A Novel Three Phase Multi-Objective Unified Power Quality Conditioner with Three Phase Fault

[1]M. K. Priyanka, [2]Dr. R. Srinu Naik, [3]S. Naveena,

[1]PG Scholar [1,]Department of Electrical Engineering, Andhra University College of Engineering(A), Visakhapatnam, India.
[2]Associate Professor, Department of Electrical Engineering, Andhra University College of Engineering(A), Visakhapatnam, India
[3]Research Scholar, Department of Electrical Engineering, Andhra University College of Engineering(A), Visakhapatnam, India

---***---

Abstract - *The integration of renewable energy sources and the development of smart grids are indeed posing new challenges. The proposal of a three-phase multi-objective unified power quality conditioner (MO-UPQC) with interfaces for solar PV panels and energy storage in batteries seems like a promising solution to address power quality issues and enable power injection into the grid. The experimental results obtained from the laboratory prototype further validate the feasibility and potential applications of the MO-UPQC. It's exciting to see the continuous development of technological solutions in the field of smart grids. This article introduces an innovative solution to tackle the evolving complexities of smart grids, especially with the surging uptake of renewable energy. The groundbreaking MO-UPQC doesn't just address power quality issues; it seamlessly integrates solar energy and battery storage, playing a pivotal role in the dependability and sustainability of modern electrical systems. This transformative technology is poised to be a game-changer in driving de-carbonization initiatives and ushering in the era of more sustainable energy networks.*

Key Words: Energy storage, Power electronics, Power quality, Renewable energy sources, Smart grids, Mat lab Software.

1.INTRODUCTION

The surging power demand and the imperative shift toward de-carbonization are posing significant technological challenges for future power grids. The rise of new players as aggregators, alongside specific operation modes, [1], [2], [3] adds an extra layer of complexity to the mix. Furthermore, the rapid proliferation of advanced electronic systems underscores the urgency of addressing power quality issues, as they can lead to substantial costs[4],[5].Tackling power quality problems is especially critical in the context of emerging micro grids[6]. It is crucial to ensure power quality standards globally, which entails guaranteeing the operation with sinusoidal and balanced currents from the load point of view, as well as the operation with sinusoidal and balanced voltages from the grid point of view. In reality, achieving this ideal scenario is challenging because voltages and currents are not always sinusoidal and balanced. When non-ideal conditions occur, various power quality problems emerge, and active solutions based on power electronics are the primary approach for mitigation.

The unified power quality conditioner (UPQC) is recognized as the most significant equipment for addressing major voltage and current power quality issues. Despite being proposed some time ago, [7], [8] the UPQC is expected to continue playing a crucial role in future power grids [9], [10], [11] Structurally, the UPQC comprises a series and a shunt power conditioner that share a common dc-link, with the control of its voltage being pivotal for the proper operation of both power conditioners It looks like you are discussing different possibilities for the structure of a power conditioner.

You have mentioned various options such as current-source converters[12], transformer-less conditioner[13], modular multilevel matrix structure[14], and hybrid topology with an isolated dc-link[15]. Additionally, you've noted other possibilities like the three-phase four-wire structure, a dual unified power conditioner, and an approach aiming to optimize the converters,[16] [17]. It seems like you are exploring a wide range of options for the power conditioner's structure, each with its unique features and advantages. Your thorough exploration of these options showcases the depth of consideration you are giving to this important decision. It's clear that the use of power electronics [18] converters and a modified unified power conditioner with a reduced dc-link [19] can bring about significant advantages for multi-objective operations. By examining the structure of a unified power conditioner, we can see that the common dc-link can be a game-changer for interfacing other technologies. For instance, integrating an energy storage system through the dc-link can unlock more functionalities and diverse operation modes, especially during power outages. This is a huge benefit for loads that require a constant supply of high-quality power. Furthermore, the shared dc-link opens up opportunities to interface with other technologies, particularly in light of the growing focus on renewables [20] and [21].

The combination of energy storage with renewables through a common dc-link presents an intriguing solution for smoothing power fluctuations from renewables, [22] and [23] without compromising power quality. The need for multi-objective systems that can enhance power quality and facilitate energy generation and storage is more pressing than ever [24], [25], and [26]. While previous approaches have mainly focused on compensating power quality problems of currents, it's crucial to address voltage issues as well. Some studies have explored the possibility of addressing multiple power quality problems and integrating with renewables, [27] and [28] but they come with limitations such as interfacing only a three-phase system without a neutral wire and lacking the capability to interface energy storage. Each approach has its own set of advantages and disadvantages, showing the complexity of the challenges involved. The idea of a novel multi-objective unified power quality conditioner (MO-UPQC) [29] is particularly intriguing as it aims to combine multiple functionalities into a single piece of equipment. This could potentially revolutionize the way we address power quality issues and integrate renewable energy sources and storage systems. The MO-UPQC setup sounds incredibly versatile and efficient! It's amazing how it can address multiple power quality issues, integrate solar PV power[30], and facilitate battery charging all in one equipment. The ability to handle multiple objectives with a single piece of equipment is truly impressive. The proposed topology for the MO-UPQC, as depicted in Fig. 1, introduces a series of ground breaking contributions that have undergone extensive validation through experimentation. These significant advancements include:

1) Unified Control Algorithm: This innovative algorithm seamlessly integrates the operation of series and shunt power conditioners with the multiport DC conditioner, effectively managing power based on the operation of solar PV panels and batteries.

2) Power Control Algorithm: The multiport DC conditioner boasts a sophisticated power control algorithm that integrates the individual interface of PV panels with an MPPT algorithm and batteries with a CC-CV battery charging algorithm, allowing for direct interfacing between these technologies.

3) Experimental Validation of Normal Operation: The series and shunt power conditioners adeptly compensate for power quality issues in a three-phase system, ensuring sinusoidal and balanced voltages on the load side and sinusoidal and balanced currents with a unitary power factor on the power grid side.

