Biogeography based optimization strategy for UPQC PI tuning on full order adaptive observer based control

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Abstract
Adaptive full order observer based control algorithm for unified power quality conditioner is presented. The full order adaptive observer based algorithm is capable of estimating fundamental positive sequence components parameters, including frequency, amplitude, and phase form power supply systems. Due to its adaptive response, monitoring accuracy, and faster detection of fundamental positive sequence components under all different loads and grid conditions, it is used for power quality improvement. In addition to full order adaptive observer based control algorithm, a biogeography-based optimization method is employed here for tuning the $K_p$ and $K_i$ gains of a proportional integral controller on unified power quality conditioner system. The proposed method minimizes the dc-link voltage oscillations and enhances its step response by optimally tuning the proportional integral controller. This is done by reducing the objective function of the integral time absolute error for different power quality perturbations. The numerical values obtained by biogeography based optimization are selected as proportional integral gains and it also improves the controller’s performance. The full order adaptive observer control integrated with biogeography based optimization algorithm is tested interface with MATLAB/Simulink on developed unified power quality conditioner under different power quality problems at different intervals. The performance results demonstrate the quick convergence rate with effective performance.

1 INTRODUCTION

The recent advancements in power electronics technology have encouraged the use of non-linear loads on a large scale [1]. This power electronics based non-linear equipment generates harmonics and harmonics leads to causes like nuisance tripping, disoperation of consumer equipment, overheat transformer units, overheat the wiring [2]. The power converter based on power electronics give rise to the degradation of power quality (PQ), resulting in higher power losses and economic loss [3]. The poor PQ causes several damages to the system and adversely affects on the utilities and customers. The poor quality issues can be reduced by the employment of power filters [4], [5]. In general, earlier passive filters have been most commonly used for harmonics elimination and mitigation of PQ problems. It can only restrict to a few harmonic compensation and they are heavy and bulky. However, their output is restricted due to lack of dynamic compensation and resonance problem [5].

To overcome these drawbacks, active power filters (APF) are developed to mitigate for current and voltage disturbances in power distribution system [6]. It can eliminate numerous PQ problems such as voltage and current harmonics, reactive power compensation, voltage flicker issues, and unbalance loading issues. The APF shunt is used for voltage regulation, reactive power compensation, load unbalancing compensation in case of three-phase wire and neutral current compensation in case of four-wire system [7]. Similarly, the APF series is used for voltage regulation, reactive power compensation, voltage sag and swell compensation, and unbalance voltage compensation (for three-phase systems) [8]. The hybrid APF is used for mitigation of both current and voltage related PQ disturbances in the system. The unified power quality conditioner (UPQC) is well known as hybrid APF, which incorporates series and shunt APF
It is considered to be the ideal hybrid APF that eliminates voltage and current harmonics simultaneously. The compensation capability of this power electronic based APF rely upon two factors. The first is the reliable accuracy of the reference signal extraction and the second is extraction of fundamental components [10]. The control strategies for reference signal generation mostly described in the literature are time and frequency domain. The frequency domain control are discrete Fourier transform [11], fast Fourier transform [12], Kalman filtering [13] and wavelet transform [14], etc. These control techniques of frequency domain are not well known being used because of implementation complexity, higher memory requirement, and high computational burden on digital signal processing (DSP) processor [15]. The time domain control strategies are p-q theory [16], d-q theory [17], and neural networks based techniques [18]. Such time domain techniques work efficiently when the voltage supply is sinusoidal, although it fails if the supply voltage is deteriorated. Also it uses low pass filter and band pass filters to filter out the signals which leads to delay in the accuracy of the reference signal extraction [19]. Due to its simple implementation and robust in control, the time domain control is more populous in the literature [20]. In the literature there are various control strategies to explain the estimation of fundamental signal of the input supply; so that the reference signals’ generation to get the gating pulses for APF is more accurate and in-phase with the actual sensed signals. To do so, in the recent year such estimation methods are adaptive notch filter [21], complex vector filter [22] and phase locked loop (PLL) [23]. Among the parameter estimation controls specified above, PLL has the ability to track supply voltage parameters effectively. However, its performance deteriorates in terms of steady state error under frequency jump or high distortion. It also has a slow dynamic response due to the existence of filters [24].

