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PQ enhancement in grid connected EV charging station using novel GVCR control algorithm for AUPQC device

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ABSTRACT

The rapid increase of environmental impacts together global warming is conquered by substantial selection of electric-vehicles (EV's) over the internal-combustion engine (ICE) vehicles. The replacement of these vehicles in transportation industry has led to reducing the running cost, ecological emissions, vehicle maintenance. The EV's are operated by available battery energy and energized through utility-grid integrated EV charging stations. It is noted that, such charging stations may introduce power-quality issues, highly impacting the electric-grid due to presence of power electronic conversion devices in EV charging stations. The primary emphasis of power-quality impacts on electrical distribution grid are counteracted by employing active universal power-quality conditioner (AUPQC) device. The main role of AUPQC has been selected for mitigation of various PQ problems on both electric-grid side and charging station by using feasible control objective. In this work, a novel generalized voltage-current reference (GVCR) control objective has been proposed for extraction of fundamental reference voltage-current signals. The key findings are simple mathematical notations, no transformations, fast response, low dv/dt switch stress, low switching loss and maximum efficiency. The main goal is design, operation and performance of proposed GVCR controlled AUPQC device has been validated under integration of various EV chargers to electric-grid by using MATLAB/Simulink computing tool, simulation results are presented for analysis and interpretation.

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1. INTRODUCTION

Nowadays, the substantial adoption of electric-vehicles (EV's) is relatively more privilege to automotive industry for efficient, flexible and convenient transportation over the internal-combustion engine (ICE) vehicles [1], [2]. In general, these EV's are operated by available DC energy in battery packs which are energized through electric-grid integrated EV charging stations. Due to rapid increase of EV's utilization, the demand of EV charging stations is also increased. To maximize the requisite demand, multiple EV charging infrastructures are installed in both urban and rural locations to cater the significant barrier to adoption of electric vehicles in rural communities. It is noted that, the setting-up such charging stations may introduce serious power-quality issues in electric-grid due to presence of non-linear power-electronic converters in EV charging stations [3], [4].

In this regard, electric-grid is proliferated due to massive AC to DC diode-bridge rectifiers (DBR's) used for charging the battery packs in EV system through energy conversion scheme. The main problem is usage of such power conversion devices, injects the harmonics currents in to the point of common coupling (PCC) of electric-grid [5]. This harmonized grid currents prompts the fundamental frequency, grid/PCC source voltage causing the crucial impacts such as non-unity power-factor, unbalanced loads, reactive power demand, so on. Moreover, crucial voltage fluctuations influencing the PCC of electric-grid like voltage-harmonics, voltage sags/swells are increased due to setting-up multiple EV charging infrastructures in both communities [6].

To enhance these PQ issues, several researchers and electrical power engineers are being developing sophisticated PQ mitigation techniques by introducing custom-power conditioning (CPC) methodology [7]-[10]. By using this CPC technology, various custom-power devices have been designed for compensation of associated voltage-current PQ problems to formulate the PCC of electric-grid as balanced, sinusoidal shape, fundamental nature as per IEC/IEEE standards [11]-[13]. The classification of CPC devices has been selected based on distinct PQ concerns which including, active power filters (APF's) [14], dynamic voltage regulators (DVR's) [15], distributed static compensators (DSTATCOM's) [16] and universal power-quality conditioners (UPQC) [17]-[19]. Among the aforementioned CPC devices, the AUPQC's has been specifically developing for power distribution system is explored in [20]. The AUPQC has the capability to mitigate any voltage and current PQ impacts on electric-grid and also reactive power exchanging with respect to demand, ensures to maintain the quality power in electric-grid powered EV charging stations.

The configuration of the AUPQC device is highlighted in reference [20], where it is utilizing the dual voltage-source inverters (VSI's) are organized as back-to-back topologies. The dual VSI's are configured as series-VSI and shunt-VSI connected to PCC of electrical distribution grid by using a common DC-link source. The primary emphasis of this work aims to enhance power-quality impacts in electrical distribution grid by employing AUPQC device. The main role of AUPQC device is selected for mitigation of power-quality problems on both electric-grid side and charging station considered as load side by using feasible control objective. The details of feasible control objectives are presented according to literature, for planning the extraction of reference voltage and current signals by sensing the PCC/grid supply voltage and non-linear load current during several EV chargers connected to grid network. The investigation conducted in [21] presents the instantaneous real power controller (IRP) [22], synchronous reference frame controller (SRF) [23] schemes are widely recognized schemes for extraction of current and voltage reference signals.

The major problem of this work is, that the above-studied reference extraction schemes are subject to several limitations such as, complex frame conversions, intricate mathematical notations and high reference signal delay, so on. However, these complex control schemes produce non-sinusoidal/non-fundamental reference current, which consists high switching frequencies in reference current signals subject to high dv/dt switch stress, more switching loss and degrading the overall efficiency [24], [25]. The main emphasis of this work is proposing a novel GVCR controller; it enables the extraction of sinusoidal/fundamental reference current and voltage signals. These generalized voltage-current reference signals help to produce feasible switching pattern to dual VSI's of AUPQC device for achieving enhanced PQ features in grid connected charging stations. The main goal is design, operation and performance of novel GVCR control algorithm driven AUPQC device has been validated under different PQ signatures using MATLAB/Simulink computing tool, simulation results are presented and verified with conventional control schemes.

2. PROPOSED METHOD

The schematic model of proposed AUPQC device for PQ improvement in EV connected in electric-grid distribution network is shown in Figure 1. The three-phase utility-grid is used for delivering the electric power to charge the batteries in EV's with the help of either on-board or off-board EV chargers. This EV charger utilizes non-linear DBR, which converts the available AC grid voltage in to constant DC battery voltage to make EV battery as full charging state through charge control. In this regard, the novel AUPQC device with proposed GVCR control scheme is used for mitigation of power-quality problems on both electric-grid side and load side charging station. The proposed AUPQC device comprises of dual VSI's which are organized as series/shunt VSI's 1, 2 are powered by common DC-link capacitor $C_{dc.c}$ with a constant voltage of $V_{dc.c}$. The series VSI-1 of AUPQC device is served as series-active compensator for counteracting the voltage problems like voltage-sag, voltage harmonics, voltage swells occurred in utility-grid. The series VSI-1 injects the required compensation voltage as in-phase voltage injection principle to make PCC/non-linear load voltage as sinusoidal shape, fundamental frequency, constant and balanced nature. The back-side line interfaced filters of series VSI-1 that allows injection of varying voltages for maintaining non-linear load voltage is constant which produces the continuous voltage support to EV chargers in charging stations.

