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Optimization of Power Quality Using the Unified Power Quality Conditioner (UPQC) with Unbalanced Loads

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ABSTRACT

The power quality (PQ) is a major issue for both electrical utilities and their customers. The nonlinear loads cause PQ problems like current harmonics, voltage harmonics, frequency deviation, voltage sag and voltage swell. A unified power quality conditioner (UPQC) is utilized in this research to minimize these PQ problems. The UPQC is made up of two active power filters (APFs), one of which is connected to the line in series and the other in parallel. The Unit Vector Template Generation (UVTG) approach is used to control the series APF, whereas the Synchronous Reference Frame (SRF) technique is used to control the shunt APF. The compensating properties of a series-shunt APFs when the loads become imbalanced have been explored. The system performance has been tested under conditions current harmonics, voltage harmonics, voltage sag, and voltage swell. The voltage harmonics are identified and reparation in a series APF using the UVTG technique, whereas the harmonics and unbalanced currents are identified and reparation in a shunt APF using the SRF method. An IEEE-519-compliant THD (Total Harmonic Distortion) of less than 5% is achieved by UPQC in simulations with unbalanced loads. The findings indicate that harmonic currents and supply voltage fluctuations were lessened by UPQC.

Keywords:

Voltage swell, Voltage-sag, Unbalance-loads, UPQC, Harmonics.

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1. INTRODUCTION

The emergence of PQ issues is unavoidable with the increasing use of nonlinear loads. Further, modern processing equipment is becoming more sensitive to PQ [1]. The main issues with PQ include voltage sag, voltage swell, transient, frequency deviation, flicker, harmonics in voltage and current, increased reactive power burden and zero sequence current [2]. These devices, equipment, nonlinear loads, and so forth draw non-sinusoidal currents from the utility. As a result, a typical power distribution system must cope with 'harmonics' in additional to reactive power support [3]. In order to further enhance PQ, flexible AC transmission system FACTS devices are used [4]. The UPQC is one of the diverse FACTS devices.

The purpose of UPQC is to recompense supply voltage flicker/imbalance, reactive power, negative sequence current, and harmonics. The UPQC can improve PQ at the point of common coupling (PCC) on power distribution or industrial power systems [5].

The UPQC is one of the finest options for providing balanced, distortion-free, and constant magnitude power to sensitive loads while also limiting harmonics, imbalance, and reactive power requested by the load and so making the entire power distribution system more healthy [6].

In (1998) Fujita and Akagi designed the first practical application of UPQC, employing a shunt APF and a series APF connected via a shared DC connection [7]. Since then, many researchers have developed this device and created a variety of topologies, models, and control methods for it.

In (2002) M. Basu and et al. designed a 1-phase and also a 3-phase UPQC-Q. As a result of this design, the series inverter injects voltage in quadrature advance to the source current, consuming no active power under steady state. The UPQC that uses quadrature voltage injection in series is known as UPQC-Q. Because the series converter injects enough voltage to sustain the load voltage at the appropriate level, the simulation results showed that the supply voltage sag had no influence on the load voltage. Additionally, the shunt converter supplied harmonics and reactive power to the load [8].

In (2005) Y. Kolhatk et al. developed a 3-phase UPQC with an enhanced (DVR) structure. In order to achieve the least voltage sag with the least amount of imbalance or no imbalance, the UPQC runs in the lowest VA optimization mode. The DVR with Sliding-mode control for improved tracking performance has been included. The load voltage was regulated, resulting in the least possible VA load on the UPQC thanks to the injection of voltage at the optimal angle [9].

In (2009) J. A. Muñoz and et al. suggested a technique for select the components for a modular unified power-quality conditioner configuration based on single-phase cells. Due to the power cells are based on single-phase converters on both the series and shunt sides, the suggested architecture does compensation for each phase separately. Also because a modular method may employ an arbitrary number of cells, the suggested design technique allowed for the selection of power semiconductors and capacitors based on an economic evaluation that allowing for the ideal number of cells to be chosen to reduce total power cell cost [10].