4) Experimental Validation of Multiport DC Conditioner: This component efficiently injects power from the solar PV panels and/or batteries into the grid while maintaining power quality on both the grid and load sides, optimizing the utilization of power grid, loads, solar PV panels, and batteries.

5) Experimental Validation of Charging Mode: The multiport DC conditioner effectively receives power from the grid to charge the batteries while ensuring power quality on both the grid and load sides. The experimental validation encompasses all possible modes of operation using a three-phase four-wire laboratory prototype.

The subsequent sections of this article will delve into the details of the topology and its operational principles (Section II), the control algorithms for various operating conditions of the power conditioners (Section III), experimental validation (Section IV), a comparison with conventional solutions (Section V), and the conclusion (Section VI). Get ready for an insightful journey through the innovative MO-UPQC technology!

2. TOPOLOGY OF THE MULTI-OBJECTIVE UNIFIED POWER QUALITY CONDITIONER

The Multi-objective Unified Power Quality Conditioner (MO-UPQC) boasts a sophisticated topology that includes the series power conditioner, the multiport DC conditioner, and the shunt power conditioner. The series power conditioner is built around a three-phase three-leg four-wire converter, with the neutral wire connected to the split DC-link. This converter is strategically linked in series with the grid and incorporates L filters with RC shunt passive filters (Lsea, Lseb, Lsec) for effective coupling. The Multi-objective Unified Power Quality Conditioner (MO-UPQC) boasts a sophisticated topology that includes the series power conditioner, the multiport DC conditioner, and the shunt power conditioner. The series power conditioner is built around a three-phase three-leg four-wire converter, with the neutral wire connected to the split DC-link. This converter is strategically linked in series with the grid and incorporates L filters with RC shunt passive filters (Lsea, Lseb, Lsec) for effective coupling.

The power conditioning system you are discussing sounds quite comprehensive and innovative! It's fascinating to see how the series power conditioner and multiport DC conditioner work together to ensure the safety and proper operation of the power grid voltages. The use of advanced technologies like multilevel interleaved-based three-port DC-DC converter, MPPT algorithm for solar PV panels, and CC-CV battery charging algorithm really demonstrates a forward-thinking approach to energy management. The direct interface for charging the batteries from the solar PV panels without the grid interface is particularly impressive, as it not only reduces the number of power converters but also increases efficiency and simplifies control complexity. The ability to operate with three voltage levels in each two-wire interface showcases the system's sophisticated voltage control and modulation capabilities. It's clear that this power

conditioning system is designed to be efficient, effective, and technologically advanced. In this discussion, we're delving into the fascinating world of shunt power conditioning. Imagine a three-phase three-leg four-wire converter where the neutral wire is directly linked to the middle point of a split dc-link. This unique setup allows for the compensation of neutral currents even with a three-leg converter. Now, picture utilizing controlled variables with a frequency that corresponds to the double of the switching frequency. This approach offers a host of advantages, including the reduction of the nominal value and size of the coupling filters (Ldca1, Ldca2, Ldcb1, Ldcb2). Let's not forget the impact of voltage harmonics, which are effectively suppressed by the series conditioner. As a result, LC filters become a viable option for coupling the power grid. And here's the kicker – the shunt conditioner operates as a voltage-source converter with current feedback, addressing issues stemming from load currents. This is just the tip of the iceberg when it comes to the potential of shunt power conditioning. The possibilities are vast, and the validation of this topology is just the beginning.
Interested in the inner workings of the Multi-objective Unified Power Quality Conditioner (MO-UPQC)? The control of the MO-UPQC involves distinct control algorithms, each with its own unique role. These algorithms are presented individually, highlighting their interdependence. Understanding these control algorithms is crucial for anyone working with MO-UPQC systems. If you have any specific questions about these algorithms or their interdependence, feel free to reach out!

3. CONTROL ALGORITHMS OF THE MULTI-OBJECTIVE UNIFIED POWER QUALITY CONDITIONER

The control algorithms for the Multi objective Unified Power Quality Conditioner (MO-UPQC) are designed to manage various power quality issues and integrate renewable energy sources. The control of the MO-UPQC involves distinct algorithms for the shunt power conditioner, series power conditioner, and multiport DC conditioner, with interdependencies among them..

3.1 Shunt Power Conditioner

To ensure the MO-UPQC operates effectively, it's crucial to synchronize with the fundamental components of the power grid voltages. This is where the phase-locked loop (PLL) proposed in comes into play. Additionally, even under challenging conditions of unbalanced and distorted grid voltages, the MO-UPQC strives to deliver balanced grid currents with minimal harmonic distortion. By utilizing a PLL, we can establish sinusoidal and balanced references in the control algorithm, allowing for operation without harmonic power on the power grid side. While this approach is effective, there are alternative strategies to consider, such as the potential for unbalanced grid currents with the goal of achieving balanced power among the three phases. However, detailed analysis of these strategies is beyond the scope of this article. In addition, to calculate the compensation currents for the shunt power conditioner, we employed the time domain p-q power theory. Implemented in the α-β coordinates, this theory involves converting the power grid voltages (vga, vgb, vgc) and the load currents (ila, ilb, ilc) to the α-β coordinates through the following transformation:

From Clarke's Transformation

The clarke's transformation defines as it uses 3 phase currents ia, ib, ic to calculate currents in the $2.phase$, orthogonal stator axis: i_α& $i\beta$.