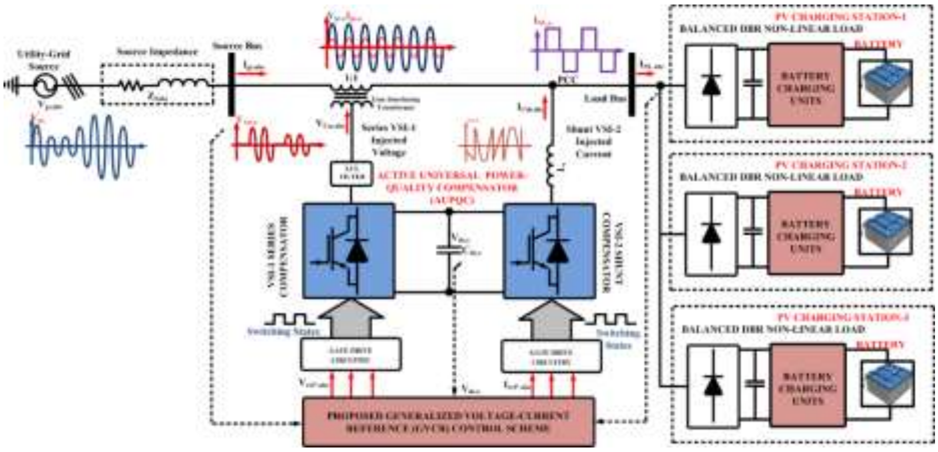


Figure 1. Schematic model of proposed AUPQC device for PQ improvement

The shunt VSI-2 of AUPQC device is served as shunt-active compensator for counteracting the harmonic currents through in-phase opposition current injection principle to recreate the grid/PCC current as balanced, sinusoidal shape, fundamental nature as per IEC/IEEE standards. The back-side line interfaced filters of shunt VSI-2 that allows injection of varying currents for reactive power regulation and also maintaining the ideal power-factor in grid/PCC point of distribution network. Thus, the AUPQC device enhances the power-quality in grid connected EV charging stations while adhering with IEEE/IEC standards through proposed GVCR control scheme, it enables the extraction of sinusoidal/fundamental reference current and voltage signals.

3. PROPOSED GVCR CONTROL ALGORITHM

The operation and performance of AUPQC device is relied on well-acclaimed proposed GVCR control algorithm for extraction of feasible voltage-current reference signals. This control algorithm helps to reduce the typical problems in regular SRF/IRP control schemes; it can produce fundamental switching frequency-based reference voltage-current signals to VSI's of AUPQC device. It is noted that, the major merits are low response latency in reference signals, no intricate mathematical transformations, and low high dv/dt switch stress, low switching loss and maximizing the overall efficiency. The extracted three-phase utility grid voltages and currents are represented as (1) and (2).

$$V_{gs.a} = V_{m.a} \sin \theta s$$

$$V_{gs.b} = V_{m.b} \, sin \left(\theta s - {}^{2\pi}/_{3}\right)$$

$$V_{gs.c} = V_{m.c} \, sin \left(\theta s + {}^{2\pi}/_{3}\right) \tag{1}$$

$$i_{gs.a} = \sum I_{ma.n} \sin(n(\omega t) - \theta_{a-n})$$

$$i_{gs.b} = \sum I_{mb.n} \sin(n\left(\omega t - \frac{2\pi}{3}\right) - \theta_{b-n})$$

$$i_{gs.c} = \sum I_{mc.n} \sin(n\left(\omega t + \frac{2\pi}{3}\right) - \theta_{c-n}) \tag{2}$$

These equivalent grid voltages and currents are multiplied and summated each other to attain average grid power ($P_{Lavg.gs}$) in a specified time instant'‘t’ is represented as (2).

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

The block diagram of proposed GVCR control algorithm for AUPQC device is depicted in Figure 2. The extracted average grid power ($P_{Lavg.gs}$) are approximated with second-order low-pass filter (SO-LPF) for allowing lower-order sequence which produce definite fundamental frequency-based reference current signals. Other side, the loss component ($P_{Loss.dc}$) is attained by comparing the actual ($V_{dc.c}$) and reference ($V^*_{dc.r}$) DC-link voltage of DC-link capacitor. Then, it produces error signals ($V_{dc.err}$) which are eliminated by using proportional-integral (PI) controller with proper proportional ($K_{p.dc}$) and integral ($K_{i.dc}$) gain values. It reduces the circulation current flow in between the series and shunt VSI-1, 2 of AUPQC device and helps to maintain DC-link voltage as constant. Thus, ($P_{Loss.dc}$) is represented as (4) and (5).

$$V_{dc.err} = V^*_{dc.r} - V_{dc.c} \tag{4}$$

$$P_{Loss.dc} = K_{p.dc}(V_{dc.err}) + K_{i.dc}\int(V_{dc.err})dt \tag{5}$$

The low-frequency fundamental reference average power ($P_{Lavg.gs}$) is summated with loss component in DC power ($P_{Loss.dc}$) for generation of actual current signal. Based on above (3) and (5), the final fundamental reference current ($i^*_{ref.abc}$) in positive sequence is represented as (6).

$$i^*_{ref.a} = \frac{V^+_{gs.a}}{\Delta V^+_{gs.abc}}\left(P_{Lavg.gs} + P_{Loss.dc}\right)$$

$$i^*_{ref.b} = \frac{V^+_{gs.b}}{\Delta V^+_{gs.abc}}\left(P_{Lavg.gs} + P_{Loss.dc}\right)$$

$$i^*_{ref.c} = \frac{V^+_{gs.c}}{\Delta V^+_{gs.abc}}\left(P_{Lavg.gs} + P_{Loss.dc}\right) \tag{6}$$

Where, ($\Delta V^+_{gs.abc}$) is the non-complex unit-vector sequence is represented as (7).