In (2011) V. Khadkikar and et al. proposed a novel approach for optimizing the use of a (UPQC). When voltage sags or swells, the UPQC series converter is programmed to compensate for this by participation load reactive power for shunt converter. Active power control theory was used to recompense for voltage swell/sag, and the UPQC's PAC method is included to coordination the reactive power of the load between the two converters. This theory is referred to as UPQC-S. Simulations and experimental studies affirmed the viability of the proposed concept of voltage swell/sag and load reactive power sharing for the UPQC series converter [11].

In (2015) A. K. Panda and et al. proposed a novel PAC-SRF-based UPQC strategy for 1-phase distribution networks. The PAC concept is utilized to introduce a necessary phase angle shift of the load voltage with respects to the supply voltage to incorporate a reactive power sharing feature for the UPQC series inverter. An SRF-based controller has been being developed for both series and shunt converters of the UPQC to eliminate distortion in load voltage and source current. An SRF-based approach is more effective for power computation in distorted conditions than other control systems. Using simulations and real-time analyses, the researchers achieved that the PAC-SRF technology offers a comprehensive tool for improving PQ [12].

In (2016) S. Devassy and et al. proposed a modified p-q theory-based control of a unified power quality conditioner incorporated into a solar photovoltaic (PV) array (PV-UPQC-S). By simulating the system in Matlab-Simulink with a mix of linear and non-linear loads, the dynamic performance of the improved p-q theory-based PV-UPQC-S was validated. Under nominal conditions, the series VSC shares a portion of the reactive power of the load, enhancing series VSC usage while also lowering shunt VSC loading. The suggested system could operate in the presence of numerous disturbances, such as irradiation variation and PCC voltage fluctuations that occur at the same time. The PV-UPQC-S system combines the notion of clean energy generation with the enhancement of power quality, hence enhancing its usefulness [13].

In (2017), Jia Yea and et al. suggested a new method for assessing the optimal UPQC size on the basis of compensation requirements, which sets the basic ratings of the series inverter, shunt inverter, and series transformer. Based on data-driven control (DDC) and variable phase angle control (PAC) methods, a UPQC system has been implemented under various compensation situations. In addition, the findings from the MATLAB and OPAL-RT simulation were demonstrated the applicability of the method and the DDC based controllers [14].

In (2018) A. Patel and et al. proposed an improved (PAC) approach for UPQC- DG to effectively compensate for imbalanced loads. PAC approaches for UPQC-DG have been developed to improve VA usage of UPQC-DG series and shunt APFs. Existing PAC approaches result in reactive power circulation and increased VA loading of the UPQC-DG in the event of unbalanced loads. Because it is based on (SRF) theory, the suggested PAC approach is robust to non-ideal voltages. Real-time simulation in Opal-RT was used to evaluate the performance of the suggested PAC approach. The simulation results display that employing the suggested PAC approach in the UPQC-DG performs well in the presence of unbalanced and non-linear loads [15].

In (2019), A. Szromba and et al. developed a novel technique for controlling the operation of UPQC series-parallel active filters. The S.Fryze's concept of load equivalent conductance was used in this study. In addition to improving the goodness of supply voltage, the proposed approach allows conventional repairs for nonactive components of load current and harmonics in source voltage. There is no need to extraction voltage and current harmonics for the control technicality given. As a result, the UPQC's control module's computing effort may be greatly decreased [16].

In (2020) A. K. Yadav and et al. suggested unified power quality conditioning system effective for compensating for supply voltage and load current in a multi-bus system. One shunt and two series VSCs are including in the MC-UPQC configuration. The MC-UPQC is a useful device for resolving PQ problems in custom power applications. This approach is applied between two transmission lines, or in other words, between several feeders, for the arrangement of voltage and current compensation as well as nonlinear loads. The improvement in power quality is examined by comparing the THD values of proposed technique and without it [17].

In (2021) S. K. Dash and et al. employed a new architecture for a PV fed open-UPQC, with an emphasis on voltage sensitive loads. The suggested PV-Open-UPQC system has been developed and implemented. The system's robustness against different voltage and current distortions has been improved with adaptive controllers for the UPQC series and shunt compensators. The ANF-based SRF controller was used to provide a suitable reference voltage in the existence of substantial voltage distortion. In a multitude of grid conditions, including as voltage sags, voltage swells, imbalances, harmonics, unexpected additions and subtractions of loads, and variations in solar irradiation, the system's performance was assessed to be acceptable [18].