→ These two currents in the fixed coordinates stator phasor are transformed to the isd ξ is currents components in the dq frame with park's transform.

s-p balanced reference frame

$$
\begin{aligned}
I_\alpha &= \frac{2}{3}[I_a \cos 0 + I_b \cos 180 + I_c \cos 240] \\
&= \frac{2}{3}[I_a + I_b(-y_2) + I_c(-1/2)] \\
&= 2/3\left[I_a - \frac{I_b}{2} - \frac{I_c}{2}\right] = \frac{2}{3}I_a - 1/3 I_b - 1/3 I_c \\
&= 2/3 I_a - 1/3(I_b + I_c) \rightarrow (1)
\end{aligned}
$$

We know that $I_a + I_b + I_c = 0$

$$\Rightarrow I_a = -(I_b + I_c) \rightarrow (2)$$

$$= 2/3 I_a - 1/3(-I_a) = 2/3 I_a + 1/3 I_a$$

$$\therefore I_\alpha = I_a$$

$$
\begin{aligned}
I_\beta &= \frac{2}{3}[I_a \cos 90^\circ + I_b \cos 30^\circ + I_c c_a 150^\circ] \\
&= \frac{2}{3}\left[0 + \frac{\sqrt{3}}{2}I_b - \frac{\sqrt{3}}{2}I_c\right] = 1/\sqrt{3}[I_b - I_c] \\
&= 1/\sqrt{3}[I_b + I_a + I_b] \\
I_\beta &= 1/\sqrt{3}I_a + a/\sqrt{3}I_b \rightarrow (3)
\end{aligned}
$$

$$\therefore \begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1/\sqrt{3} & 2/\sqrt{3} & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}.$$

$$\therefore \begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} = 2/3 \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \rightarrow (4)$$

Above transformation is called clarke's transformation.

Now Inverse clarke's transformation is given by

$$\begin{bmatrix} f_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & i \\ -1/2 & \sqrt{3}/2 & 1 \\ -1/2 & \sqrt{3}/2 & 1 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}$$

$$\therefore \underset{(\alpha\beta 0)}{C} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{2}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/2 & 1/2 \end{bmatrix} \rightarrow (5)$$

$$\text{Inverse clarks} = \sqrt{2}/3 \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix}$$

To Determine the Compensation currents for shunt power Conditioner, the time domain P-q power theory was considered. Since it is implemented in the $\alpha - \beta$ coordinates, the power grid voltages (v_{ga}, v_{gb}, v_{gc}) & the load currents (i_{la}, i_{l_b}, i_{lc}) are conviled to $\alpha - \beta$ coordinates by applying clarke's transformation

$$\begin{bmatrix} x_0 \\ x_\alpha \\ x_\beta \end{bmatrix} = \underbrace{\sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}}_{[c]} \begin{bmatrix} x_{q_1,}\}_a \\ x_{l,} l_b \\ x\{_{1,}\}_1 \end{bmatrix} . \rightarrow (6)$$

x can be either Voltage of current. for 3- ϕ, V, I the $\alpha, \beta, 0$ coordinates: can be. expressed as

$$\begin{bmatrix} v_\alpha \\ v_k \\ v_0 \end{bmatrix} = [c] \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \rightarrow (7)$$

$$P = VI = V_{abc} \cdot I_{abc} = V_a I_a + V_b I_b + V_c I_c$$

$$q_{\alpha\beta b} = V_{\alpha\beta 0} \cdot I_{\alpha\beta 0} = [c][v_{abc} \cdot I_{abc}].$$

$$= [c] q_{abc}$$

$P - q$ power theory components:-

$$P = v_{\alpha\beta 0} \cdot i_{\alpha\beta 0} = v_\alpha i_\alpha + v_\beta \cdot i_\beta \rightarrow (8)$$

$$v_{\alpha\beta 0} = v_{\alpha\beta 0} \cdot i_{\alpha\beta 0} = \begin{bmatrix} 0 \\ 0 \\ v_\alpha i_\beta - v_\beta i_\alpha \end{bmatrix} \rightarrow (9)$$

$$q_{\alpha\beta_0} = \|q_{\alpha\beta_0}\| = v_\alpha i_\beta - v_\beta i_\alpha \rightarrow (10)$$

After determining voltage & currents in $\alpha - \beta$ coordinates: the Power components of $P - q$ power theory specified as

$$P = v_\alpha i_\alpha + v_\beta i_\beta \longrightarrow \text{Real} \rightarrow (11)$$

$$q = v_\beta i_\alpha - v_\alpha i_\beta \rightarrow \text{Imaginary} \rightarrow (12)$$

$$P_o = V_0 i_0 \longrightarrow \text{Zero sequence} \rightarrow (13)$$

It is necessary to separate each power into two components.

(1) Average value ($\bar{P}_0$)

(2) Oscillating value ($\tilde{p}$)

for such purpose a digital low pass filters are used

$$P_x = \tilde{p} - \bar{P}_0 \longrightarrow (14)$$

$$q_x = q \rightarrow (15)$$

shunt power conditioner regulates Dc-link voltage $(Vdc_1, V_{dc_2},)$ With additional variable (P_{dc}) which is added to P_x

$$P_x = \tilde{P} - \overline{P_0} + P_{dc} \rightarrow (16)$$

If power from RES matches the charging power of the batteries. Then, the operating power of the multiport DC Conditioner (P_{mp}) in the interface with dc-link is expressed as

$$P_{mp} = V_{dca} i_{dca} + V_{dcb} i_{dcb} \rightarrow (17)$$

(17) is added to (16)

$$\therefore P_x = \tilde{P} - \overline{P_0} + P_{dc} + P_{mp} \rightarrow (18)$$

where P_{mp} $\rightarrow$ defines the shunt power conditioner injects or absorbs active power .Considering this strategy, the VI in PV panels (V_{dc}, ide A) & in batteries ($V_{dc} b$, idc b) changes while dc-link voltage $(v_{dc1}, V_{d\,c_2})$ are maintained to be controlled by shunt controllers.

$$P_x = P_{dc} + P_{mp} \rightarrow (19)$$

After determining the values of $P_x q_x$, the instantaneous values that defines the operating reference currents for shunt power conditioner are determined in $\alpha - \beta$ coordinates.

