II of IUPQC device by using the sinusoidal multi-carrier pulse-width modulation (SMC-PWM) with certain triangular carriers. The feasible switching states operate the series VSC's-I, II for injection of compensated voltage of $V_{CS-I.abc}$ (V) and $V_{CS-II.abc}$ (V) into both feeders A and B. It reshapes the critical non-linear load voltages of feeders A and B as balanced, fundamental frequency, and sinusoidal in-phase form. Similarly, the final fundamental reference current signals ($i^*_{ref.abc-III,IV}$) is produced by proposed IVCVR control algorithm, which is summated with actual utility-current waveform ($I_{ugs.abc-A,B}$) of feeders A and B for generation of feasible switching pattern to both parallel VSC's-III, IV of IUPQC device by using the hysteresis current controller as gate-drive circuitry with certain hysteresis limits. The feasible switching states operate the parallel VSC-III, IV for injection of requisite compensation current of $I_{CSh\text{-}III.abc}$ (A), $I_{CSh\text{-}IV.abc}$ (A) into both feeders A and B. It reshapes the source/PCC current of feeders A and B as balanced load, fundamental frequency, ideal-power factor, constant reactive-power support, and sinusoidal in-phase form. The flow-chart procedure of proposed IVCVR control algorithm is illustrated in Figure 3. The schematic diagram of the proposed IVCVR controlled IUPQC device for PQ enhancement in a utility-grid-powered multi-feeder distribution network is depicted in Figure 4.