In (2021) M. P. Behera emploed a 3-phase system with a Photovoltaic Generator (PVG)-based (UPQC) controlled by a Fuzzy Logic Controller (FLC). It was found that the FLC-controlled system performed better than the traditional (without-FLC) control method under steady state conditions. It has been shown that the voltage across the load remains constant even when the source voltage is changed. In this work, a new control algorithm has been developed and presented with supporting results after comparing it with the conventional method [19].

In (2022) L. Meng and et al. studied the generation of dc-link voltage ripple and its effects on 1-phase UPQC. The 1-phase UPQC's parallel and series converters were controlled by two different algorithms to minimize the ripple in the dc-link voltage. To avoid voltage ripple from reaching the control loop in the case of a parallel converter, a notch filter was installed in the outside voltage loop of the converter, and to reduce source current harmonics, it was proposed that particular order harmonics compensation be included in the inner current loop. The series converter used the dc-link voltage feedback to limit the impact of voltage ripple on compensation function. According to the simulation and experimental findings, utilizing a fixed dc-link capacitance has been reduced the supply current THD compared to the traditional control methods [20].

The steady-state study of UPQC under various operating circumstances is the basis for this paper. In this work, section 2 discusses the system architecture and the concept of UPQC control techniques. While section 3 summarizes the results of the MATLAB/Simulink simulation, and Section 4 concludes the study.

2. UPQC CONTROL STRATEGY

The Unified Power Quality Conditioner consists of a shunt and series APFs collection with a DC link capacitor connecting them as illustrated in (Fig. 1). The shunt APF is the most viable for dealing with the current issues, also known as DSTATCOM [21]. The series compensation devices known as DVR offer interrupted voltage supply to the load in the event of voltage sag/swell, voltage fluctuations, and so on [22]. All current-related problems, including, power factor improvement, current harmonic compensation, reactive power compensation and load imbalance compensation, are compensated for using the shunt APF [23]. In contrast, the series transformer is used to connect the series APF to the line.

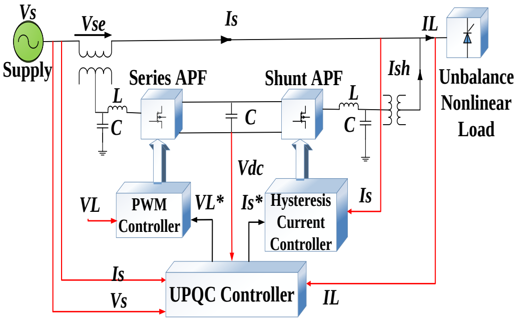

Fig. 1 Schematic of the UPQC

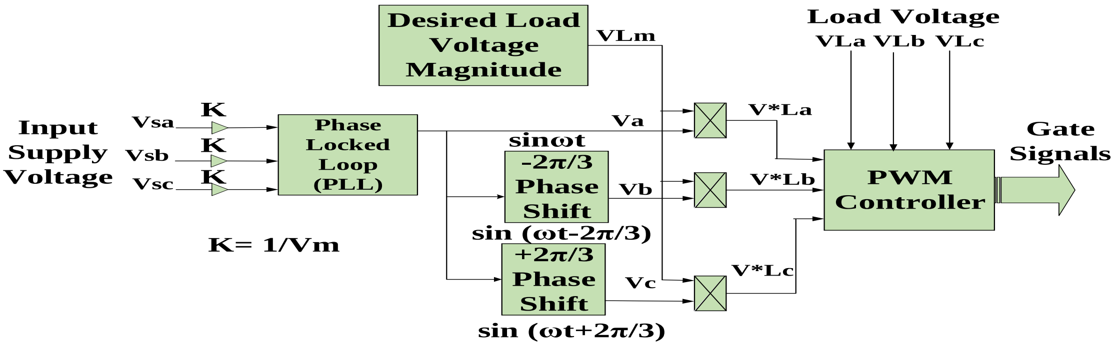

Fig. 2 Series converter controller employing UVTG technique [24]

A. Control of Series APF.

The series filter is controlled by a simple algorithm. The notion of (UVTG) is employed as a control approach for series APF. Fig. (2) depicts a schematic of a UVTG-based series inverter control block. The load voltage (V_{Labc}) should be sinusoidal and balanced with the required amplitude. To accomplish this, an inverter with an appropriate voltage set between the PCC and the load is utilized. It essentially injects voltages in the opposite direction of the source voltage's imbalance and/or distortion, and these voltages cancelling one another out. As a result, the load voltage is balanced, maintaining the desired magnitude while presenting no distortion [24].