$$i = \frac{p}{v} = v^{-1} p \rightarrow (20)$$

Oscillating portion of instantaneous active current is on α-axis. (-ve sign is for current direction)

$$i_{p\alpha} = \frac{v_\alpha}{v_\alpha^2 + v_\beta^2} (-\tilde{p}) \rightarrow (21)$$

on β -axis

$$i_{\beta\tilde{p}} = \frac{v_\beta}{v_\alpha^2 + v_\beta^2} (-\tilde{p}) \rightarrow (22)$$

for Instantaneous reactive current on α axis ξ β axis

$$i_\alpha = \frac{V_\beta}{V_\alpha^2 + v_\beta^2}(-q),\ i_\beta = \frac{-v_\alpha}{V_\alpha^2 + v_\beta^2}(-q) \rightarrow (23)$$

from $\alpha\beta$ currents. calculating ∴

$$\begin{bmatrix} 1_\alpha^* \\ i_k^* \end{bmatrix} = (V_\alpha^2 + v_\beta^2)^{-1} \begin{bmatrix} v_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} P_x \\ q_x \end{bmatrix} \rightarrow (24)$$

By doing inverse clarke's transformation.

$$i_0^* = \sqrt{3}\left[\frac{[i_{ga} + i_{gb} + i_{gc}]}{3} \rightarrow (25)\right.$$

$$\begin{bmatrix} is_{sh}^* \\ i_{shb}^* \\ i_{shc}^* \end{bmatrix} = \sqrt{2}/3 \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_0^* \\ i_\alpha^* \\ i_\beta^* \end{bmatrix} \rightarrow (26)$$

3.2 Series Power Conditioner:-

To determine the compensation voltages for the series power conditioner, it is necessary to know the nominal voltage (vPLL–a,b,c′′) and the power grid voltage (vg–a,b,c′′). Hence, the compensation voltages are determined according to

$$v_S{}^* e\{a,b,c\} = v\mathrm{PLL}\{a,b,c\} - v g\{a,b,c\} \rightarrow (27).$$

During the occurrence of sags or swells, the compensation voltages are adjusted to maintain the load voltages with the nominal values and sinusoidal waveform. Therefore, the PLL has an important influence on the convergence of such strategy. Since the power follow can be established in bidirectional mode between the shunt and the series power conditioner, the load can be supplied with nominal voltages (in frequency and amplitude) in steady-state operation. Moreover, the necessary power can also be supplied by the energy storage system interfaced by the multiport dc conditioner. To control the series power conditioner to produce this voltage, a strategy is used expressing the voltage produced by the converter as a function of the voltages. As a result, it can be established as

$$v_S{}^* e\{a,b,c\}[k] = M_A \frac{v_{PLL\{a,b,c\}}[k] - v_{g\{a,b,c\}}[k]}{v\mathrm{dc1} + v\mathrm{dc2}} \rightarrow (28)$$

where MA is the amplitude of the modulator and vse–a,b,c′′∗ is the signal that is compared with the modulator to obtain the desired voltage produced by the series power conditioner (measured in the points ase, bse, and cse identified).

3.3 Multiport DC Conditioner:-

Regarding the multiport dc conditioner, it's all about efficient power management. This system has two interfaces: one with the RES (solar PV panels, unidirectional power operation) and one with the storage system (batteries, bidirectional power operation). The interface with the solar PV panels utilizes a P&O algorithm to control MPPT operation, ensuring maximum power extraction. While the intricacies of this algorithm are beyond the scope of this article, it's crucial to understand that it enables the extraction of maximum power from the solar PV panels. The control algorithm proposed in this article handles this power, either injecting it into the power grid through the shunt conditioner or storing it in the batteries. Keep in mind that only native DC sources can be directly connected to the MO-UPQC.

The multiport dc conditioner's innovative design dynamically updates the duty cycle and utilizes carrier signals to control the state of the IGBTs. This allows for precise control of each current with a frequency that is twice the switching frequency. Depending on the solar PV panel voltage level, the voltage vxa1xa2 can have three distinctive levels, providing multilevel and interleaved operation. The storage system interface primarily operates on constant current, but alternative methods such as constant voltage charging and constant power discharging can also be used. During charging and discharging, the current control aligns with the power management needs of the external grid, which can receive power from the solar PV panels or the power grid. The current control during the charging process is defined by

$$V_{xb*xb_2}[k] = V_{dcb}[k] + \frac{L_{dcb1} + L_{dcb_2}}{T}\left(i_{d_{cb}}[k+1] - i_{d_{cb}}[k]\right) \rightarrow (29)$$

while the Current Control during the discharging Process is defined by

$$V_{xb_1*b_2}[k] = V_{dcb}[k - \frac{L_{dcb_1} + L_{dcb_2}}{T}(i_{dcb}(k+1] - i_{dcb}[k]) \rightarrow (30)$$

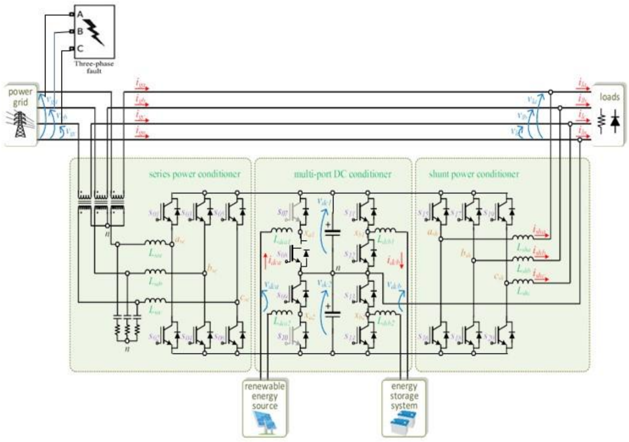

Fig -1: Topology of the proposed three-phase MO-UPQC with multiport dc interfaces

4.EXPERIMENTAL VALIDATION OF MULTI-OBJECTIVE UNIFIED POWER QUALITY CONDITIONER

4.1 Simulation Diagrams of MO-UPQC model :-

The system is been designed and simulated as per in figure 2, and the description of the above section is been followed to execute the system and get the results.