Apart from frequency and time domain control strategies, state observer based control schemes are also found in the literature. The state observer is used to estimate the harmonic components present in the grid system. As in [25], a new SOGI-PLL architecture is designed in integration with the adaptive observer algorithms for addressing parameters estimation during frequency jump and distortion. So, a better performance is achieved during parameters estimation after the use on adaptive observer with SOGI-PLL. However, such integrated PLLs are highly non-linear, and therefore, their stability analysis becomes difficult. The first observer was proposed by Lunenberger [26], which approximately predict the unknown state variables in the system. Further, in [27] the virtual phase voltage is generated through fundamental components after eliminating harmonic components from the distorted grid with use of a full order observer method. The full order adaptive observer control on the basis of adaptive theory [28] and observer theory [29] is proposed to estimate the unknown parameters of the supply voltages which work independently with other controllers in [30]. The full order observer is widely used in various fields (especially in motor drives) due to its remarkable abilities in dealing with various disturbances in the motors [31]. Although the full order adaptive observer method is formulated in non-linear structure. But passivity and Lyapunov based arguments guarantee that the proposed full order observer is able to evaluate the actual supply voltage parameters with zero steady state error. This full order adaptive observer approach has the advantages of not relying on PLL as compared to most existing parameter estimation methods; it excludes the possible use of phase detection (PD), zero steady state error, better dynamic response, and smaller overshoot. This full order adaptive observer control has the feature for estimating the FPSC, amplitude, and grid frequency which are required in design of control algorithm for mitigation of PQ issues. After a comprehensive literature survey, the full order adaptive observer method is found to be useful in mitigating above-said issues and not one is used in PQ applications.

The proportional integral (PI) controller is one of the oldest and most reliable error regulators. Because of robust performance and easy to implementation it is widely used in industrial control systems [32]. The PI controller’s parameters ($K_p$ and $K_i$) are calibrated using a trial and error approach for certain system operating conditions. However, such method does not produce good optimized values and leads to generate surges and overshoots. Currently, several intelligent techniques have been recommended, to enhance the traditional PI parameters tuning method like the genetic algorithm [33], particle swarm optimization [34], ant colony optimization [35]. But it sometimes shares disadvantages such as dependency of initial point parameters, premature convergence phenomenon, converges to local mina and deteriorate population diversity. To overcome this, the biogeography based optimization (BBO) is a new type of evolutionary algorithm which has been widely used in a variety of real-world problems [36]. The BBO method is implemented for self-tuning PI controller gains by enhancing the migration efficiency and overcoming the untimely convergence. It is a synthetic discipline that massively relying on the theories and data collected from earth sciences, population genetic, systematic, and ecology [37]. The advantages of BBO method over other optimization are that the probable candid population delivers optimum result in the current iteration and it will be retained for subsequent iterations. Thus to provide a better global optimum solution among the population is obtained [36]. To optimize the PI gains for several areas, numerous literature use BBO techniques such in [36, 38], the BBO algorithm is employed for tuning the PI controller on synchronous machine. Similarly, here in this, an attempt is made to combine the effectiveness of the BBO in tuning PI controller to further enhance the UPQC controller performance when subjected to different PQ disturbances.

In this paper, UPQC control strategy is developed to extract the three-phase reference current/voltage signals. It is based on full order adaptive observer control. The algorithm performance is evaluated under different PQ problems such as sag, swell, harmonics, balanced, unbalanced, and non-sinusoidal. A Lyapunov function based justification was given to make sure that the proposed full order observers are locally stable at every operating point as well as voltage parameter estimation approach has zero steady state error, although the frequency varies. The full order observer method is more robust when
compared to reduced order observer on parameters variations, model parameter uncertainties, and harmonic noise. The full order observer control has an advantage of the fast and precise specified component extraction, less computational burden as compared to SOGI-PLL makes it useful for mitigation of PQ issues. Apart from the extraction of unknown variable, the full order observer also directly measure all state variables of the system. The BBO algorithm is also employed in UPQC controller to optimize PI gains parameters and this goal is achieved by minimizing the function integral time absolute error (ITAE) as one of the performance criteria. The BBO is motivated by the migration of species between suitable habitats environment. It includes both exploration and exploitation search technique at the same time. This makes the search technique the fastest growing nature inspired algorithm for solving practical optimization problems. The BBO method in optimizing the PI controller gains enhances the performance of UPQC when subjected to different PQ disturbances. The performance analysis of the UPQC system has examined the specifications of harmonic mitigation and dc-link voltage regulation. The complete simulation results of the proposed control approach have been provided using MATLAB/SIMULINK software on UPQC system. The developed system is implemented on real time to validate the proposed approach and adequate results have been described for verification.