The UVTG signal is produced by multiplying the measured input supply voltage by a gaining equal to $K=1/V_m$, where V_m is the peak amplitude of the basic supply voltage [25]. For synchronizing with a supply voltage, a phased locked loop (PLL) is used, which produces a phase angle for a voltage (ωt) corresponding to phase (A) [26]. PLL output at fundamental frequency is identical to the terminal voltage [27]. The (ωt) in equation (1) is then used to construct the three-phase balanced unit vectors [25].

$$\left.\begin{aligned} Va &= sin(\omega t) \\ Vb &= sin(\omega t - 120) \\ Vc &= sin(\omega t + 120) \end{aligned}\right\} \quad ….. (1)$$

When multiplying the needed load voltage magnitude V_{Lm} by UVT (V_{abc}), the reference load voltage signal obtained, as shown below [25]:

$$V^*_{Labc} = V_{Lm} \, .V_{abc} \qquad ….. (2)$$

The load voltage should be equal to the reference load voltage in order to ensure distortion-free load voltages. The series inverter´s PWM controllers compare the reference load voltage (V^*_{Labc}) to the actual load voltage (V_{Labc}) to generate switching signals for the IGBT switches.

B. Control of Shunt APF.

The shunt APF presented in this study is utilized to recompense the nonlinear load's current harmonics and reactive power [28]. The shunt APF is controlled using (SRF) theory, as illustrated in (Fig. 3) [29]. The suggested SRF-based shunt APF reference supply-current signal generating method uses source voltages, load currents, and dc link voltages [28]. As shown in equation (3), the basic component of load current is extracted by applying the abc-dq0 (Park's) transformation, and the (ωt) signal required for this conversion is generated by applying the source voltages to PLL [29].

$$\begin{bmatrix} Id \\ Iq \\ Io \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos\omega t & -sin\omega t & 1/2 \\ \cos(\omega t - \frac{2\pi}{3}) & -sin(\omega t - \frac{2\pi}{3}) & 1/2 \\ cos(\omega t + \frac{2\pi}{3}) & -sin(\omega t + \frac{2\pi}{3}) & 1/2 \end{bmatrix} \begin{bmatrix} ILa \\ ILb \\ ILc \end{bmatrix} \; ….. (3)$$

$$\begin{bmatrix} Id \\ Iq \\ Io \end{bmatrix} = \mathrm{T} \begin{bmatrix} ILa \\ ILb \\ ILc \end{bmatrix}$$

A PI controller evaluates the needed active current (I_{dloss}) by comparing the dc-link voltage to its reference value (V_{dc}). The load current average component ($\overline{ILd}$) is extracted from the d-axis component using a low pass filter, as demonstrated in equation (4) [30].

$$ILd = \overline{ILd} + \widetilde{ILd} \qquad ….. (4)$$

The source current fundamental reference component is computed by combining the needed active current (I_{dloss}) as well as ($\overline{ILd}$) as shown in equation (5) [28].