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

The reference voltage signal for series VSI-1 of AUPQC device is extracted through non-complex unit-vector sequence is differentiated with actual grid voltage is represented as (8).

$$UV_{gs.a} = \frac{V_{NL.a}}{\Delta V^+_{gs.abc}} = sin\theta s$$

$$UV_{gs.b} = \frac{V_{NL.b}}{\Delta V^+_{gs.abc}} = sin\left(\theta s - {}^{2\pi}/_{3}\right)$$

$$UV_{gs.c} = \frac{V_{NL.c}}{\Delta V^+_{gs.abc}} = sin\left(\theta s + {}^{2\pi}/_{3}\right) \tag{8}$$

The extracted unit-vector signal ($UV_{gs.abc}$) is compared with reference voltage magnitude ($V_{r.m}$), then it delivers final voltage reference signal (V^*_{refabc}) which is represented as (9).

$$V^*_{ref.a} = UV_{gs.a} * V_{r.m}$$

$$V^*_{ref.b} = UV_{gs.b} * V_{r.m}$$

$$V^*_{ref.c} = UV_{gs.c} * V_{r.m} \tag{9}$$

Finally, the reference current ($i^*_{ref.abc}$) signal is compared with actual grid current ($i_{gs.abc}$), for generation of possible switching pattern to shunt VSI-2 of AUPQC device for compensation of current PQ issues by using hysteresis current controller (HCC) drive circuitry. And also, the final reference voltage signal ($V^*_{ref.abc}$) is compared with triangular carrier signals ($V_{Cabc.ref}$) for generation of possible switching pattern to series VSI-1 of AUPQC device for compensation of voltage PQ issues by using sinusoidal pulse-width modulation (SPWM) gate-drive circuitry. The overall schematic diagram of novel GVCR controlled AUPQC device for PQ enhancement in grid connected EV charging station is depicted in Figure 3. The operation and performance of novel GVCR control algorithm driven AUPQC device is validated under different PQ signatures using MATLAB/SIMULINK computing tool, simulation results are presented and verified with conventional control schemes. The system Simulink data is presented in Table 1.

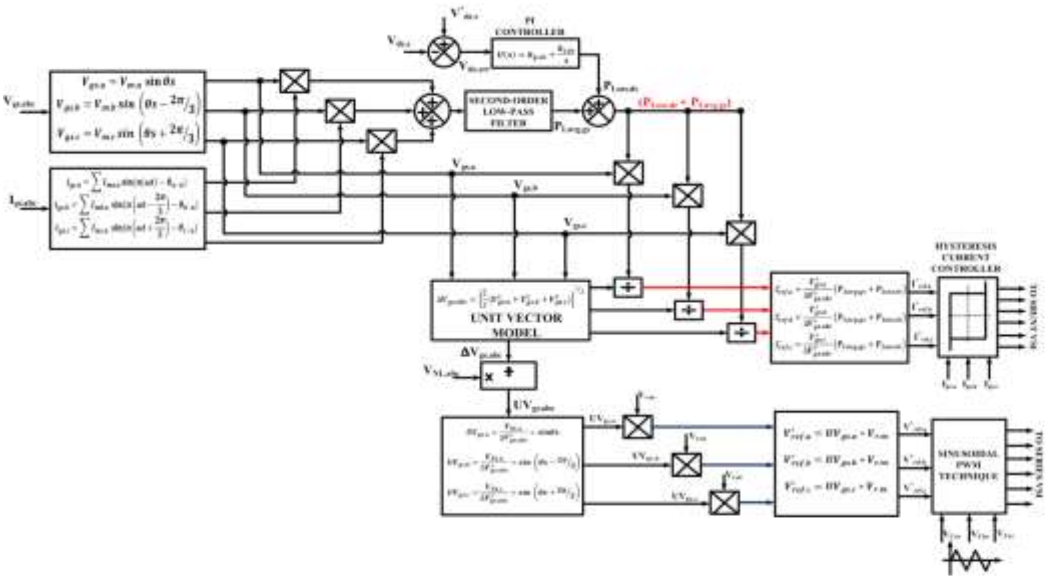


Figure 2. Block diagram of proposed GVCR control algorithm for AUPQC device

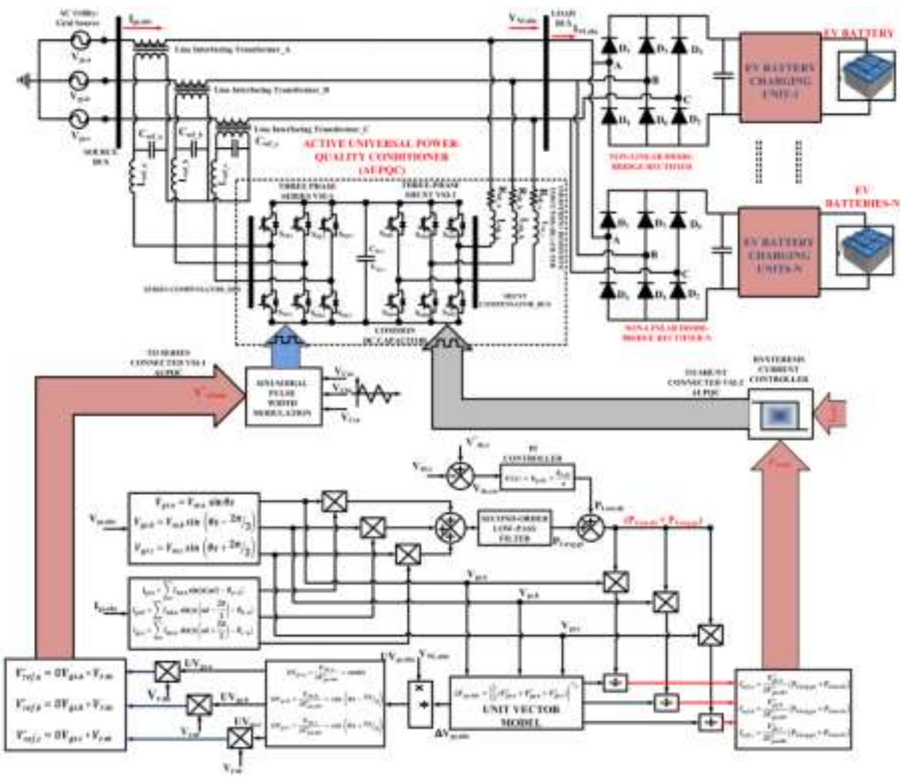


Figure 3. Overall schematic diagram of novel GVCR controlled AUPQC device for PQ enhancement in grid connected EV charging station

4. RESULTS AND DISCUSSION

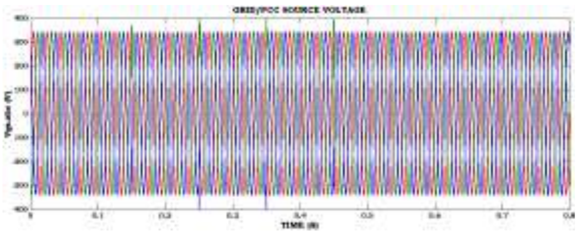
The overall schematic diagram of novel GVCR controlled AUPQC device for PQ enhancement in grid connected EV charging station is depicted in Figure 3. The operation and performance of novel GVCR control algorithm driven AUPQC device is validated under different PQ signatures using MATLAB/SIMULINK computing tool, simulation results are presented and verified with conventional control schemes. The system Simulink data is presented in Table 1.