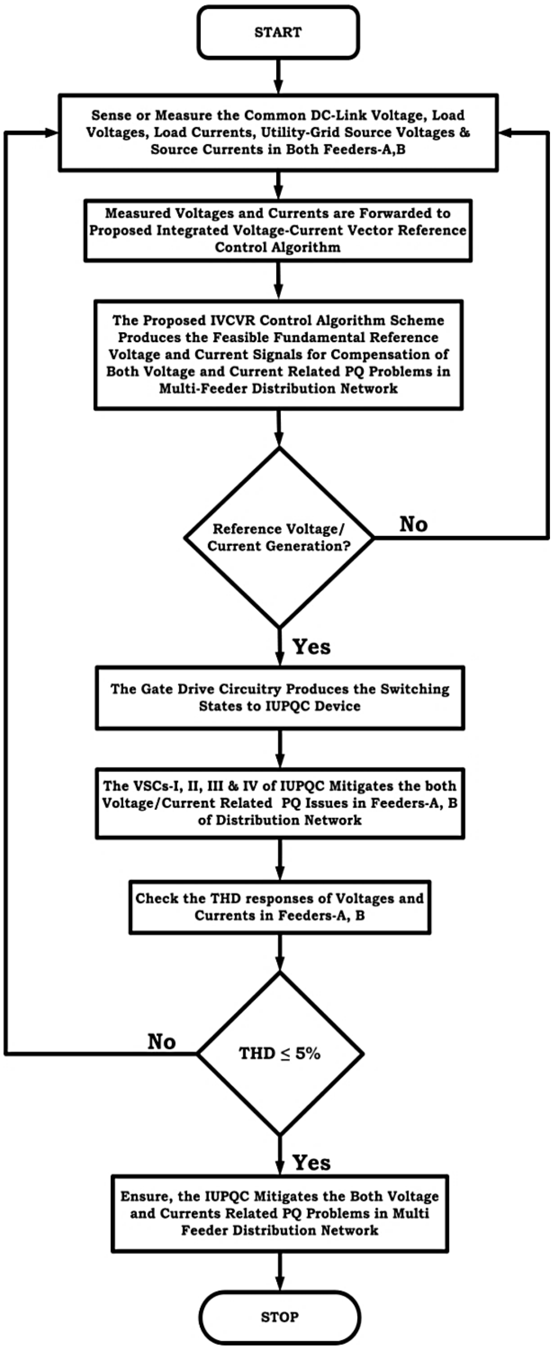

Figure 3. Flow-chart procedure of the proposed IVCVR control algorithm

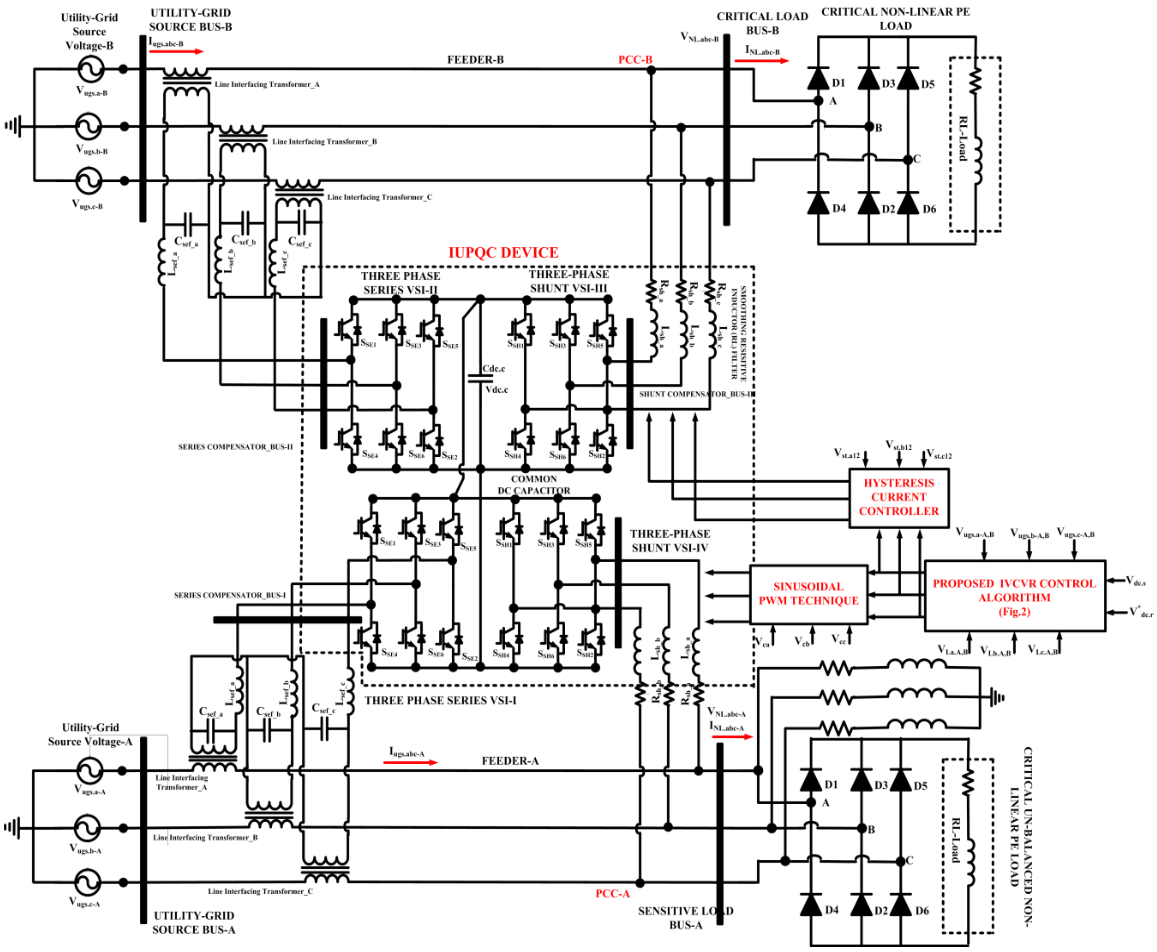

Figure 4. Schematic diagram of proposed IVCVR controlled IUPQC device for PQ enhancement in a utility-grid-powered multi-feeder distribution network

4. RESULTS AND DISCUSSION

4.1. Mitigation of voltage relevant PQ problems in feeder A using newly proposed IVCVR controlled VSC-I of IUPQC device

The operation and performance of newly proposed IVCVR algorithm controlled IUPQC device has been investigated under definite PQ problems by using MATLAB/Simulink software-computing tool. The Simulink data of proposed IVCVR controlled IUPQC model is illustrated in Table 1. The simulated results of mitigation of voltage relevant PQ problems in feeder A using newly proposed IVCVR controlled VSC-I of IUPQC device is presented in Figure 5. The feeder A of multi-feeder distribution network is powered through three-phase utility-grid voltage of 415 V_{rms}; 50 Hz is shown in Figure 5(a). In this feeder A, some of voltage deviations such as such as voltage harmonics, voltage interruptions, voltage-sag, voltage-swell are occurred and affecting the load apparatus in feeders-A which delivers unreliable and discontinuous power-flow. In this mode, the voltage relevant PQ issues are mitigated by utilizing VSC-I of IUPQC device which is acted as SAF, integrated to PCC of distribution feeders-A through 1:1 line interfaced transformers-A. The newly proposed IVCVR control algorithm extracts the unique reference voltage signals which are used to produce the feasible switching pattern to VSC-I of IUPQC device by using the SMC-PWM with certain triangular carriers. In this way, the time period before t-0.05 sec is considered as pre-distorted/healthy condition, and then the utility-grid voltage source is maintained as constant voltage of 340 V.

During the time period 0.05 sec < t < 0.15 sec, the utility-grid has been distorted with 5^{th} and 7^{th} harmonics which affects the continuous operation of critical unbalanced non-linear PE load is shown in Figure 5(a). Thus, the proposed IVCVR controlled series VSC-I of IUPQC device is functioned as SAF for mitigation of voltage harmonics into PCC of feeder A. The series VSC-I injects the requisite compensated voltage of $V_{CS\text{-}I.abc}$ (V) as in-phase voltage mitigation principle which reshapes the critical unbalanced non-linear PE load voltage as balanced, fundamental frequency and sinusoidal in-phase form, maintained with a value of 340 V as shown in Figures 5(b) and 5(c). The THD spectrum of utility-grid source voltage during voltage harmonics in feeder A is measured as 20.62% and the THD spectrum of critical unbalanced non-linear PE load voltage during voltage harmonics compensation in feeder A is measured as 1.05%, which is well complying within the IEEE-519/2022 standards as depicted in Figures 5(d) and 5(e).

Table 1. Simulink data

S. No	Simulation data	Values	
		Feeder A	Feeder B
1	Utility-grid source voltage	$V_{ugs.abc-A,B}$ = 415 V_{rms}, 50 Hz	
2	Critical load data	Un-balanced critical NL-PE load-A $V_{UNL.abc-A}$ = 415 Vrms, 50 Hz, $R_{UNL.abc-A}$ = 30 Ω, $L_{UNL.abc-A}$ = 20 mH	Balanced critical NL-PE load-B $V_{NL.abc-B}$ = 415 Vrms, 50 Hz, $R_{NL.abc-B}$= 30 Ω, $L_{NL.abc-B}$ = 20 mH
3	Source impedances	$R_{ugs.abc-A,B}$ = 0.15 Ω, $L_{ugs.abc-A,B}$ = 0.9 mH	
4	1:1 line transformer	$V_{tr.A,B}$ = 415 V, $P_{tr.A,B}$ = 5 KVA, $X_{tr.A,B}$ = 10% of leakage reactance	
5	Series VSI-C,II line filter	$L_{s.I,II}$ = 3 mH, $C_{s.I,II}$ = 100 µF	
6	Parallel VSC-III, IV line filter	$R_{sh.III}$ = 0.001 Ω, $L_{sh.III}$ = 10 mH	
7	Common DC-link source capacitor and DC voltage	$C_{dc.cs}$ = 1500 µF, $V_{dc.cs}$ = 880 V	
8	PI controller	$K_{p.dc}$= 1.5, $K_{i.dc}$ = 0.1	