$$Isd^* = \overline{ILd} + I_{dloss} \qquad ….. (5)$$

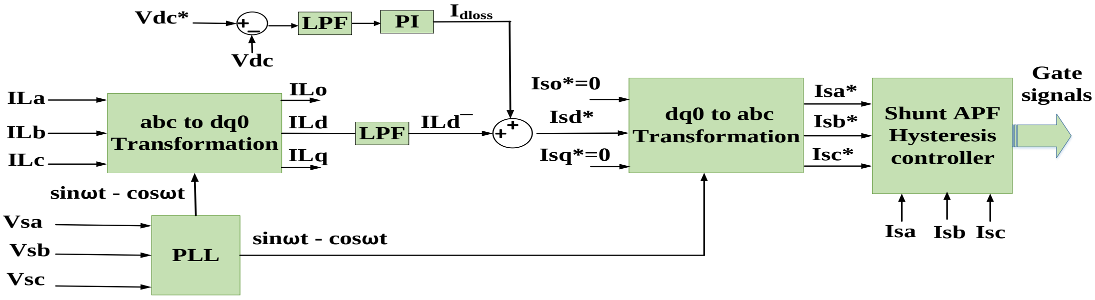

Fig. 3 Shunt converter Controller Employing SRF technique [29]

To correct for harmonics, imbalance, distortion, and reactive power in the source current, the suggested technique sets the zero- and negative-sequence components of the source current reference (Iso* and Isq*) in the zero- and q-axes to be zero [28]. Using dq0 to abc inverse Park's transform, the 3-phase balanced reference supply currents (I_{sabc}^{*}) are obtained from (Isd^{*}) in equation (6) [30].

$$\begin{bmatrix} Isa* \\ Isb* \\ Isc* \end{bmatrix} = T^{-1} \begin{bmatrix} Isd* \\ 0 \\ 0 \end{bmatrix} \qquad \ldots..(6)$$

A hysteresis band current controller compares the generated reference source currents (Is_{abc}^{*}) with the measured source currents (Is_{abc}) to provide IGBT switching signals that compensate for all current-related issues including reactive power, current harmonic, zero- and negative-sequence components, dc-link voltage control, and load-current imbalance.

3. RESULTS AND DISCUSSIONS

Matlab/Simulink is utilized in this study to investigate the 3Phase-3Wire UPQC approach, where sag/swell source voltage, distorted source voltages, unbalanced and distorted load current are popular issues in distribution networks. Table I shows the UPQC parameters. As shown below, the control techniques for UPQC with imbalance Loads were used in three cases:

3.1 UPQC performance for voltage and current harmonics reduction.

A three phase load with various impedances is connected to the grid to simulate an imbalanced load. The currents pulled by the load have uneven amplitudes, where the imbalance nonlinear load was employed to assess UPQC operation. Throughout order to produce supply voltage distortion in the entire 3-phase, a harmonic supply voltage was created between t=0.1sec and t=0.2sec by connecting a 5th (15 percent of the fundamental supply-voltage) and a 7th (15 percent of the fundamental supply-voltage) in series with the major voltage, as shown in Fig. 4(a). This distortion is done on purpose to investigate the harmonic compensating capabilities of UPQC to supply voltage. The sum of the 5th and 7th harmonics is injected into the series APF to compensate for voltage harmonics, as shown in Fig.4(b), which resulting a distortion-free voltage, as illustrated in Fig. 4(c). The Shunt APF compensates for the current harmonics created by the nonlinear load to achieve distortion-free source current, also reparation the zero/negative current sequences to obtain balanced source current, as shown in the schematic of Fig. 4(d).