Table 1. System Simulink data

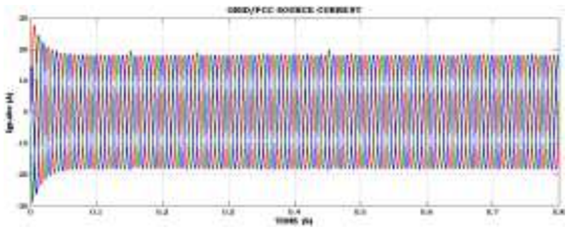
S. No	Simulink components	Values
1	Utility-grid voltage	$V_{gs.abc}$=415 V, F_{gs}=50 Hz
2	Utility-grid impedance	R_{gs}=0.1 Ω, L_{gs}=0.9 mH
3	DBR non-linear load impedance (Number of EV chargers)	Charger 1-$R_{NL.abc}$=5 Ω to 25 Ω, $L_{NL.abc}$-30 mH Charger 2-$R_{NL.abc}$=15 Ω to 25 Ω, $L_{NL.abc}$-30 mH Charger 3-$R_{NL.abc}$=25 Ω to 25 Ω, $L_{NL.abc}$-30 mH
4	DC-link voltage and capacitor value	$V_{dc.c}$=880 V, $C_{dc.c}$=1500 μF
5	Shunt VSI-2 filter	R_{shf}=0.1 Ω, L_{shf}=5 mH
7	PI gain values	$K_{p.dc}$=0.5, $K_{i.dc}$=0.15

4.1. Compensation of current harmonics in utility-grid/PCC of distribution system under single EV-charger by using proposed GVCR controlled shunt VSI-2 of AUPQC device

The simulation results of current harmonics compensation in utility-grid/PCC of distribution system under single-EV charger by using proposed GVCR controlled shunt VSI-2 of AUPQC device is shown in Figure 4. The single EV charger consists of one DBR load which is powered by three-phase distribution system via three-phase utility-grid source with a voltage of $V_{gs.abc}$-415V_{rms} and constant system frequency of F_{gs}-50 Hz is shown in Figure 4(a) The front-end three-phase DBR is used for charging the batteries in EV system through AC to DC conversion process. During this conversion process that DBR injects the dangerous harmonic currents in to utility-grid/PCC affecting the sinusoidal and fundamental nature of grid/PCC current, also disturbing the other-loads interface. In this regard, the shunt VSI-2 of AUPQC device with proposed GVCR control algorithm is employed for compensation of dangerous harmonic currents at utility-grid/ PCC of distribution network. Mainly, the proposed GVCR algorithm enables the extraction of fundamental reference currents helps to produce the feasible switching states to shunt VSI-2 of AUPQC device for PQ enhancement as per IEC/IEEE standards. It maintains the utility-grid/PCC current as balanced and sinusoidal shape with a value of 18A for delivering the non-linear DBR load current of 16A as shown in Figures 4(b) and (c). The shunt VSI-2 operated as in-phase opposition compensation principle which injects the requisite compensation current of 8A as shown in Figure 4(d), respectively. For this compensation, thus utility-grid/PCC current is served as in-phase with the PCC source voltage to maintain ideal power factor at grid/PCC of distribution network is shown in Figure 5. The THD spectrum during current harmonics compensation is shown in Figure 6. In that, the THD spectrum analysis of non-linear load current of single-EV charger integration is computed with a value of 30.18% and the THD spectrum analysis of utility-grid/PCC source current is computed with a value of 1.64% is depicted in Figures 6(a) and (b) which is well-being as per IEEE-519/2014 limits.



(a)



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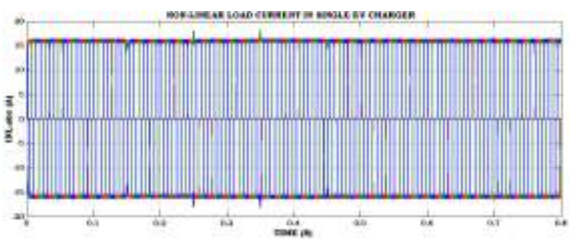
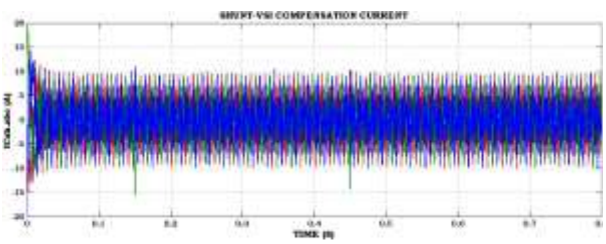


(c)



(d)

Figure 4. Compensation of current harmonics in utility-grid/PCC of distribution system under single-EV charger using proposed GVCR controlled shunt VSI-2 of AUPQC device: (a) utility grid/PCC source voltage, (b) grid/PCC source current, (c) non-linear load current in single EV charger, and (d) shunt VSI-2 compensation current (from top to bottom)