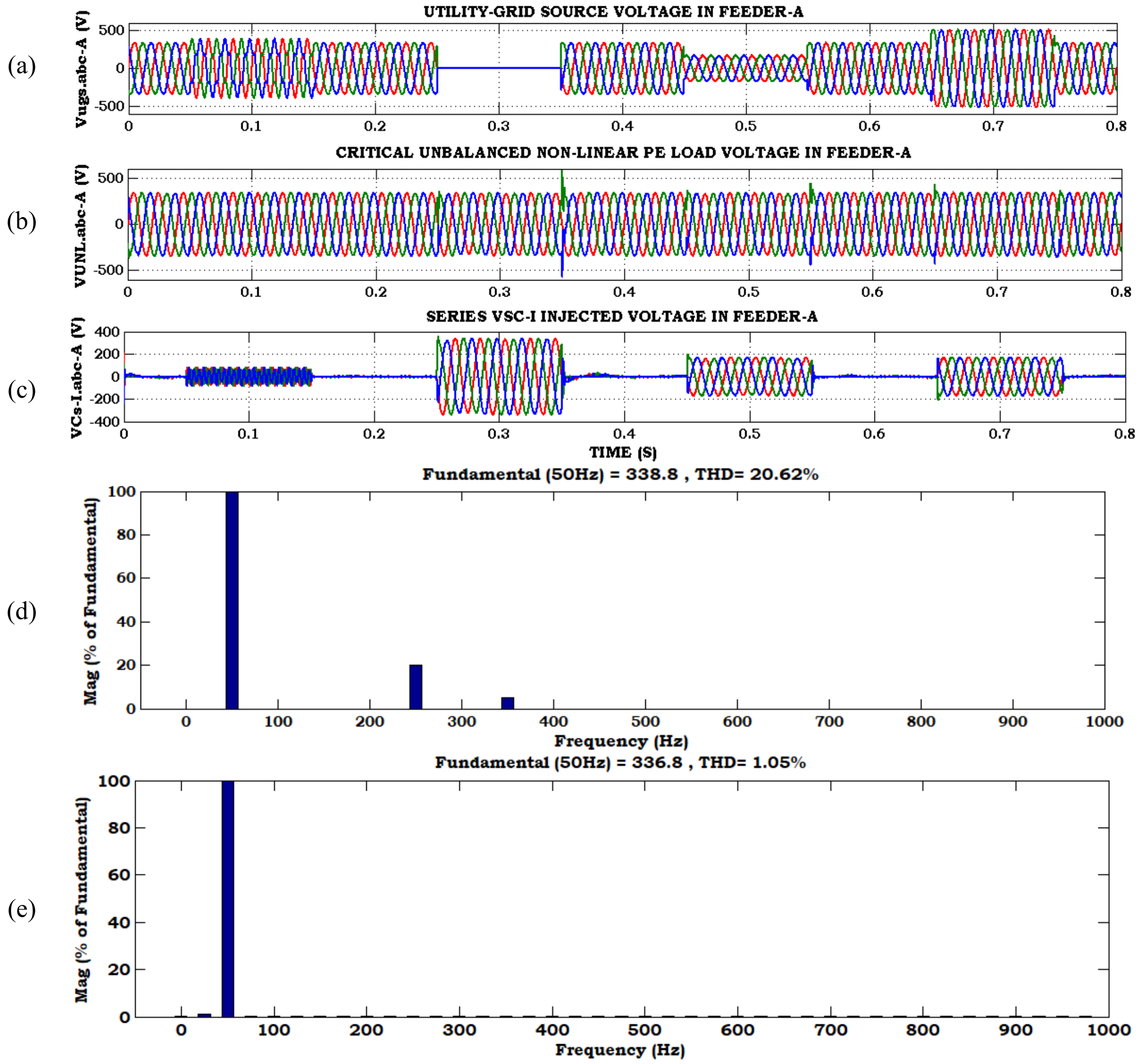

Figure 5. Simulated results of mitigation of voltage relevant PQ problems in feeder A using newly proposed IVCVR controlled VSC-I of IUPQC device: (a) utility-grid source voltage ($V_{ugs.abc-A}$ (V)), (b) critical un-balanced non-linear load voltage ($VUNL_{.abc-A}$ (V)), (c) series VSC-I injected voltage ($V_{Cs-I.abc}$ (V)), (d) THD spectrum of utility-grid source voltage, and (e) THD spectrum of critical un-balanced non-linear load voltage

The voltage interruptions also occurred during the time period 0.25 sec < t < 0.35 sec, the utility-grid voltage has been decreased by 100% due to sudden interruptions which affects the critical unbalanced non-linear load voltage, which is decreased from 340 V to 0 V is shown in Figure 5(a). Thus, the IVCVR controlled series VSC-I of IUPQC device injects the requisite compensated voltage of +340 V into PCC of feeder A as voltage-lifting technique for regulation of critical non-linear PE load voltage as constant and balanced with a value of 340 V is shown in Figures 5(b) and 5(c). The voltage sag is also occurred during the time period 0.45 sec < t < 0.55 sec, the utility-grid voltage has been decreased by 50% due to sudden short-circuit faults which affects the critical unbalanced non-linear load voltage is decreased from 340 V to 170 V is shown in Figure 5(a). Thus, the IVCVR controlled series VSC-I of IUPQC device injects the requisite compensated voltage of +170 V into PCC of feeder A as voltage-lifting technique for regulation of critical non-linear PE load voltage as constant and balanced with a value of 340 V is shown in Figures 5(b) and 5(c).

Moreover, the voltage swell is also occurred during the time period 0.65 sec < t < 0.75 sec, the utility-grid voltage has been increased by 50% due to sudden load removal which affects/mal-function of the critical unbalanced non-linear load voltage is increased and over-voltage from 340 V to 510 V is shown in Figure 5(a). Thus, the IVCVR controlled series VSC-I of IUPQC device injects the requisite compensated voltage of -170 V into PCC of feeder A as voltage-lifting technique for regulation of critical non-linear PE load voltage as constant and balanced with a value of 340 V is shown in Figures 5(b) and 5(c).

4.2. Mitigation of current relevant PQ problems in feeder A using newly proposed IVCVR controlled VSC-IV of IUPQC device

The simulated results of mitigation of current relevant PQ problems in feeder A using newly proposed IVCVR controlled VSC-IV of IUPQC device is presented in Figure 6. The feeder A of multi-feeder distribution network is powered through three-phase utility-grid voltage of 415 V_{rms}; 50 Hz is shown in Figure 6(a). In this feeder A, some of current relevant PQ issues are current harmonics, unbalanced load, load reactive-power demand, non-ideal power-factor has occurred due to usage of critical unbalanced non-linear PE controlled loads. This type of loads injects the harmful odd harmonics with a unbalanced nature into PCC of feeder A affecting the entire load apparatus due to thermal losses, which damages the other loads connected in feeders-A. In this mode, the current relevant PQ issues are mitigated by utilizing VSC-IV of IUPQC device, which is acted as parallel active filter (PAF), integrated to PCC of distribution feeders-A through line interfaced filters. The newly proposed IVCVR control algorithm extracts the unique reference voltage signals which are used to produce the feasible switching pattern to VSC-IV of IUPQC device by using the HCC gate-drive circuitry.