2 | SYSTEM LAYOUT

The Figure 1 demonstrates the system configuration of a generic series and shunt conditioner. The two converters connected back to back through common dc link form the combined series and shunt power conditioners and termed as UPQC.

A DC capacitor ($C_{dc}$) is used as an energy storage component connected back to back, and formed dc-link voltage across the two converters. This DC capacitor has the main function of setting dc voltage source characteristics on the common dc link. Therefore, the power that flows through the series converter into the dc link must be balanced with the power that flows over the shunt converter and vice versa. The $L_{se}$ and $L_{sh}$ interfacing inductance are used to interface the converters. The output of the one converter is integrated in series with series transformer to the ac mains while the second one is attached in parallel with the power distribution network. Ripple filters ($R_f, C_f$) are taken to bypass the harmonics generated due to switching the converters. The devices
requirement for design of UPQC and parameters of proposed control algorithm under non-linear loads are listed in Appendix section 9.1.

3 | CONTROL ALGORITHM

The Figure 2(a) depicts the block diagram of proposed full order adaptive observer algorithm. The control plan for generalized three wire UPQC is shown in Figure 2(b). Here, the reference signal generation for both APFs are broadly illustrated using proposed full order adaptive observer algorithm. This algorithm is used to extract fundamental components (FC) from point of common coupling (PCC). The switching sequences for shunt APF are generated after comparing actual utility supply currents to the reference supply currents in the SPWM controller. Similarly, the switching sequences for series APF are generated when comparing actual utility load voltage to the reference load voltage in the SPWM controller. Finally, a BBO algorithm technique has been used for PI controller parameters tuning instead of manual tuning. This section includes all aspects of the control algorithm sub-section wise along with BBO for PI controller gain tuning. The parameters listed in Appendix A1 are given to confirm the effective response of the proposed controller in UPQC system. In observed performance, MATLAB-Simulink based simulation of the UPQC system is carried out as shown in Figure 2(b).

3.1 | Parameter estimation and design using full order adaptive observer

The single-phase supply is expressed as $v_{ps} = V_p \sin(\omega t + \theta) = V_p \sin \xi$. Where $V_p$ is grid voltage amplitude, $\omega$ is grid angular frequency, and phase angle $\xi = [0, 2\pi]$. The given grid voltage and its derive model can be illustrated [23] as following expressions.

$$\dot{x} = \begin{bmatrix} 0 \\
\psi
\end{bmatrix}$$  

where $x = \begin{bmatrix} x_1 \\
x_2
\end{bmatrix} = \begin{bmatrix} V_p \sin(\omega t + \theta) \\
V_p \omega \cos(\omega t + \theta)
\end{bmatrix}$; $A = \begin{bmatrix} 0 & 1 \\
-\psi & 0
\end{bmatrix}$ with $\psi = \omega^2$. Therefore,

$$\dot{x} = \begin{bmatrix} 0 & 1 \\
-\psi & 0
\end{bmatrix} \begin{bmatrix} V_p \sin(\omega t + \theta) \\
V_p \omega \cos(\omega t + \theta)
\end{bmatrix} = \begin{bmatrix} V_p \sin(\omega t + \theta) \\
-\omega^2 V_p \cos(\omega t + \theta)
\end{bmatrix}$$  

Because parameter ‘x’ has relationship between grid voltage and its derivate, so its output $y$ components should also be related with input grid voltage therefore,

$$y = Cx$$  

where $C = [1 \ 0]$. From (1) and (3) the rank$[CC^T] = 2$ of the given system is observable where $\omega$ is frequency of the system. For the dynamic system model (1) with unknown grid frequency, the parameter derived from the voltage of the grid is now being restructured as an adaptive observer design problem. An adaptive observer for system (1) with zero steady state error is proposed in the following section to estimate state $x$ and fundamental frequency $\omega$. The grid voltage parameters which includes frequency ($\omega$), amplitude ($V_p$), and phase angle ($\xi$) are estimated with observer gains without steady state errors based on the estimated state $x$ and fundamental frequency $\omega$. To determine so, system (1) can be rewritten as,