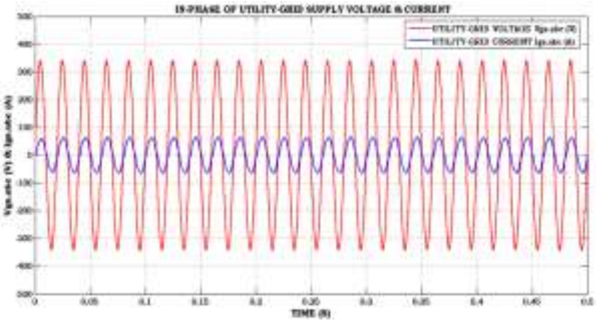
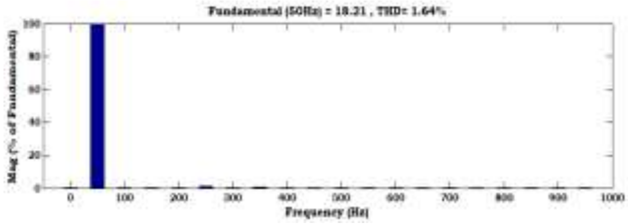
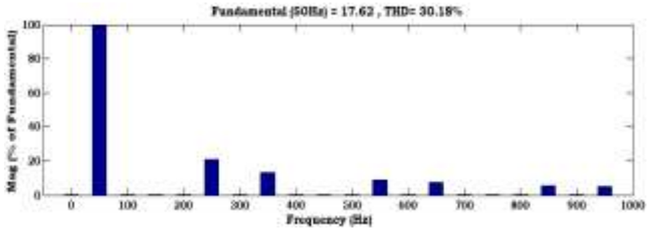


Figure 5. In-phase of grid/PCC voltage and current



(a)

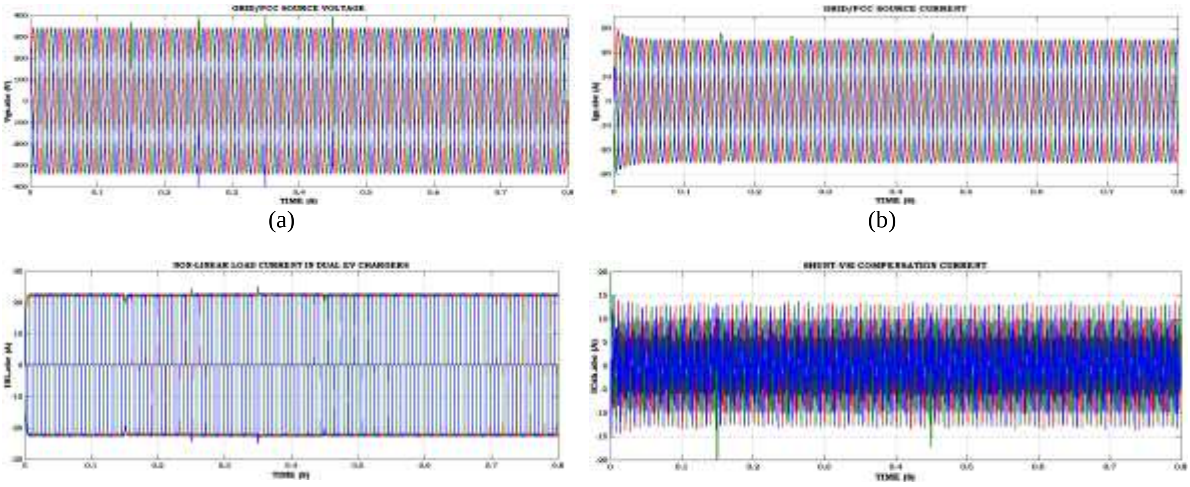


(b)

Figure 6. THD spectrum analysis, (a) THD spectrum of non-linear load current and (b) THD spectrum of utility-grid/PCC current

4.2. Compensation of current harmonics in utility-grid/PCC of distribution system under two EV-chargers by using proposed GVCR controlled shunt VSI-2 of AUPQC device

The simulation results of current harmonics compensation in utility-grid/PCC of distribution system under two-EV chargers by using proposed GVCR controlled shunt VSI-2 of AUPQC device is shown in Figure 7. These two EV chargers consist of dual DBR’s which are powered by three-phase distribution system via three-phase utility-grid source with a voltage of $V_{gs.abc}$-415V_{rms} and constant system frequency of F_{gs}-50 Hz is shown in Figure 7(a). The front-end three-phase DBR is used for charging the batteries in EV system through AC to DC conversion process. During this conversion process that DBR injects the dangerous harmonic currents in to utility-grid/PCC affecting the sinusoidal and fundamental nature of grid/PCC current, also disturbing the other-loads interface. In this regard, the shunt VSI-2 of AUPQC device with proposed GVCR control algorithm is employed for compensation of dangerous harmonic currents at utility-grid/PCC of distribution network. Mainly, the proposed GVCR algorithm enables the extraction of fundamental reference currents helps to produce the feasible switching states to shunt VSI-2 of AUPQC device for PQ enhancement as per IEC/IEEE standards. It maintains the utility-grid/PCC current as balanced and sinusoidal shape with a value of 25A for delivering the non-linear DBR load current of 22A as shown in Figures 7(b) and (c). The shunt VSI-2 operated as in-phase opposition compensation principle which injects the requisite compensation current of 13A as shown in Figure 7(d), respectively. For this compensation, thus utility-grid/PCC current is served as in-phase with the PCC source voltage to maintain ideal power factor at grid/PCC of distribution network is shown in Figure 8. The THD spectrum during current harmonics compensation is shown in Figure 9. In that, the THD spectrum analysis of non-linear load current of dual-EV chargers’ integration is computed with a value of 29.87% and the THD spectrum analysis of utility-grid/PCC source current is computed with a value of 2.12% is depicted in Figures 9(a) and (b) which is well-being as per IEEE-519/2014 limits.



(a) (b)

(c) (d)

Figure 7. Compensation of current harmonics in utility-grid/PCC of distribution system under two-EV chargers by using proposed GVCR controlled shunt VSI-2 of AUPQC device: (a) utility grid/PCC source voltage, (b) grid/PCC source current, (c) non-linear load current in two EV chargers, and (d) shunt VSI-2 compensation current (from top to bottom)

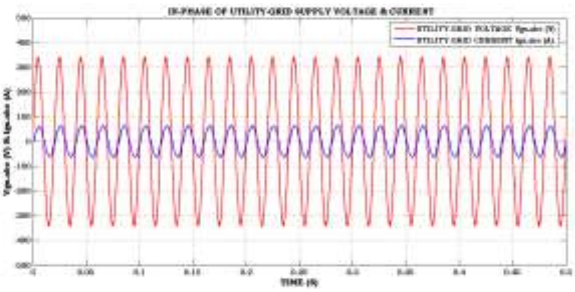
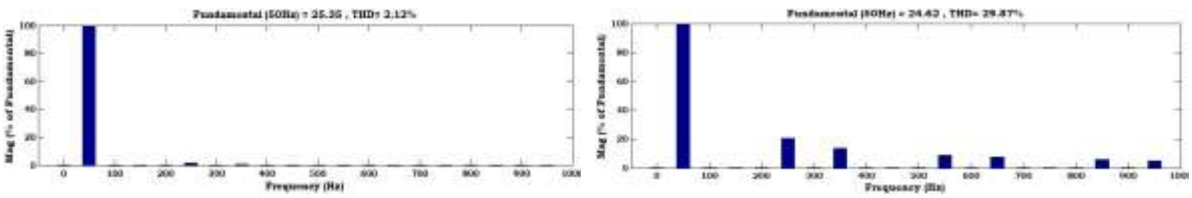