During current compensation, the VSC-IV mitigates the utility-grid/PCC source current, which is regulated as balanced and sinusoidal form with a value of 33 A for furnishing continuous energy to critical unbalanced non-linear PE load of 35 A is depicted in Figures 6(b) and 6(c). The IVCVR controlled parallel VSC-IV of IUPQC device is operated as in-phase opposition current mitigation principle, which injects the requisite compensation current of $I_{CSh\text{-}IV.abc}$ (A) of 17.5 A in to feeder A is shown in Figure 6(d). It can reshape the source/PCC current of feeder A as linear nature, balanced load, fundamental frequency, ideal-power factor, constant reactive-power support, and sinusoidal in-phase form. It is noted that, the parallel VSC-IV regulates the source/PCC current, which is in-phase of grid voltage is considered as ideal power-factor is shown in Figure 6(e). Also, the DC-link controller of IVCVR algorithm regulates DC side capacitor voltage of VSC-IV, which is maintained as constant with a value of 880 V is shown in Figure 6(f). The THD spectrum of critical unbalanced non-linear PE load current in feeder A is measured as 18.15%, and the THD spectrum of utility-grid/PCC source current during current compensation in feeder A is measured as 3.07%, which is well complying within the IEEE-519/2022 standards as shown in Figures 6(g) and 6(h).

4.3. Mitigation of voltage relevant PQ problems in feeder B using newly proposed IVCVR controlled VSC-II of IUPQC device

The simulated results of mitigation of voltage relevant PQ problems in feeder B using newly proposed IVCVR controlled VSC-II of IUPQC device is presented in Figure 7. The feeder B of multi-feeder distribution network is powered through three-phase utility-grid voltage of 415 V_{rms}; 50 Hz is shown in Figure 7(a). In this feeder B, some of voltage deviations such as such as voltage-sag, voltage-swell, voltage harmonics are occurred and affecting the load apparatus in feeders-B which delivers the unreliable and discontinuous power-flow. In this mode, the voltage relevant PQ issues are mitigated by utilizing VSC-II of IUPQC device, which is acted as SAF, integrated to PCC of distribution feeders-B through 1:1 line interfaced transformers-B. The newly proposed IVCVR control algorithm extracts the unique reference voltage signals, which are used to produce the feasible switching pattern to VSC-II of IUPQC device by using the SMC-PWM with certain triangular carriers. In this way, the time period before t-0.15 sec is considered as pre-distorted/healthy condition and then the utility-grid voltage source is maintained as constant voltage of 340 V.

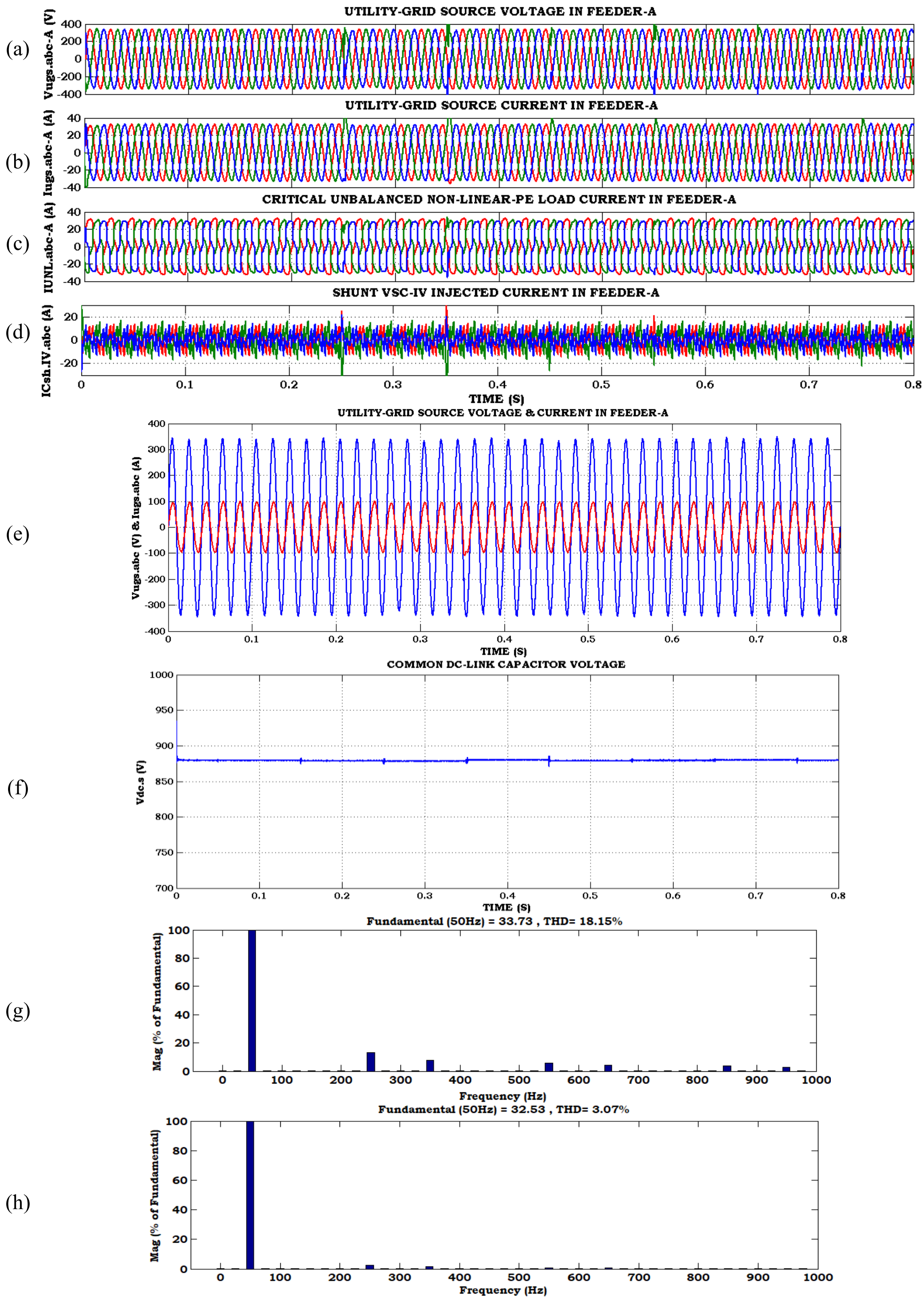

Figure 6. Simulated results of mitigation of current relevant PQ problems in feeder A using newly proposed IVCVR controlled VSC-IV of IUPQC device: (a) utility-grid voltage source ($V_{ugs.abc\text{-}A}$ (V)), (b) utility-grid source current ($I_{ugs.abc\text{-}A}$ (V)), (c) critical unbalanced non-linear PE load current ($I_{UNL.abc\text{-}A}$ (A)), (d) parallel VSC-IV injected current, (e) utility-grid source voltage and current ($I_{Csh\text{-}IV.abc}$ (A)), (f) common DC-link capacitor voltage, (g) THD spectrum of critical unbalanced non-linear PE load current, and (h) THD spectrum of utility-grid source current