$$\dot{x} = Ax - \begin{bmatrix} 0 \\
\psi
\end{bmatrix} y$$  

$$\dot{x} = \begin{bmatrix} 0 & 1 \\
0 & 0
\end{bmatrix} \begin{bmatrix} x_1 \\
x_2
\end{bmatrix} - \begin{bmatrix} 0 \\
\psi
\end{bmatrix} \begin{bmatrix} 1 & 0 \\
0 & 1
\end{bmatrix} \begin{bmatrix} x_1 \\
x_2
\end{bmatrix},$$

$$\begin{bmatrix} x_1 \\
x_2
\end{bmatrix} = \begin{bmatrix} V_p \sin(\omega t + \theta) \\
-\omega^2 V_p \cos(\omega t + \theta)
\end{bmatrix}$$

On solving (4) we have the theoretical and observer estimation results are same. This will also conclude from comparing (2) and (5). It can be Hurwitz matrix since the given dynamical system is observable. The symmetrical matrix $A$ is called a stable matrix if every eigen value of $A$ has strictly negative part real [28]. Then ‘$A$’ is a stability matrix because $\dot{x} = Ax$
asymptotically stable when, \( x \to 0 \) as \( t \to \infty \). The developed circuit is asymptotically stable if the Jacobian of dynamical system is Hurwitz at fixed point. So the matrix \( A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \) is modified for observable dynamic system (4) to obtain the full order adaptive observer [20] as follows.

\[
\dot{x} = Ax - \begin{bmatrix} 0 \\ \hat{y} \end{bmatrix} y + O_b(C\hat{x} - y), \quad x(0) = x_0
\]  

(6)

where \( \hat{x} \) and \( \hat{y} \) are the estimation state \( x \) and unknown parameter \( \psi \), respectively, of the system. The given linear system (4) is also observable, which has observer gain matrix \( O_g \), to assure that new observable matrix \( A_k = A + O_gC \) is Hurwitz. This helps to ensure that there exists \( P_k = P_k^T > 0 \) and \( Q_k = Q_k^T > 0 \) such that:

\[
A_k^T P_k + P_k A_k = -Q_k < 0
\]  

(7)

Thus, the estimation errors \( \hat{x} = \hat{x} - x \) and \( \hat{y} = \hat{y} - y \) can be defined for state \( x \) and unknown parameter \( y \) to filter out during process. It also acclaimed that the observer matrix \( A_k \) acts as a filter to estimate the unknown states from the measured quantities. By substituting the dynamics estimated errors in system (6) with help of (7),

\[
\dot{\hat{x}} = A_k \hat{x} - \begin{bmatrix} 0 \\ \hat{y} \end{bmatrix} y
\]  

(8)

where the parameter \( \lambda > 0 \). So the derivative \( V(\hat{x}, \hat{y}) \) is able to be describe as,

\[
\dot{V}(\hat{x}, \hat{y}) = -\hat{x}^T Q_k \hat{y} - \hat{x}^T P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y \hat{y} + \frac{2}{\lambda} \hat{y} \hat{\dot{y}}
\]  

(9)

Given that \( \hat{y} \) is a constant, \( \hat{\dot{y}} = \dot{\hat{y}} \) can be reduced and the possible adaptive update law can be constructed as,

\[
\dot{\hat{y}} = \lambda \hat{x}^T P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y
\]  

(10)

\[
= \lambda [\hat{x}_1 - x_1 \hat{x}_2] P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y - \lambda [0 \times \hat{x}_2] P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y, \quad \hat{y}(0) = \hat{y}_0
\]  

(11)

From system (1), the following states can be designed, \( x_1 = y \) and \( x_2 = \hat{x} = \hat{y} \), which modified the (11) as the following expression.

\[
\dot{\hat{y}} = \lambda [\hat{x}_1 - y \hat{x}_2] P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y - \lambda [0 \times \hat{x}_2] P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y
\]  

(12)

\[
\hat{y}(0) = \hat{y}_0
\]

State variable \( b \) and its dynamics are edited by adaptive observer as

\[
\dot{b} = \lambda [\hat{x}_1 - y \hat{x}_2] P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y + \hat{y}(0)
\]  

(13)