Figure 8. In-phase of grid/PCC voltage and current

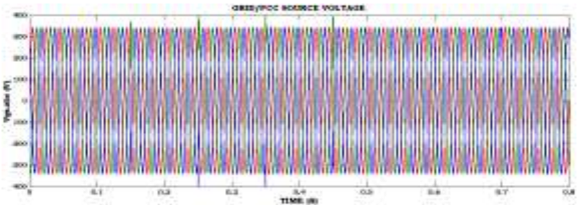


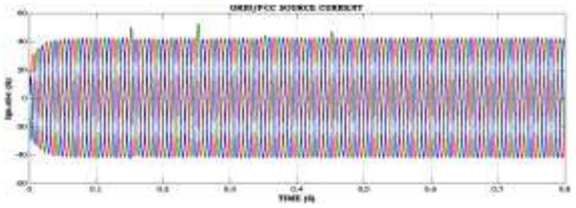
(a) (b)

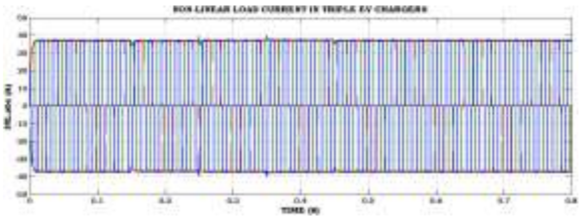
Figure 9. THD spectrum analysis (a) THD spectrum of non-linear load current and (b) THD spectrum of utility-grid/PCC current

4.3. Compensation of current harmonics in utility-grid/PCC of distribution system under three EV-chargers by using proposed GVCR controlled shunt VSI-2 of AUPQC device

The simulation results of current harmonics compensation in utility-grid/PCC of distribution system under three-EV chargers by using proposed GVCR controlled shunt VSI-2 of AUPQC device is shown in Figure 10. These three EV chargers consist of triple DBR's which are powered by three-phase distribution system via three-phase utility-grid source with a voltage of $V_{gs.abc}$-415V_{rms} and constant system frequency of F_{gs}-50 Hz is shown in Figure 10(a). The front-end three-phase DBR is used for charging the batteries in EV system through AC to DC conversion process. During this conversion process that DBR injects the very dangerous/harmful harmonic currents in to utility-grid/PCC affecting the sinusoidal and fundamental nature of grid/PCC current, also disturbing the other-loads interface. In this regard, the shunt VSI-2 of AUPQC device with proposed GVCR control algorithm is employed for compensation of dangerous harmonic currents at utility-grid/PCC of distribution network. Mainly, the proposed GVCR algorithm enables the extraction of fundamental reference currents helps to produce the feasible switching states to shunt VSI-2 of AUPQC device for PQ enhancement as per IEC/IEEE standards. It maintains the utility-grid/PCC current as balanced and sinusoidal shape with a value of 42A for delivering the non-linear DBR load current of 37A as shown in Figures 10(b) and (c). The shunt VSI-2 operated as in-phase opposition compensation principle which injects the requisite compensation current of 20A as shown in Figure 10(d), respectively. For this compensation, thus utility-grid/PCC current is served as in-phase with the PCC source voltage to maintain ideal power factor at grid/PCC of distribution network is shown in Figure 11. The THD spectrum during current harmonics compensation is shown in Figure 12. In that, the THD spectrum analysis of non-linear load current of triple-EV chargers' integration is computed with a value of 29.23% and the THD spectrum analysis of utility-grid/PCC source current is computed with a value of 3.03% is depicted in Figure 12(a) and (b), which is well-being as per IEEE-519/2014 limits.


(a)


(b)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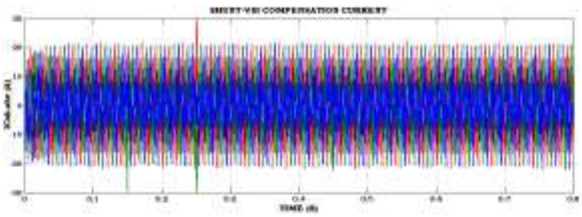

(d)

Figure 10. Compensation of current harmonics in utility-grid/PCC of distribution system under three-EV Chargers by using proposed GVCR controlled shunt VSI-2 of AUPQC device: (a) utility grid/PCC source voltage, (b) grid/PCC source current, (c) non-linear load current in three EV chargers, and (d) shunt VSI-2 compensation current (sub-figure representation from top to bottom)

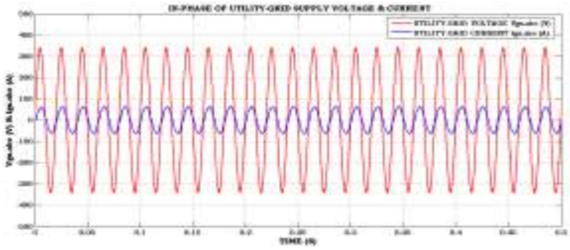
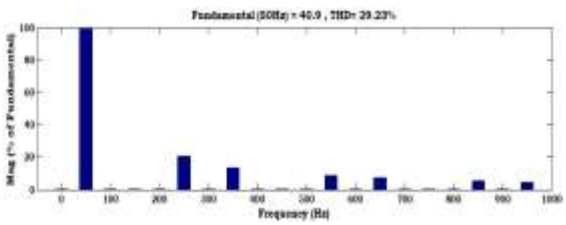
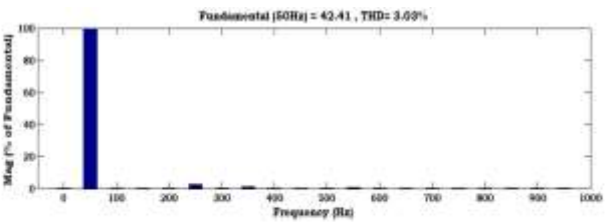