The voltage sag is also occurred during the time period 0.15 sec < t < 0.25 sec, the utility-grid voltage has been decreased by 50% due to sudden short-circuit faults, which affects the critical balanced non-linear load voltage is decreased from 340 V to 170 V is shown in Figure 7(a). Thus, the IVCVR controlled series VSC-II of IUPQC device injects the requisite compensated voltage of +170 V into PCC of feeder B as voltage-lifting technique for regulation of critical non-linear PE load voltage as constant and balanced with a value of 340 V is shown in Figures 7(b) and 7(c).

Similarly, the voltage swell is also occurred during the time period 0.35 sec < t < 0.45 sec, the utility-grid voltage has been increased by 50% due to sudden load removal, which affects/mal-function of the critical unbalanced non-linear load voltage is increased and over-voltage from 340 V to 510 V is shown in Figure 7(a). Thus, the IVCVR controlled series VSC-II of IUPQC device injects the requisite compensated voltage of -170 V into PCC of feeder B as voltage-lifting technique for regulation of critical non-linear PE load voltage as constant and balanced with a value of 340 V is shown in Figures 7(b) and 7(c).

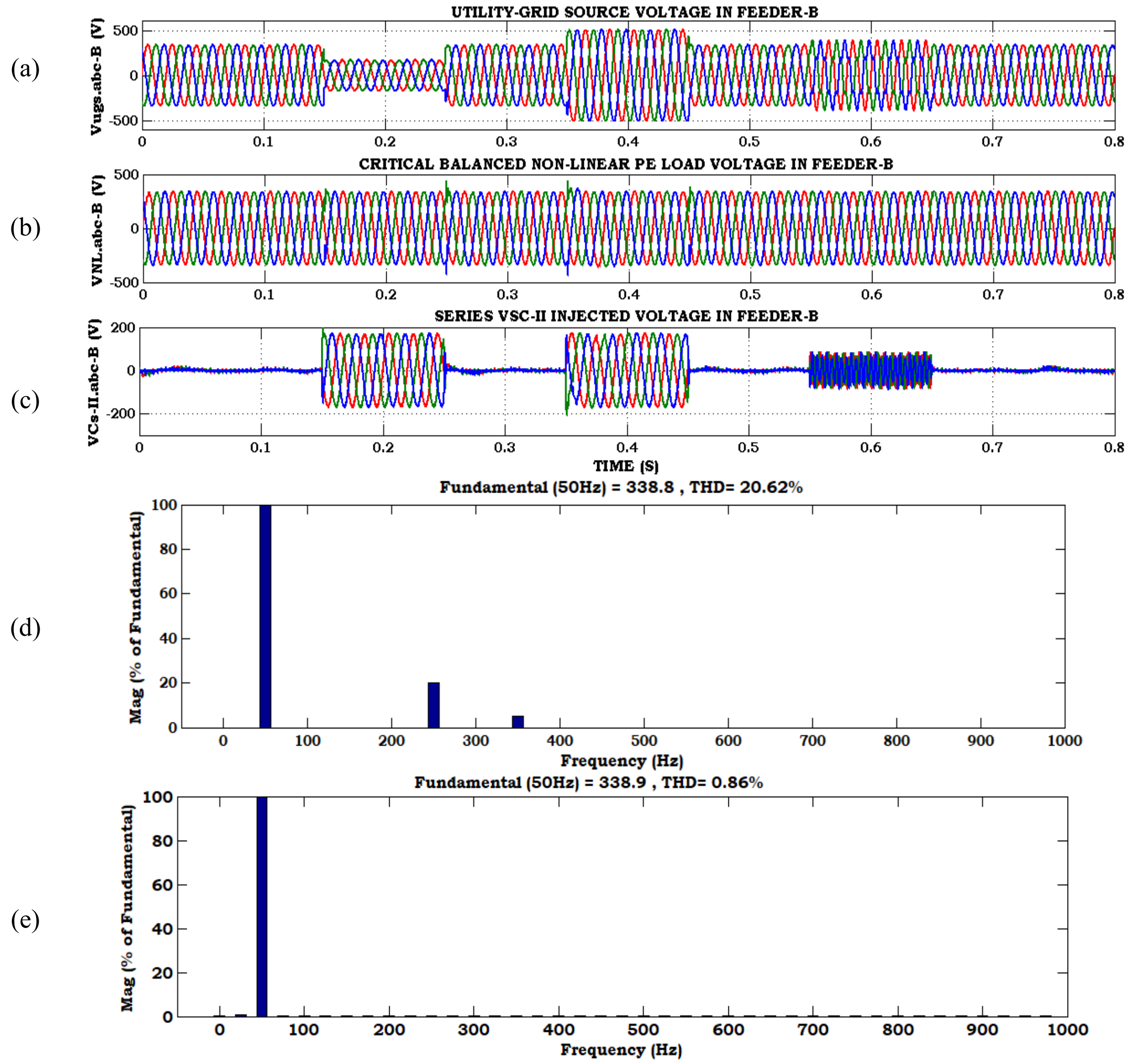

Figure 7. Simulated results of mitigation of voltage relevant PQ problems in feeder B using newly proposed IVCVR controlled VSC-II of IUPQC device: (a) utility-grid source voltage ($V_{ugs.abc\text{-}B}$ (V)), (b) series VSC-II injected voltage ($V_{Cs\text{-}II.abc}$ (V)), (c) critical balanced non-linear load voltage ($VNL._{abc\text{-}B}$ (V)), (d) THD spectrum of utility-grid source voltage, and (e) THD spectrum of critical balanced non-linear load voltage

During the time period 0.55 sec < t < 0.65 sec, the utility-grid has been distorted with 5th and 7th harmonics which affects the continuous operation of critical balanced non-linear PE load is shown in Figure 7(a). Thus, the proposed IVCVR controlled series VSC-II of IUPQC device is functioned as SAF for mitigation of voltage harmonics into PCC of feeder B. The series VSC-II injects the requisite compensated voltage of $V_{CS\text{-}II.abc}$ (V) as in-phase voltage mitigation principle which reshapes the critical balanced non-linear PE load voltage as fundamental frequency and sinusoidal in-phase form, maintained with a value of 340 V as shown in Figures 7(b) and 7(c). The THD spectrum of utility-grid source voltage during voltage harmonics in feeder B is measured as 20.62% and the THD spectrum of critical balanced non-linear PE load voltage during voltage harmonics compensation in feeder B is measured as 0.86%, which is well complying within the IEEE-519/2022 standards as depicted in Figures 7(d) and 7(e).