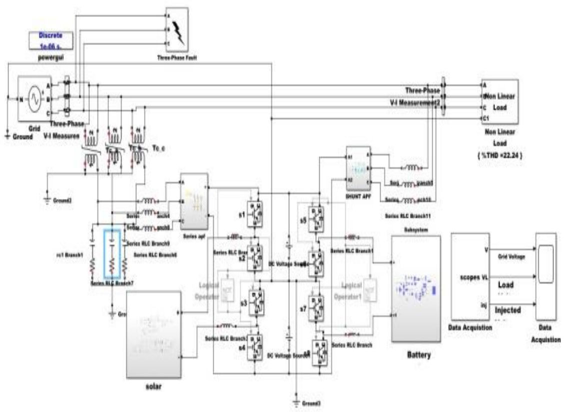

Fig. 2 The MO-UPQC with three phase fault in MATLAB Simulink

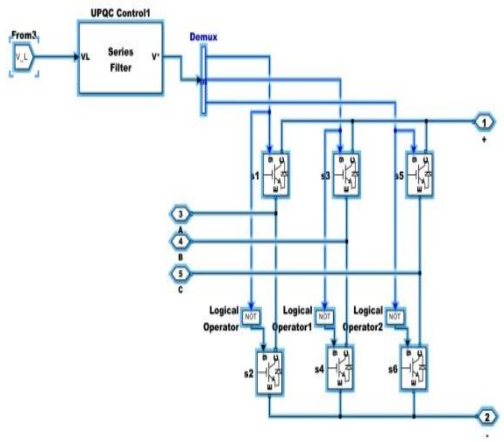

Fig. 3 Series Active Power Conditioner

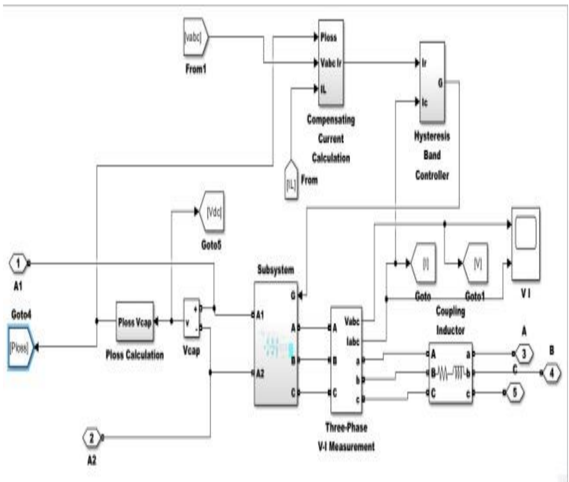

Fig. 4 Shunt Active Power Conditioner

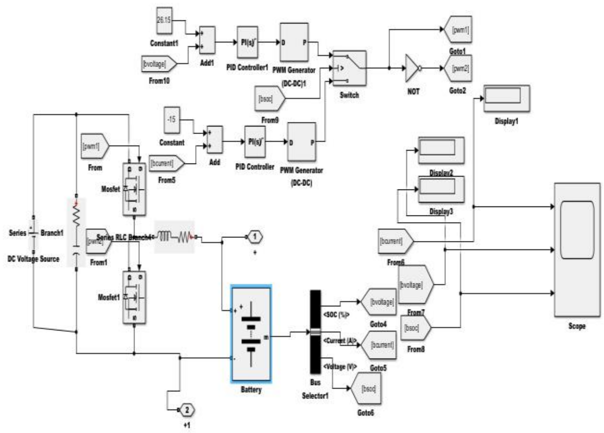

Fig. 5 Battery Management System

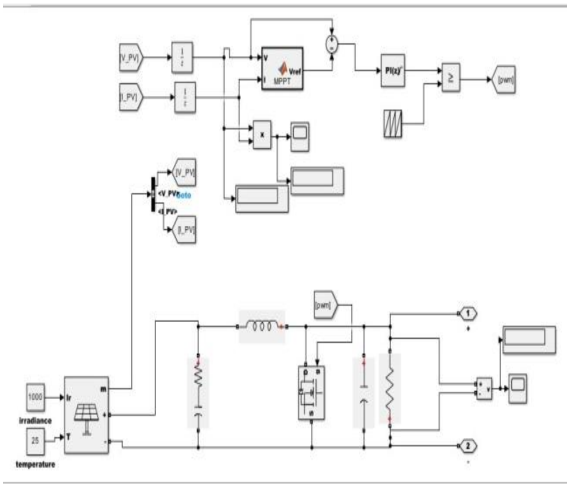

Fig. 6 Renewable Energy System

This section presents the developed three-phase four-wire laboratory prototype of the MO-UPQC (10 kVA, 400 V, 50 Hz), as well as the main experimental results obtained. Fig. 2 shows the laboratory workbench, where it is possible to identify the developed prototype. It is important to highlight that this is a preindustrial prototype, and it was experimentally validated connected to the low-voltage power grid, i.e., without any HIL or controlled voltage source, thus validating its functionality.

It is also noteworthy the fact that the equipment was developed for the integration into an electrical panel, as can be seen in Fig. 2. The following main components were used: IGBTs model SKM100GB125DN; gate-drivers model SKHI22AH4R; current transducers LA100P; voltage transducers CYHVS025A. For coupling the series conditioner, three individual low-frequency transformers were used, each one with nominal characteristics of 230 V / 115 V, 50 Hz. In terms of control, two DSP TMS320F28335 were employed, one responsible for control-ling the series power conditioner and the other responsible for controlling the shunt power conditioner and the multiport dc conditioner. In terms of switching (f_{sw}) and sampling frequency (f_s), the values of 20 kHz and 40 kHz were considered, respectively. The main parameters of the system are summarized in Table 1.