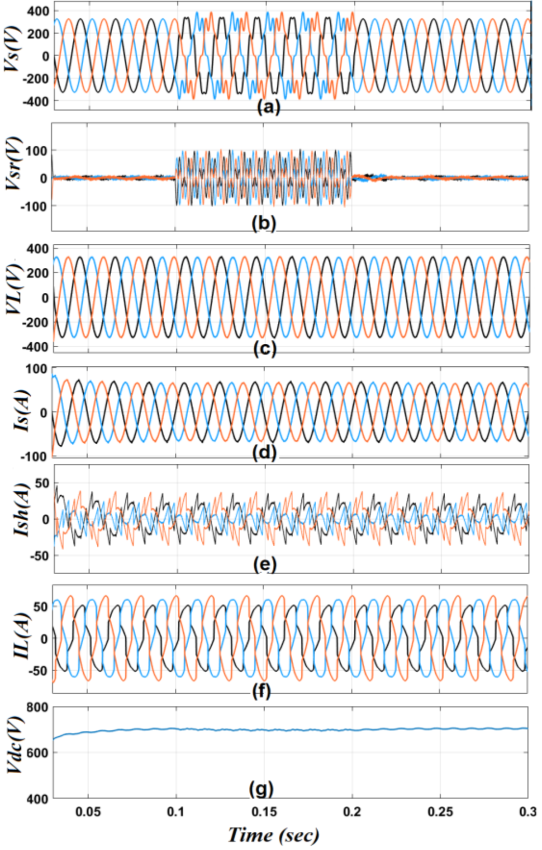

Fig. 4: The results of the simulation for case (1): (a) Source voltage, (b) Compensating voltage, (c) Load-voltage, (d) Source current, (e) Compensation-current, (f) The current in loads (g) Dc-voltage.

The THD of load voltage has reduced from 21.26% to 1.29%, as shown in Fig. 5. The source currents, as shown in Fig. 6, are completely balanced with a THD of 1.62 %, while the load current has a THD of 16.74%. The THD is maintained under the IEEE Standard 519 standard of 5%. The shunt APF injects compensatory currents to provide a balanced source current with low distortion, whereas the series APF maintains a steady voltage at the load with minimal distortion.

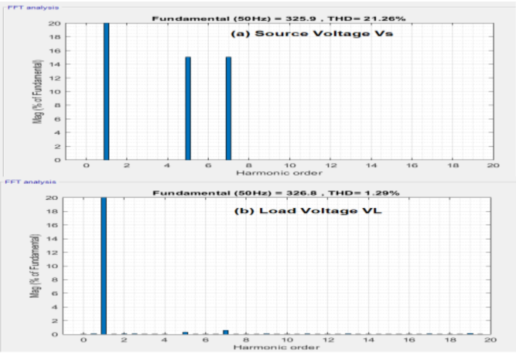

Fig. 5 the THD at voltage harmonics compensation: (a) Load current, (b) source current.

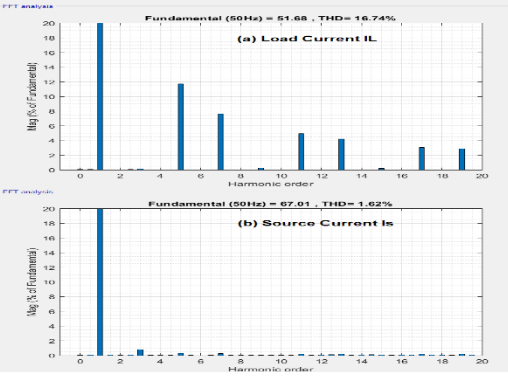

Fig. 6 the THD at current harmonics compensation: (a) Load current, (b) source current.

Table (I) the UPQC parameters

Supply	400V, 50Hz
DC-link	V_{dc} = 700V, C_{dc} = 5000 µF
Series APF	L_{se}=5mH, C_{se}=100µF, R_{cs}=5Ω
Shunt APF	L_{sh}=2 mH C_{sh}=200 µF Rc_{sh}=5Ω
Unbalance-Linear Load	15 Ω /20mH, 10 Ω /15mH, 5 Ω /10mH
Unbalance Nonlinear Load	Load1:3-phase diode rectifier followed by R–L load with R=20Ω and L=20 mH + Load2: 15 Ω /20mH, 10 Ω /15mH, 5Ω /10mH

3.2 UPQC performance for voltage sag mitigation.

The operation of UPQC has been tested using voltage sag with an unbalanced linear load. Between 0.1 and 0.2 seconds, 25% of the source's three-phase voltage sag occurs. Fig. 7(a-e) show the source voltage, compensation voltage, load voltage, source current, shunt current, load current, and Dc-link voltage, respectively. In order to maintain a constant voltage magnitude at the load terminals, a difference voltage was injected through the series inverter during sag, as shown in Fig. 7 (b). When the series inverter injects actual power, the voltage on the DC connection lowers. The load voltage is maintained constant by using a series APF as displayed in Fig 7(c).