Figure 11. In-phase of grid/PCC voltage and current



(a)



(b)

Figure 12. THD spectrum analysis (a) THD spectrum of non-linear load current and (b) THD spectrum of utility-grid/PCC current

4.4. Compensation of voltage PQ issues in utility-grid/PCC of distribution system by using proposed GVCR controlled series VSI-1 of AUPQC device

The simulation results of voltage PQ issues compensation in utility-grid/PCC of distribution system by using proposed GVCR controlled series VSI-1 of AUPQC device is shown in Figure 13. In general, these EV chargers consist of several DBR's which are powered by three-phase distribution system via three-phase utility-grid source voltage of $V_{gs.abc}$-415V_{rms} and constant system frequency of F_{gs}-50 Hz is shown in Figure 13(a). The front-end three-phase DBR is used for charging the batteries in EV system through AC to DC conversion process. In this case, the voltage harmonics, voltage sags/swells are developed in utility-grid/PCC of distribution network, these voltage PQ issues affecting the continuous power-flow to EV charging stations. Due to these voltage disturbances, the front-end DBR's are not properly functioned for charging the EV batteries. In this regard, the series VSI-1 of AUPQC device with proposed GVCR control algorithm is employed for compensation of voltage interruptions such as voltage harmonics, voltage sags/swells at utility-grid/PCC of distribution network. Mainly, the proposed GVCR algorithm enables the extraction of fundamental reference voltages helps to produce the feasible switching states to series VSI-1 of AUPQC device for PQ enhancement as per IEC/IEEE standards. Before time period t_p<0.15 sec is considered as pre-sag state, in this state utility-grid/PCC voltage is maintained as constant potential value of 340V.

The voltage-sag has been developed in this time period (0.15 sec<t<0.25 sec), then the utility-grid/PCC voltage is decreased by 50% which is calculated as 170V and affecting the non-linear DBR load voltage as inconstant. In this period, the series VSI-1 of AUPQC device injects the required compensation voltage of 170V to maintain load voltage is constant of 340V. Similarly, the voltage-swell has been developed in this time period (0.35 sec<t<0.45 sec), then the utility-grid/PCC voltage is increased by 50% which is calculated as 510V and misoperations of non-linear DBR load voltage as inconstant. In this period, the series VSI-1 of AUPQC device extracts the additional compensation voltage of 170V to maintain load voltage is constant of 340V. However, the voltage-harmonics has been developed in this time period (0.6 sec<t<0.7 sec), then the utility-grid/PCC voltage is affected as non-sinusoidal and fundamental nature. In this period, the series VSI-1 of AUPQC device injects the compensation voltage as in-phase opposition compensation principle to maintain non-linear DBR load voltage is balanced, sinusoidal shape and fundamental nature as per IEEE standards as shown in Figures 13 (a)-(c). The THD spectrum during voltage harmonics compensation is shown in Figure 14. In that, the THD spectrum analysis of utility-grid/PCC voltage is computed with a value of 20.62% and the THD spectrum analysis of non-linear DBR voltage is computed with a value of 2.02% is depicted in Figures 14(a) and (b), which is well-being as per IEEE-519/2014 limits.

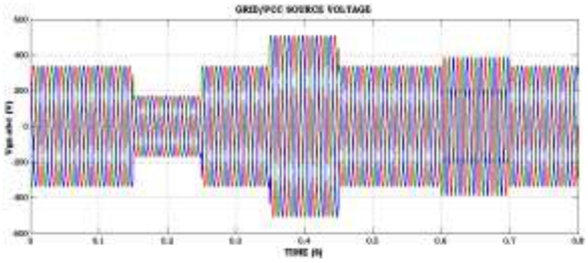
The THD comparisons and graphical view of non-linear DBR load current and utility-grid/PCC current under integration of various EV chargers are illustrated in Table 2 and Figure 15. In graphical view, it is noted that the proposed GVCR control scheme values are shown in Figure 15(a) provides the feasible compensation current for mitigation of harmonic current distortions and also maintains the good harmonic profile compared to conventional IRP control scheme as shown in Figure 15(b). The THD comparisons and graphical view of utility-grid/PCC voltage and non-linear DBR load voltage under integration of various EV chargers are illustrated in Table 3 and Figure 16. In graphical view, it is noted that the proposed GVCR control scheme values are shown in Figure 16(a) provides the feasible compensation voltage for mitigation of voltage harmonics and also maintains the good harmonic profile compared to conventional SRF control scheme are shown in Figure 16(b).

Table 2. THD comparisons of non-linear DBR load current and utility-grid/PCC current under integration of various EV chargers

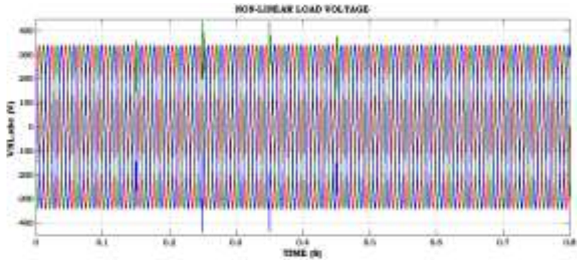
Current THD (%)	Conventional IRP controlled AUPQC device [24]		Proposed GVCR controlled AUPQC device	
	Non-linear DBR load current	Utility-grid/PCC current	Non-linear DBR load current	Utility-grid/PCC current
Integration of single-EV charger	30.08%	2.87%	30.18%	1.64%
Integration of dual-EV chargers	29.60%	3.91%	29.87%	2.12%
Integration of triple-EV chargers	28.05%	6.05%	29.23%	3.03%

Table 3. THD comparisons of utility-grid/PCC voltage and non-linear DBR load voltage under integration of various EV chargers

Voltage THD (%)	Conventional SRF controlled AUPQC device [25]		Proposed GVCR controlled AUPQC device	
	Utility-grid/PCC voltage	Non-linear DBR load voltage	Utility-grid/PCC voltage	Non-linear DBR load voltage
Integration of single-EV charger	20.62%	2.76%	20.62%	1.01%
Integration of dual-EV chargers	20.62%	3.29%	20.62%	1.56%
Integration of triple-EV chargers	20.62%	4.82%	20.62%	2.02%



(a)