Table -1:
MAIN PARAMETERS OF THE SYSTEM

Parameters	**Values**	**Units**
Lsec{a,b,c}, Lshe{a.b.c}	3	mH
C{1,21	4.7	mF
C(1,2,3)	10	uF
R{1,2,3}	10	S
Ldca{1,2}, Lach{1,2}	2	mH
fs	20	kHZ
fsw	40	kHZ
fsw	40	kHZ
Vg{a,b,c}	400	V
Vdcl, Vdc2	800	V
Vdca, Vdcb	400	V

4.2 PERFORMANCE ANALYSIS OF MULTI-OBJECTIVE UNIFIED POWER QUALITY CONDITIONER.

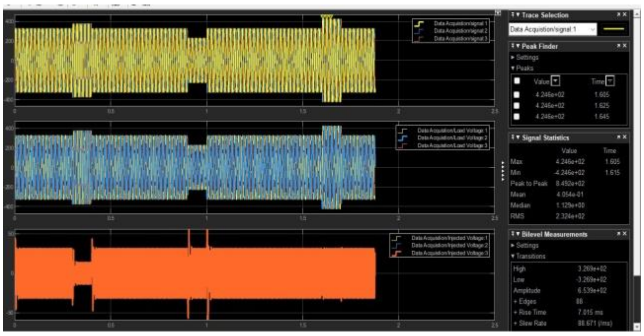

Chart -1 Data Acquisition of MO-UPQC of Grid voltage, Load voltage, Injected voltage source voltage during sag.

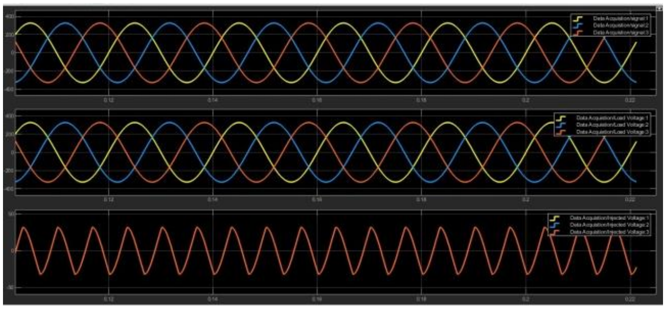

Chart 1. shows the source voltage of UPQC during sag is shown. On Y-axis voltage is represented and on X-axis time is represented. Initially the UPQC is not working but when harmonics is generated in the source voltage. In order to mitigate these harmonics of swell, sag etc, The UPQC starts working. The voltage sag generated at 0.9 t0 1p.u. and source voltage changes from 1p.u to 1.7.Inorder to maintain 1p.u at load voltage some voltage is injected from UPQC.

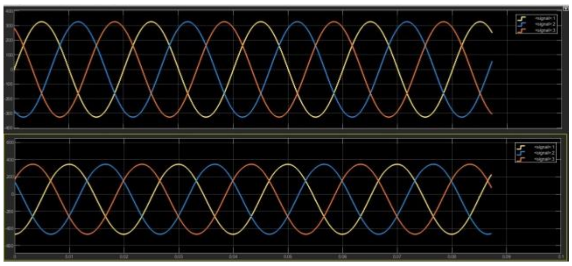

Chart 2 Input V,I of MO-UPQC of Grid

The Chart 1shows the input voltage and input current from the power grid with a balanced sinusoidal waveforms. The voltage of 400v is given to the grid. X-axis represents the time and Y-axis represents the voltage and current.

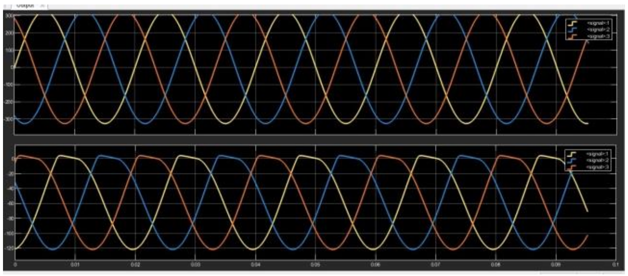

Chart 3. Output of Load voltage ,Load current during sag after application of UPQC

In chart 3 load voltage of UPQC is shown. After operation of UPQC the sag from time 0.06 sec to 0.12 sec is removed. UPQC removes the voltage sag problems. The total load voltage becomessinusoidal and gains its original magnitude which is 326 V. The load current of UPQC is contains harmonics and is non-linear due to presence of non-linear load. X-axis represents the time and Y-axis represents the voltage and current.

Chart 4. Waveform of Series Active Power Filters

Series APF is used to mitigate all problems related to voltage unbalance and disturbance. It mitigate the voltage unbalance in source voltage i.e. voltage dip/rise so that the load voltage become perfectly balanced and regulated. it is the source voltage during sag. Sag time interval is 0.3 sec to 0.4 sec. The sag is due to voltage unbalance that may be caused due to faults. The voltage injected by series APF is shown. The injected voltage time interval is 0.3 sec to 0.4 sec. By injecting voltage in this time interval the load side voltage is made completely balanced and sinusoidal. The DC voltage is constant. X-axis represents the time and Y-axis represents the voltage.

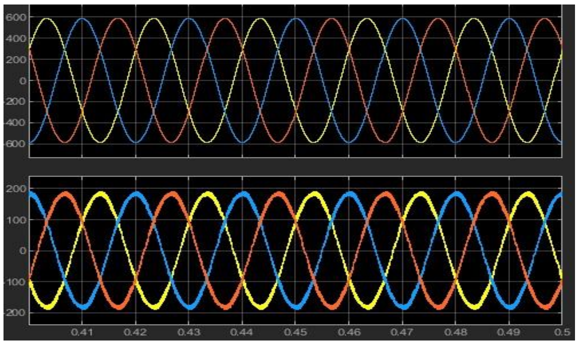

Chart 5. Waveform of Shunt Active Power Filters

Shunt APF is used to remove problems due to current harmonics. So it makes current drawn from source completely sinusoidal which is effected by load current harmonics. Experimental results of the three-phase shunt power condi-tioner in transient-state during operation start, with the operation of the batteries through the multiport dc conditioner, showing the power grid currents (i_{ga}, i_{gb}, i_{gc}), the voltages in the dc-link (v_{dc1}, v_{dc2}), and the voltage (v_{dcb}) and current (i_{dcb}) in the batteries. X-axis represents the time and Y-axis represents the voltage and current.