4.4. Mitigation of current relevant PQ problems in feeder B using newly proposed IVCVR controlled VSC-III of IUPQC device

The simulated results of mitigation of current relevant PQ problems in feeder B using newly proposed IVCVR controlled VSC-III of IUPQC device is presented in Figure 8 (see Appendix). The feeder B of the multi-feeder distribution network is powered through three-phase utility-grid voltage of 415 V_{rms}; 50 Hz is shown in Figure 8(a). In this feeder B, some of current relevant PQ issues are current harmonics, load reactive-power demand; non-ideal power-factor has occurred due to usage of critical balanced non-linear PE controlled loads. This type of loads injects the harmful odd harmonics into PCC of feeder B affecting the entire load apparatus due to thermal losses which damages the other loads connected in feeder B. In this mode, the current relevant PQ issues are mitigated by utilizing VSC-III of IUPQC device which is acted as PAF, integrated to PCC of distribution feeders-B through line interfaced filters. The newly proposed IVCVR control algorithm extracts the unique reference voltage signals, which are used to produce the feasible switching pattern to VSC-III of IUPQC device by using the HCC gate-drive circuitry.

During current compensation, the VSC-III mitigates the utility-grid/PCC source current is regulated as balanced and sinusoidal form with a value of 21 A for furnishing continuous energy to critical balanced non-linear PE load of 20 A is depicted in Figures 8(b) and 8(c). The IVCVR controlled parallel VSC-III of IUPQC device is operated as in-phase opposition current mitigation principle which injects the requisite compensation current of $I_{CSh\text{-}III.abc}$ (A) of 10 A in to feeder B is shown in Figure 8(d). It can reshape the source/PCC current of feeder B as linear nature, fundamental frequency, ideal-power factor, constant reactive-power support, and sinusoidal in-phase form. It is noted that, the parallel VSC-III regulates the source/PCC current is in-phase of grid voltage is considered as ideal power-factor is shown in Figure 8(e). Also, the DC-link controller of IVCVR algorithm regulates DC side capacitor voltage of VSC-III which is maintained as constant with a value of 880 V is shown in Figure 8(f). The THD spectrum of critical balanced non-linear PE load current in feeder B is measured as 30.02%, and the THD spectrum of utility-grid/PCC source current during current compensation in feeder B is measured as 2.68%, which is well complying within the IEEE-519/2022 standards as shown in Figures 8(g) and 8(h). The THD's spectrum comparisons and graphical view of utility-grid source voltage and critical unbalanced/balanced non-linear PE load voltages of conventional SRF and newly proposed IVCVR controlled IUPQC device in feeders A and B is illustrated in Table 2, Figure 9. The THD's spectrum comparisons and graphical view of utility-grid/PCC source current and critical unbalanced/balanced non-linear PE load currents of conventional SRF and newly proposed IVCVR controlled IUPQC device in feeders A and B are illustrated in Table 3, Figure 10. Among the certain compensation methodologies, the proposed IVCVR controlled IUPQC device has been actively mitigating the both voltage/current relevant PQ issues in both feeders A and B of the distribution network with complying with IEEE-519/2022 standards.

Table 2. THD spectrum comparison of utility-grid source voltage and critical unbalanced/balanced non-linear PE load voltages under certain compensation methods in feeders A and B

THD (%)	Utility-grid source voltage		Critical unbalanced non-linear PE load voltage of feeder A	Critical balanced non-linear PE load voltage feeder B
	Feeder A	Feeder B		
Without IUPQC	20.62%	20.64%	20.62%	20.64%
With conventional SRF controlled IUPQC device [28]	20.62%	20.63%	2.12%	1.14%
With newly proposed IVCVR controlled IUPQC device	20.62%	20.62%	1.05%	0.86%

Table 3. THD spectrum comparison of utility-grid/PCC source current and critical unbalanced/balanced non-linear PE load currents under certain compensation methods in feeders A and B

THD (%)	Critical unbalanced non-linear PE load current of feeder A	Critical balanced non-linear PE load current of feeder B	Utility grid/PCC source current	
			Feeder A	Feeder B
Without IUPQC	18.18%	30.02%	8.18%	30.02%
With conventional IRP controlled IUPQC device [29]	18.15%	30.03%	4.85%	5.08%
With newly proposed IVCVR controlled IUPQC device	18.15%	30.02%	3.07%	2.68%