The following expression is obtain on substituting (13) into (11) and integrating on both sides of (12) gives,

\[
\hat{y} = b - \lambda \begin{bmatrix} 0 \frac{v^2}{2} \end{bmatrix} P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y + \hat{y}(0)
\]  

(14)

Specifically by choosing, \( \hat{y}(0) = b(0) - \lambda \begin{bmatrix} 0 \frac{v_0^2}{2} \end{bmatrix} P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} \) the adaptive update law can be modified as

\[
\dot{\hat{y}} = \lambda \begin{bmatrix} 0 \frac{v^2}{2} \end{bmatrix} P_k \begin{bmatrix} 0 \\ 1 \end{bmatrix} y
\]  

(15)

To illustrate the stability of the observer and examine the steady state accuracy of the estimated states; subsisting (13) and (15) into the derivatives of the Lyapunov function (10) gives,

\[
\dot{V}(\hat{x}, \hat{y}) = -\hat{x}^T Q_k \hat{x} \leq 0
\]  

(16)

The closed loop system constructed by (6), (13), and (15) is therefore globally stable. The filtering term obtain with observer gain matrix \( O_k(C\hat{x} - y) \) has no effect on the system model when steady state reaches as \( \hat{x} = x \). When \( \hat{x} \neq x \), then dynamic error will be stable providing the \( A_C \) matrix is Hurwitz. Hence, error \( \hat{x} = x - \hat{x} \) converges to zero. Therefore there is a zero steady state error in estimating the system state \( x \) and unknown parameters \( \psi \). Using the estimated state \( \hat{x} \) and unknown parameter \( \psi \), the system frequency \( \omega \), amplitude \( v \), and voltage phase angle \( \zeta \) can be evaluated in the following manner,

\[
\dot{\omega} = \sqrt{\dot{\hat{y}}} \quad \dot{v} = \sqrt{\frac{\hat{x}^2}{2} + \frac{\hat{x}_2^2}{\dot{\hat{y}}}^2} \quad \text{and} \quad \zeta = \arctan \left( \frac{\hat{x}_1}{\hat{x}_2} \right)
\]  

(17)

The proposed full order adaptive observer as shown in Figure 2(a) can estimate the actual grid voltage parameters which includes frequency, phase angle, and amplitude with zero steady state error. The bold line in Figure 2(a) represents array inputs and outputs while the other one includes single input.
3.2 Reference signal generation using observer control strategy for UPQC controller

The generation of the reference signal for UPQC controller relies on the fundamental positive sequence components (FPSC) of the PCC signals. The extraction of FPSC from PCC voltage is a significant important work [10] for the generation of reference load voltage and supply current in UPQC controller.

In this paper, the fundamental components $(\tilde{x}_1,\tilde{x}_2)$ are estimated using full order adaptive observer [30] as can be seen from Figure 2(a), the full order adaptive observer will provide fundamental in phase $(\tilde{x}_1 \approx \tilde{v}_{/\alpha})$ and quadrature $(\tilde{x}_2 \approx \tilde{v}_{/\beta})$ components of the input signal $(\tilde{v})$.

In order to extract FPSC from the input voltages $(\tilde{v}_{abc})$ a full order adaptive observer control algorithm is used as given in Figure 2(b). The three phase voltages $(\tilde{v}_{a}, \tilde{v}_{b}, \tilde{v}_{c})$ of the PCC are transformed into two phase voltages $(\alpha-\beta)$ frame using Clark transformation matrix. To extract the fundamental positive in-phase components $(\tilde{v}_{/\alpha}^+, \tilde{v}_{/\beta}^+)$ and its quadrature components $(\tilde{q}_{/\alpha}^+, \tilde{q}_{/\beta}^+)$; the $\alpha$-components $r_{\alpha}$ and $\beta$-components $r_{\beta}$ are filtered using proposed full order adaptive observer filters. The relationship between FPSC and fundamental components $(\tilde{v}_{/\alpha}, \tilde{v}_{/\beta})$ is illustrated as

\[
\tilde{v}_{/\alpha}^+ = \frac{1}{2}(\tilde{v}_{/\alpha} + q_{/\beta}) \tag{18}
\]

\[
\tilde{v}_{/\beta}^+ = \frac{1}{2}(\tilde{v}_{/\beta} - q_{/\alpha}) \tag{19}
\]