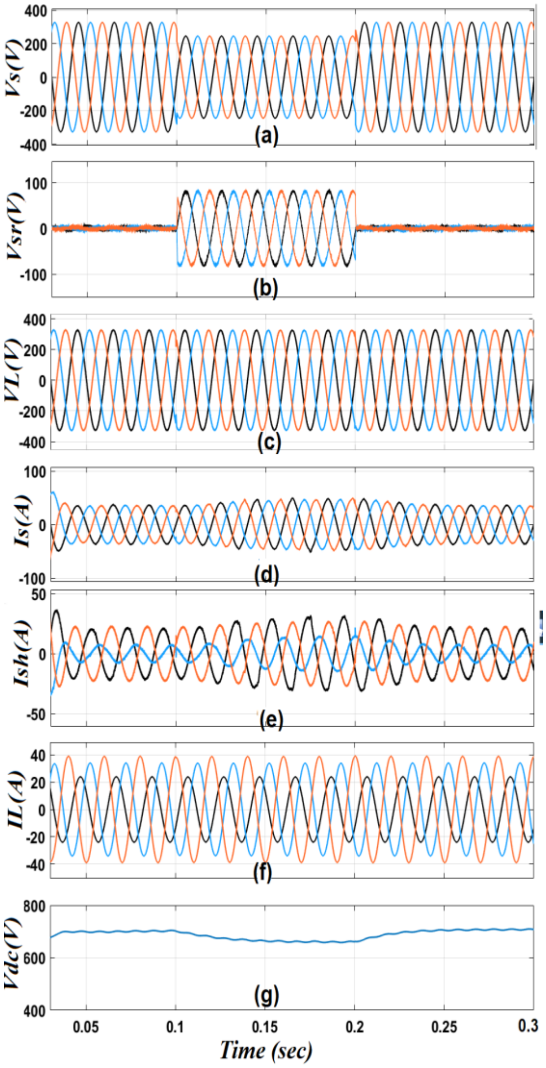

Fig. 7: The results of the simulation for case (2): (a) Source voltage, (b) Compensating voltage, (c) Load-voltage, (d) Source current, (e) Compensation-current, (f) The current in loads (g) Dc-voltage.

The shunt APF draws actual power from the grid and sends it to the series APF through the Dc-link capacitor. The shunt inverter must take more current from the grid to maintain system power balance. Under voltage sag conditions, the compensated source currents are fully balanced with a THD of 2.56%, while the THD value for load voltage is 1.02%. Notwithstanding the the voltage drop on the supply, which causes a drop in dc voltage, the shunt inverter maintains a constant dc-voltage at (700Vdc), as shown in Fig 7(g).

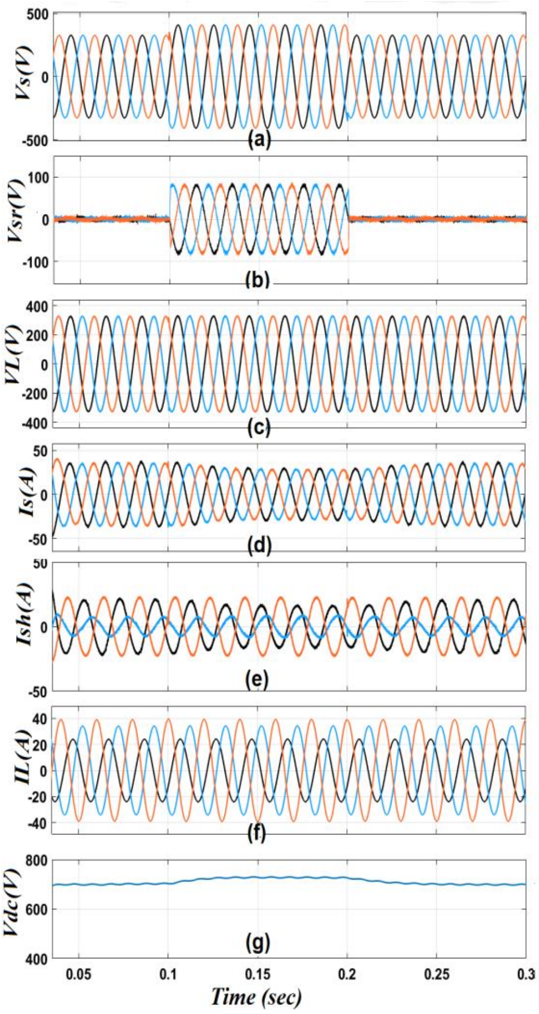

Fig. 8: The results of the simulation for case (3): (a) Source voltage, (b) Compensating voltage, (c) Load-voltage, (d) Source current, (e) Compensation-current, (f) The current in loads (g) Dc-voltage.