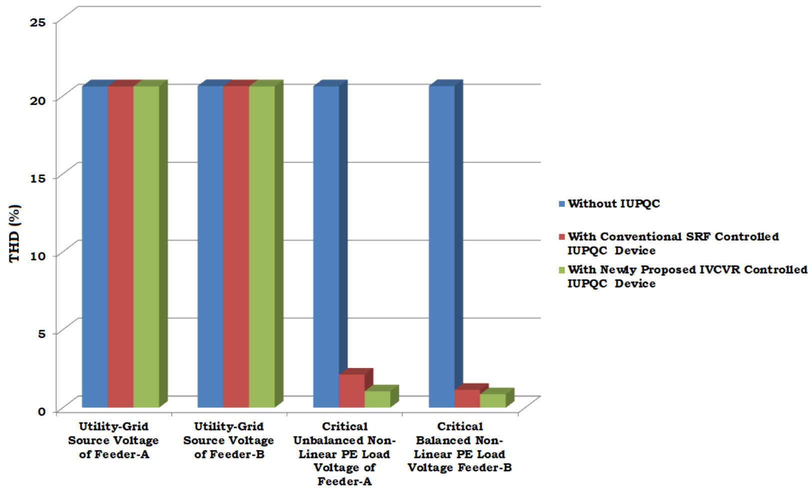

Figure 9. Graphical view THD’s spectrum of voltage values

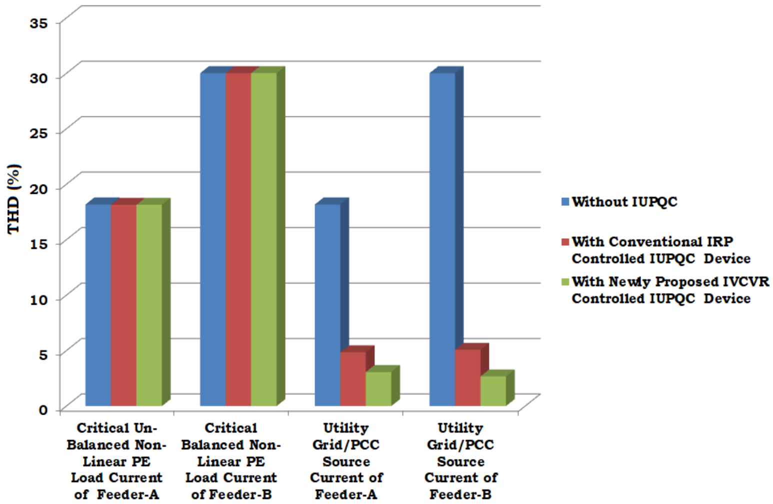

Figure 10. Graphical view THD’s spectrum of current values

5. CONCLUSION

In this work, the working and performance of newly proposed IVCVR controlled IUPQC device has been proposed for enhancing the power-quality in feeders A and B of utility-grid powered multi-feeder distribution network. The IUPQC device is most influenced compensation device, it can mitigate both voltage/current relevant PQ issues accordingly and also regulates the power-factor, reactive-power regulation, load balancing are the additional advantages. The utility-grid specifications of feeders A and B can be reshaped as linear, balanced, fundamental frequency and sinusoidal in-phase form. The newly proposed IVCVR control algorithm is the key component in compensation methodology; it can easily extract the fundamental current/voltage vector reference signals. These extracted reference signals have low transient delay, fast dynamic response designed by virtue of simple transformations/mathematical calculations among the conventional SRF/IRP controllers. The extracted reference voltage-current signals are used to produce the feasible switching pattern to VSC’s of IUPQC device by using suitable gate-drive circuitry with low dv/dt stress and attain maximum efficiency. Among the certain compensation methodologies, the THD spectrum of voltage/current values in both feeders A and B of distribution network is well within the complying of IEEE-519/2022 standards.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
CH. V. Ramachandra Rao	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓
M. Arun		✓		✓		✓	✓	✓		✓	✓	✓	✓	
B. Suresh Babu	✓		✓	✓	✓	✓	✓			✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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APPENDIX