The FPSC of PCC voltage in $\alpha-\beta$ frame $(\tilde{v}_{/\alpha}^+, \tilde{v}_{/\beta}^+)$ are again converted using inverse Clarks transformation matrix to extract FPSC of PCC voltages in stationary frame $(\tilde{v}_{abc})$ in order to get reference signals for both APFs. The reference signals generation for shunt APF control is such that the currents carried from the PCC are balanced positive sequence under all PQ conditions and irrespective of the loads as depicted in Figure 2(b). By filtering the dot product of the load voltages $(\tilde{v}_{abc})$ and currents $(\tilde{i}_{abc})$, the average load power $(P_{avg})$ is obtained. The actual dc-link capacitor voltage $(V_{dc})$ is compared with a constant reference voltage $(V_{dc}^*)$ value. The UPQC’s dc bus is controlled using a PI controller at its required reference voltage value. The error voltage $(V_e)$ is generated when reference de-link voltage $(V_{dc}^*)$ and sensed dc bus voltage $(V_{dc})$ are compared with each order. The $V_e$ is passed through PI controller which yields power loss components $(P)$ for APFs of the UPQC [20]. But the shunt APF will maintain the desired de-link voltage. Therefore [7], the reference power to be extracted from the grid is then derived as, $P_{ref} = P_{avg} + P$. Then, the balanced positive sequence reference grid input current $(\tilde{i}_{abc}^*)$ are calculated as

\[
\tilde{i}_{abc}^* = \frac{\tilde{v}_{abc}^*}{(\tilde{v}_{/\alpha}^+)^2 + (\tilde{v}_{/\beta}^+)^2} P_{ref} \tag{20}
\]

Now these reference currents $(\tilde{i}_{abc}^*)$ are compared with the sensed actual currents $(\tilde{i}_{abc})$ in a carrier based sinusoidal pulse width modulation (SPWM) controller to generate gate pulse sequences corresponding to shunt APF as observed in Figure 2(b).

The purpose of the series APF is to protect sensitive loads from PCC voltage disturbances. Figure 2(b) also showed the gate pulse generation with the help of reference load voltage for series compensator. The amplitude of FPSC of PCC voltage is determined as

\[
V_{ip} = \sqrt{(\tilde{v}_{/\alpha}^+)^2 + (\tilde{v}_{/\beta}^+)^2} \tag{21}
\]

This magnitude of actual voltage is used for evaluating three phase unit templates of PCC voltages [21] as

\[
\tilde{v}_{abc}^* = \frac{\tilde{v}_{abc}}{V_{ip}} \tag{22}
\]

The product of the peak reference voltage $(V_{ip})$ and unit templates $(\tilde{v}_{abc}^*)$ will produce the reference load voltages $(\tilde{v}_{abc}^*)$ which help in generating gating sequence in a SPWM controller as demonstrated in Figure 2(b).

3.3 PI controller gains estimation using BBO algorithm optimization technique

A proportional integral (PI) controller using biogeography based optimization (BBO) is incorporated to improve the dynamic behaviour of a UPQC system. In biogeography [36], the migration of species from one island to different islands relies on numerous suitability index constraints. This includes water resources, vegetation habitat diversity, temperature, land area, and several other indexes. The major concern here to implement BBO [38] is to change the PI controller parameters as quickly as possible by reducing the predetermined fitness feature to enhance the transient response of the DC voltage step on the UPQC device. The fitness function can be formed in the time domain by different performance specifications, one of them is formed as following.

\[
F(K) = \min \{ITAE((1 - e^{-\rho}) (M_p + E_{ss}) + e^{-\rho} (t_s - t_f))\} \tag{23}
\]

where $K = [K_p, K_i]$ is a parameters gain of PI controller. The ITAE, $M_p$, $E_{ss}$, $t_s$ and $t_f$ are integral time multiplied by absolute error value, maximum overshoot, steady state error, settling time, and rise time, respectively, of the performance criteria in the time domain. The value of $\rho$ which is a weighting factor has some effects on system parameters. If $\rho < 0.7$ then its effects on system parameters is to reduce $t_s$ and $t_f$. Whereas, if $\rho > 0.7$ then its effects on system parameters is to reduce $M_p$ and $E_{ss}$. 