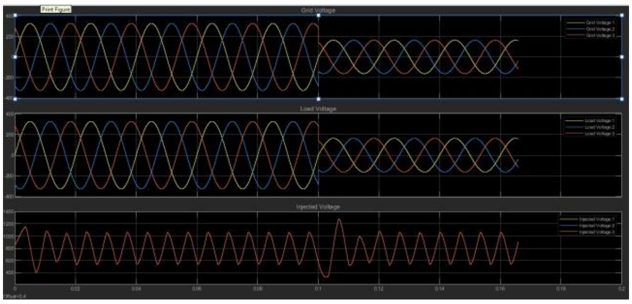

Chart 6. Waveform of Voltage Mitagation

The series APF part of UPQC is responsible for voltage mitigation. The magnitude of load voltage is now 326 V. the injected voltage during swell condition is shown. The voltage is injected between time interval 0.1 sec to 0.2 sec. After injecting this voltage the load voltage becomes completely balanced. X-axis represents the time and Y-axis represents the voltage.

3. CONCLUSIONS

The article introduces a new MO-UPQC, which is different from the traditional unified power quality conditioner. It includes a multiport DC conditioner connected to the common DC-link of the series and shunt power conditioners, enabling interface with renewable energy sources (such as PV panels) and energy storage systems (batteries). The article thoroughly presents the proposed topology, its main principle of operation, and the distinct control algorithms for different operation modes, supported by extensive experimental results. The experiments were conducted using a three-phase four-wire laboratory prototype, demonstrating the effectiveness of power quality compensation for voltage and current harmonics, load voltage and grid current balancing, and reactive power compensation. The bidirectional power operation of the multiport DC conditioner was also validated, showing power sharing among the renewable energy source, energy storage system, and power grid through the shunt power conditioner. The experimental results demonstrate the feasibility of operating the proposed MO-UPQC. Additionally, the article suggests potential applications of the MO-UPQC, such as serving as an energy backup system during power outages and coordinated operation with the power grid for voltage and frequency control. Finally, a comparative study between the proposed MO-UPQC and conventional structures is presented.

REFERENCES

[1] K. M. Muttaqi, Md. R. Islam, and D. Sutanto, "Future power distribution grids: Integration of renewable energy, energy storage, electric vehicles, superconductor, and magnetic bus," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 2, Mar. 2019, Art. no. 3800305, doi: 10.1109/TASC.2019.2895528.

[2] J. E. Huber and J. W. Kolar, "Applicability of solid-State transformers in today's and future distribution grids," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 317–326, Jan. 2019, doi: 10.1109/TSG.2017.2738610.

[3] B. Kroposki et al., "Autonomous energy grids," *IEEE Power Energy Mag.*, vol. 18, no. 6, pp. 37–46, Nov./Dec. 2020, doi: 10.1109/MPE.2020.3014540.

[4] D. Lineweber and S. McNulty, "The cost of power disturbances to industrial and digital economy companies," EPRI CEIDS Consortium for Electric Infrastructure to Support a Digital Society, pp. 1–98, Jun. 2001.

[5] R. Targosz and D. Chapmann, "The cost of poor power quality," Applica-tion Note - European Copper Institue - Leonardo Energy, no. 3, May 2012.

[6] I. Khan, A. S. Vijay, and S. Doolla, "Nonlinear load harmonic mitigation strategies in microgrids: State of the art," *IEEE Syst. J.*, vol. 16, no. 3, pp. 4243–4255, Sep. 2022, doi: 10.1109/JSYST.2021.3130612.

[7] H. Akagi, "New trends in active filters for power conditioning," *IEEE Trans. Ind. Appl.*, vol. 32, no. 6, pp. 1312–1322, Nov./Dec. 1996, doi: 10.1109/28.556633.

[8] H. Fujita and H. Akagi, "The unified power quality conditioner: The integration of series active filters and shunt active filters," *IEEE Trans. Power Electron.*, vol. 13, no. 2, pp. 315–322, Mar. 1998, doi: 10.1109/PESC.1996.548626.

[9] S. K. Dash and P. K. Ray, "A new PV-open-UPQC configura-tion for voltage sensitive loads utilizing novel adaptive controllers," *IEEE Trans. Ind. Inform.*, vol. 17, no. 1, pp. 421–429, Jan. 2021, doi: 10.1109/TII.2020.2986308.

[10] J. Han, X. Li, Y. Jiang, and S. Gong, "Three-phase UPQC topology based on quadruple-active-bridge," *IEEE Access*, vol. 9, pp. 4049–4058, Jan. 2021, doi: 10.1109/ACCESS.2020.3047961.

[11] T. S. Prakash, P. S. Kumar, and R. P. S. Chandrasena, "A novel IUPQC for multi-feeder systems using multilevel converters with grid integration of hybrid renewable energy system," *IEEE Access*, vol. 8, pp. 44903–44912, Mar. 2020, doi: 10.1109/ACCESS.2020.2977754.

[12] P. E. Melín et al., "Analysis, design and control of a unified power-quality conditioner based on a current-source topology," *IEEE Trans. Power Del.*, vol. 27, no. 4, pp. 1727–1736, Oct. 2012, doi: 10.1109/TP-WRD.2012.2199524.