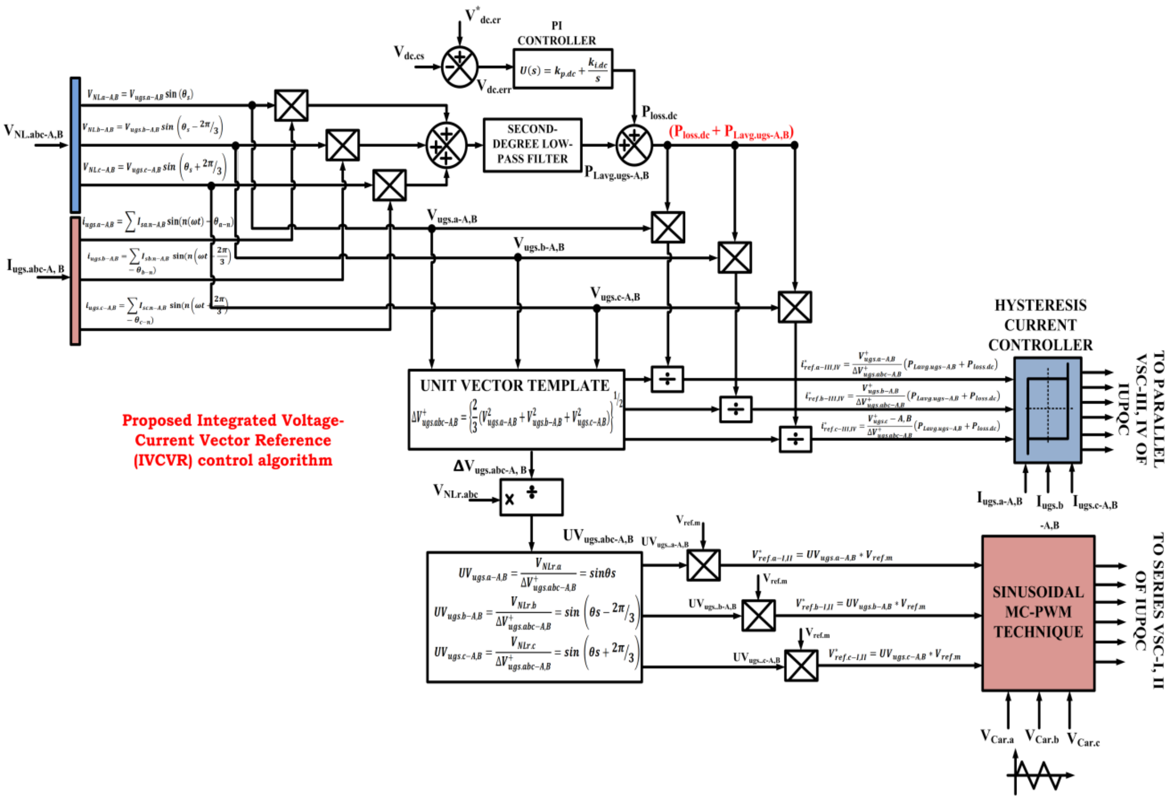


Figure 2. Block diagram of novel IVCVR control algorithm for IUPQC device

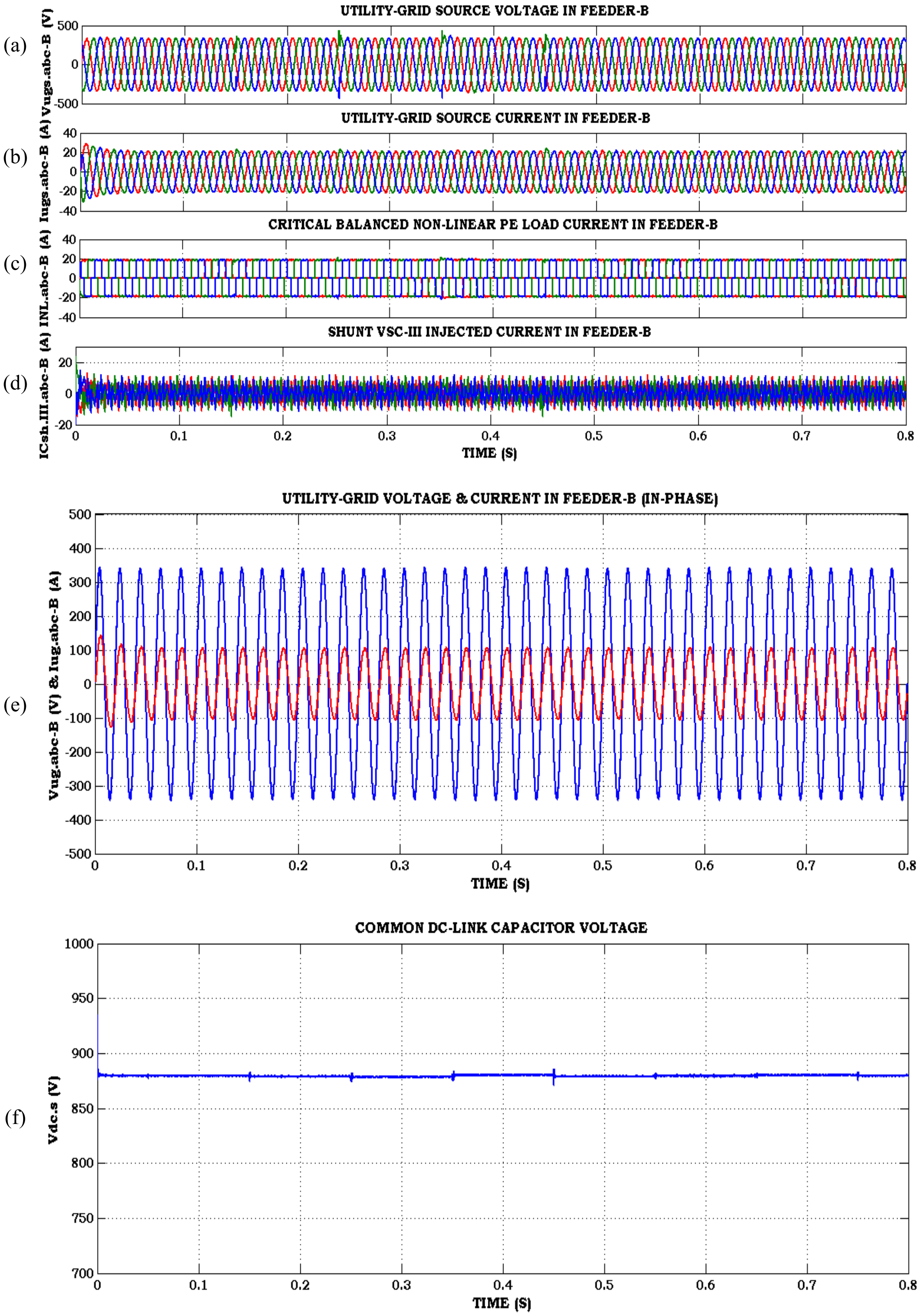
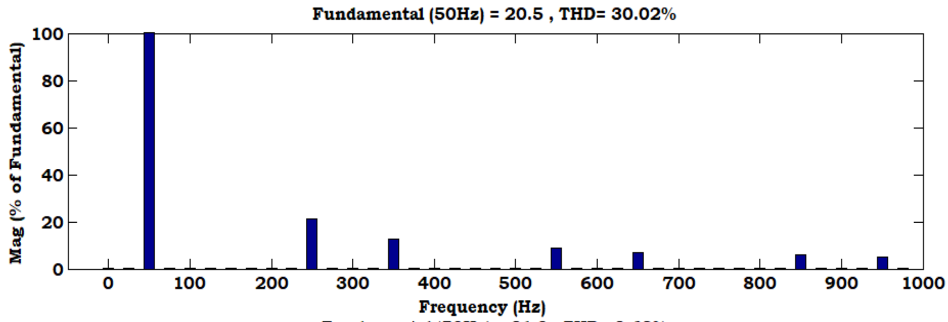


Figure 8. Simulated results of mitigation of current relevant PQ problems in feeder B using newly proposed IVCVR controlled VSC-III of IUPQC device: (a) utility-grid voltage source, (b) utility-grid source current, (c) critical balanced non-linear PE load current, (d) parallel VSC-III injected current, (e) utility-grid source voltage and current, and (f) common DC-link capacitor voltage

(g) 

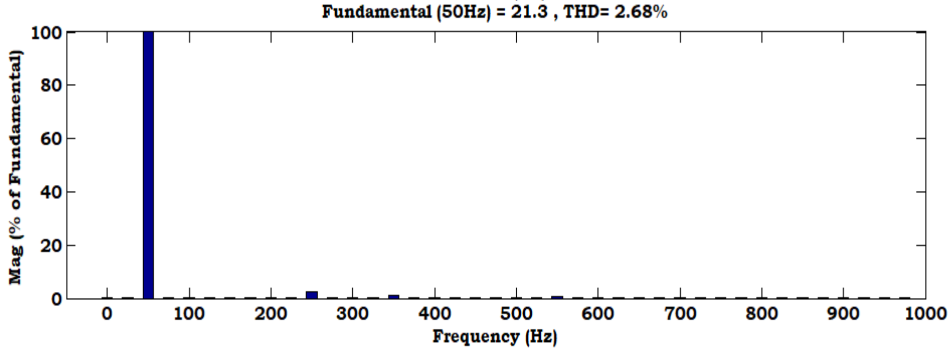
(h) 

Figure 8. Simulated results of mitigation of current relevant PQ problems in feeder B using newly proposed IVCVR controlled VSC-III of IUPQC device: (g) THD spectrum of critical balanced non-linear PE load current and (h) THD spectrum of utility-grid source current (continued)

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