3.3 UPQC performance for voltage swells mitigation.

When the UPQC is not connected to the system, any increases in the system's supply voltage result in an increase in the load voltage, which may cause damage to the system's connected devices. The functioning of the UPQC was investigated during a 25% swell in the 3-phase source voltage that occurs between 0.1 and 0.2 sec. Fig. 8(a) depicts the source voltage rise during a voltage swell. The series-inverter absorbs excess voltage in voltage swell situations and keeps the load voltage at fixed magnitude, as illustrated in Fig. 8 (c). As shown in Fig. 8(d), the source current is lowered to return the surplus power produced by the voltage spike to the supply. The THD of load voltage is 1.12% and the THD of source current is 3.09% under swell voltage conditions.

4. CONCLUSION

The control strategy (UVTG and SRF) based UPQC in the presence of imbalance linear/nonlinear loads are discussed in this work. The Matlab/Simulink-based simulation was carried out to validate the provided analysis. Per the simulation findings, the proposed control approach can successfully compensate for current/voltage harmonics, voltage-sag, and voltage-swell, and the proposed methods can efficiently compensate for non-linearity and imbalance in load. When utilizing UPQC, the source current is uninfluenced by unbalanced nonlinear loads, and the waveform becomes sinusoidal, with the source current totally balanced and its THD reduced to 1.62%, while the load voltage's THD was reduced from 21.62% to 1.29%. The suggested approach compensated adequately for the load voltage and source current harmonics in order to comply with IEEE Standard 519.

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تحسين جودة القدرة باستخدام مكيف جودة القدرة الموحد مع احمال غير متزنة

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الملخص

تعد جودة القدرة مشكلة رئيسية تواجه كل من الشبكات الكهربائية وعملائها. تسبب الأحمال غير الخطية مشاكل في جودة القدرة مثل توافقيات التيار وتوافقيات الفولتية وانحراف التردد وانخفاض الفولتية وزيادة الفولتية. تم استخدام نموذج لجهاز مكيف جودة القدرة الموحد في هذا البحث لتقليل مشاكل جودة القدرة. حيث يتكون مكيف جودة القدرة الموحد من عاكس التوالي وعاكس التوازي ويسميان ايضا (بمرشحات القدرة النشطة)، أحدهما متصل بخط الشبكة على التوالي والآخر متصل على التوازي بالشبكة. تم استخدام طريقة توليد قالب متجه الوحدة للسيطرة على مرشح القدرة النشط التوالي بينما تم استخدام تقنية الاطار المرجعي المتزامن للسيطرة على مرشح القدرة النشط التوازي. تم استخدام المحاكاة في هذه الدراسة لاختبار الخصائص التعويضية لمرشح التوالي ومرشح التوازي عندما تكون الاحمال غير متوازنة، حيث تم اختبار أداء النظام تحت ظروف توافقيات التيار والفولتية وانخفاض الفولتية بالاضافة الى زيادة الفولتية. يتم تحديد توافقيات الفولتية وتعويضها في مرشح التوالي باستخدام طريقة توليد قالب متجه الوحدة بينما يتم تحديد تيارات التوافقيات وعدم التوازن وتعويضها في مرشح التوازي باستخدام طريقة تقنية الاطار المرجعي المتزامن. وفقًا لنتائج المحاكاة ، فان مكيف جودة القدرة الموحد قد خفف من تأثير التغيرات في فولتية المصدر وتيارات التوافقيات على خط القدرة بأحمال غير متوازنة ، حيث كان إجمالي التشوه التوافقي لفولتية الحمل وتيار المصدر أقل من 5٪ ، وفقًا لمعيار IEEE-519.

الكلمات الداله :

انخفاض الفولتية، زيادة الفولتية, أحمال غير متوازنة ، التوافقيات، مكيف جودة القدرة الموحد.