[13] V. S. P. Cheung, R. S. C. Yeung, H. S. H. Chung, A. W L. Lo, and W. Wu, "A transformer-less unified power quality conditioner with fast dynamic control," *IEEE Trans. Power Electron.*, vol. 33, no. 5, pp. 3926–3937, May 2018, doi: 10.1109/ECCE.2017.8096545.

[14] Q. Xu, F. Ma, A. Luo, Z. He, and H. Xiao, "Analysis and control of M3C-based UPQC for power quality improvement in medium/high-voltage power grid," *IEEE Trans. Power Electron.*, vol. 31, no. 12, pp. 8182–8194, Dec. 2016, doi: 10.1109/TPEL.2016.2520586.

[15] T. Koroglu, A. Tan, M. M. Savrun, M. U. Cuma, K. C. Bayindir, and M. Tumay, "Implementation of a novel hybrid UPQC topology endowed with an isolated bidirectional DC–DC converter at DC link," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 3, pp. 2733–2746, Sep. 2020, doi: 10.1109/JESTPE.2019.2898369.

[16] A. M. Rauf, A. V. Sant, V. Khadkikar, and H. H. Zeineldin, "A novel ten-switch topology for unified power quality conditioner," *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 6937–6946, Oct. 2016, doi: 10.1109/TPEL.2015.2509510.

[17] R. M. Santos, J. Cunha, and M. Mezaroba, "A simplified con-trol technique for a dual unified power quality conditioner," *IEEE Trans. Ind. Electron.*, vol. 61, no. 11, pp. 5851–5860, Nov. 2014, doi: 10.1109/TIE.2014.2314055.

[18] B. Ambati and V. Khadkikar, "Optimal sizing of UPQC considering VA loading and maximum utilization of power-electronic converters," *IEEE Trans. Power Del.*, vol. 29, no. 3, pp. 1490–1498, Jun. 2014, doi: 10.1109/TPWRD.2013.2295857.

[19] S. B. Karanki, N. Geddada, M. K. Mishra, and B. K. Kumar, "A modified three-phase four-wire UPQC topology with reduced DC-link voltage rat-ing," *IEEE Trans. Ind. Electron.*, vol. 60, no. 9, pp. 3555–3566, Sep. 2013, doi: 10.1109/TIE.2012.2206333.

[20] A. K. Giri, S. Arya, and R. Maurya, "Compensation of power quality problems in wind-based renewable energy system for small consumer as isolated loads," *IEEE Trans. Ind. Electron.*, vol. 66, no. 11, pp. 9023–9031, Nov. 2019, doi: 10.1109/TIE.2018.2873515.

[21] S. Devassy and B. Singh, "Design and performance analysis of three-phase solar PV integrated UPQC," *IEEE Trans. Ind. Appl.*, vol. 54, no. 1, pp. 73–81, Jan. 2018, doi: 10.1109/TIA.2017.2754983.

[22] N. Saxena, I. Hussain, B. Singh, and A. Vyas, "Implementation of a grid-integrated PV-battery system for residential and electrical vehicle ap-plications," *IEEE Ind. Electron.*, vol. 65, no. 8, pp. 6592–6600, Aug. 2018, doi: 10.1109/TIE.2017.2739712.

[23] V. Rallabandi, O. M. Akeyo, N. Jewell, and D. M. Ionel, "Incorporating battery energy storage systems into multi-MW grid connected PV sys-tems," *IEEE Trans. Ind. Appl.*, vol. 55, no. 1, pp. 638–647, Jan. 2019, doi: 10.1109/TIA.2018.2864696.

[24] S. R. Ghatak, S. Sannigrahi, and P. Acharjee, "Multi-objective approach for strategic incorporation of solar energy source, battery storage system, and DSTATCOM in a smart grid environment," *IEEE Syst. J.*, vol. 13, no. 3, pp. 3038–3049, Sep. 2019, doi: 10.1109/JSYST.2018.2875177.

[25] K. K. Prasad, H. Myneni, and G. S. Kumar, "Power quality improvement and PV Power injection by DSTATCOMWith variable DC link voltage control from RSC-MLC," *IEEE Trans. Sustain. Energy*, vol. 10, no. 2, pp. 876–885, Apr. 2019, doi: 10.1109/TSTE.2018.2853192.

[26] Q. Liu, Y. Li, L. Luo, Y. Peng, and Y. Cao, "Power quality management of PV Power plant with transformer integrated filtering method," *IEEE Trans. Power Del.*, vol. 34, no. 3, pp. 941–949, Jun. 2019, doi: 10.1109/TP-WRD.2018.2881991.

[27] L. G. Campanhol, S. O. Silva, A. A. Oliveira, and V. D. Bacon, "Single-stage three-phase grid-tied PV system with universal filter-ing capability applied to DG systems and AC microgrids," *IEEE Trans. Power Electron.*, vol. 32, no. 12, pp. 9131–9142, Dec. 2017, doi: 10.1109/TPEL.2017.2659381.

[28] P. Ray, P. K. Ray, and S. K. Dash, "Power quality enhancement and Power flow analysis of a PV integrated UPQC system in a distribution network," *IEEE Trans. Ind. Appl.*, vol. 58, no. 1, pp. 201–211, Jan. 2022, doi: 10.1109/TIA.2021.3131404.

[29] S. Devassy and B. Singh, "Performance analysis of Solar PV array and bat-tery integrated unified power quality conditioner for microgrid systems," *IEEE Trans. Ind. Electron.*, vol. 68, no. 5, pp. 4027–4035, May 2021, doi: 10.1109/TIE.2020.2984439.

[30] J. Wang, K. Sun, H. Wu, J. Zhu, Y. Xing, and Y. Li, "Hybrid connected unified power quality conditioner integrating distributed generation with reduced power capacity and enhanced conversion efficiency," *IEEE Trans. Ind. Electron.*, vol. 68, no. 12, pp. 12340–12352, Dec. 2021, doi: 10.1109/TIE.2020.3040687