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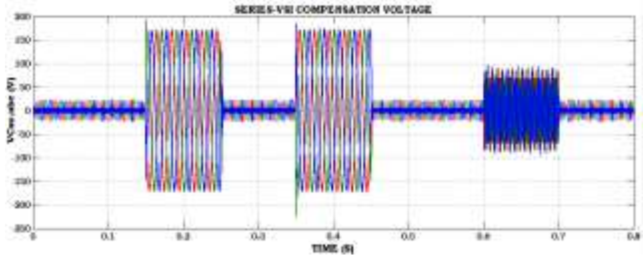
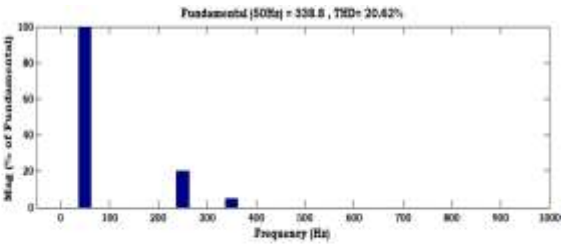
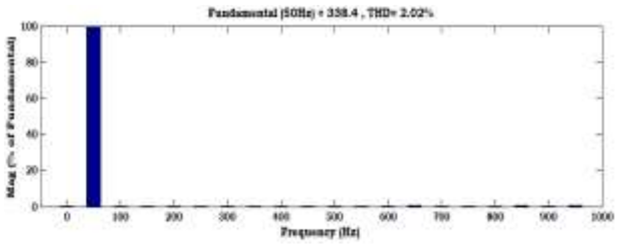


(c)

Figure 13. Compensation of voltage PQ issues in utility-grid/PCC of distribution system by using proposed GVCR controlled series VSI-1 of AUPQC device, (a) utility grid/PCC source voltage, (b) non-linear DBR load voltage, and (c) series VSI-1 compensation voltage (from top to bottom)

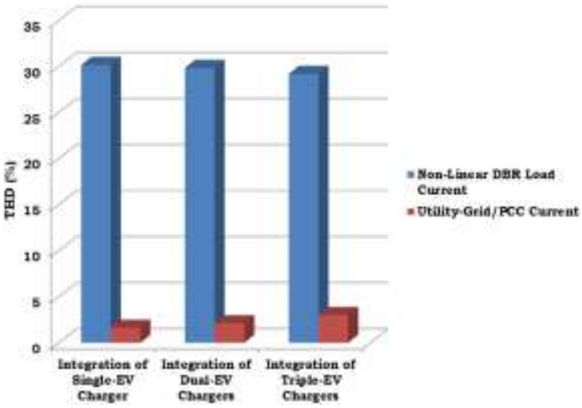


(a)

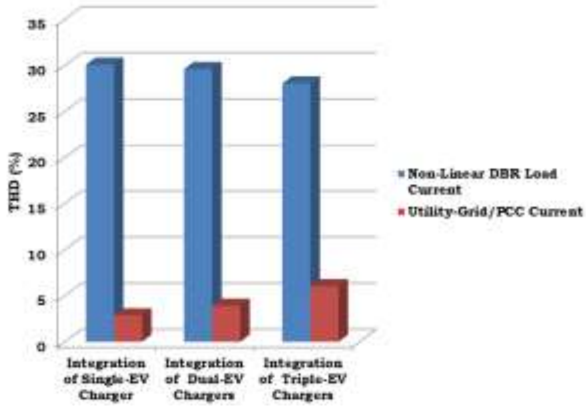


()b

Figure 14. Harmonic spectrum analysis during voltage harmonic compensation (a) THD spectrum of grid/PCC voltage and (b) THD spectrum of non-linear load voltage

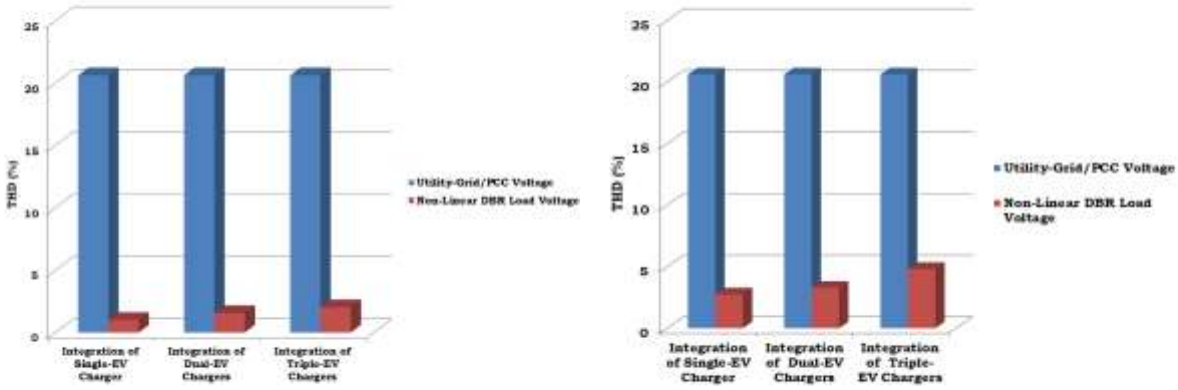


(a)



(b)

Figure 15. Graphical view of non-linear DBR load current and utility-grid/PCC current under integration of various EV chargers (a) in proposed GVCR control scheme and (b) in conventional IRP control scheme



(a) (b)

Figure 16. Graphical view of utility-grid/PCC voltage and non-linear DBR load voltage under integration of various EV chargers (a) in proposed GVCR control scheme and (b) in conventional SRF control scheme

5. CONCLUSION

In this work, a novel GVCR control scheme has been proposed to accomplish an attractive compensation strategy of AUPQC device for mitigation of both current and voltage PQ issues in utility-grid and end-level EV charging station. The proposed GVCR algorithm enables the extraction of fundamental reference currents helps to produce the feasible switching states to shunt and series VSI's-1,2 of AUPQC device for PQ enhancement as per IEC/IEEE standards. It is noted that, low response delay, without any complex mathematical transformations low dv/dt switch stress, low switching loss and maximizing the overall efficiency are the key merits of proposed GVCR control schemes. It provides the feasible compensation current/voltage for mitigation of harmonic currents/voltage distortions in utility-grid connected EV charging station and maintains the good harmonic profile compared to conventional IRP/SRF control schemes. The operation and performance of proposed GVCR controlled AUPQC device is presented and validated under integration of various EV chargers by using MATLAB/Simulink computing tool, simulation results are well-being complying with IEEE-519/2014 standards.

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