The BBO utilizes the Habitat Suitability Index (HSI) to recognize the best approach [37]. If the environment is conductive, the HSI will be high while low HSI express unfavourable atmosphere for the species. The species shift from one location to different place is described by the emigration rate ($\lambda$) and immigration rate ($\mu$). The higher value of $\mu$ point out the appearance of species from the neighbouring environment and the higher value of $\lambda$ indicate population explosion in an environment [37].

The total number of species summarized to an ecosystem is probabilistically calculated as

$$P_s(t + \Delta T) = P_s(t)(1 - \lambda_s \Delta t - \mu_s \Delta t) + P_{s-1}(t) \lambda_s \Delta t + P_{s+1}(t) \mu_s \Delta t$$

(24)

where, $P_s$ is the probability of species in an HIS for $s$ species with $s_{\text{max}}$ as a maximum number of species that a habitat can hold. To determine the emigration rate $\mu$ and the immigration rates $\lambda$ in terms of maximum emigration ($E$) and maximum immigration ($I$) for the species summarized to a habitat $H$ is calculated as

$$\mu_s = \frac{E_s}{s_{\text{max}}} \quad \text{and} \quad \lambda_s = I \left(1 - \frac{s}{s_{\text{max}}} \right)$$

(25)

The $|V_{\text{dref}} - V_{\text{dactual}}|$ should be zero to improve the HIS. The species which are relocated from one habitat to another is known as migration. This species emigrated from the ecosystem with the probability of $P_{\text{mod}}$ in the process of migration. The population in environment transformed and the process is known as mutation which further improves HSI, given by

$$m(s) = m_s \left( 1 - \frac{P_s}{P_{\text{mod}}} \right)$$

(26)

where, $m(s)$ indicates the mutation rate for the species $s$, $P_{\text{mod}}$ is a probability of emigrated in habitats, and $m_s$ is the maximum mutation rate. After considering the BBO parameters given in the Table 1, the following BBO algorithm is employed for obtaining PI controller parameters.

By implementing this algorithm in MATLAB/SIMULINK environment, the optimal PI controller gains ($K_p = 125.43$ and $K_i = 1.0$) are estimated with optimum cost function $F(K)$ is 1935 as shown in Figure 3(a). By the use of this $K_p$ and $K_i$ values, UPQC is giving better response when compare to trails and error methods values which also enhance performance of UPQC controller to improve power quality.

Here BBO optimization uses the number of species 20, two design variables ($K_p$ and $K_i$) for 50 iteration values. Figure 3(a) depicts the variation of objective function $F(K)$ values related to iterations which settled at 1935 after 11th iteration. Figure 3(b,c) illustrates the performance of $K_p$ and $K_i$ plots for DC-link voltage, that is recorded to setting value of 125.43, 1.0, respectively.

To evaluate the response and effectiveness of PI controller with BBO technique, the DC-link voltage is represented with above-said PQ issues and it is expressed in Figure 3(d) with its zoomed version. The zoomed view of Figure 3(d) demonstrates the clear pictorial view of variation of rise time ($t_r$), settling time ($t_s$), and maximum peak over-shoot ($M_p$) for both tuning processes. The rise time is considered at 100% of the final value (i.e., 700) and 2% tolerance band (i.e., 686–714) is preferred for underdamped system. The details of time response parameter are listed in Table 2.

Table 2 and Figure 3(d) and its zoomed version show that BBO is maintaining the DC link more stable and quicker as compared to manual tuning process. It has faster rise time ($t_r$), better settling time ($t_s$), less peak over shoot ($M_p$), and tolerance band slightly less as compared to manual PI gains value. The optimized value of $K_p$ and $K_i$ obtained from BBO will also be used in PI controller to monitor the UPQC system, the results are discussed in the next section.

### TABLE 1 BBO parameters for obtaining pi controller gains

| Parameter            | Symbol | Value |
|----------------------|--------|-------|
| Number of generation | $N_g$  | 20    |
| Total species size   | $N_p$  | 20    |
| Population dimension | $N_d$  | 2     |
| Maximum rate of emigration | $E$     | 1     |
| Maximum rate of immigration | $I$     | 1     |
| Mutation rate        | $m(s)$ | 0.04  |

### Algorithm 1 Procedure for Obtaining Parameters of PI Controller Using BBO Algorithm

1: Initialize: Number of generation ($N_g$), total species size ($N_p$), population dimension ($N_d$), maximum rate of emigration ($E$), maximum rate of immigration ($I$), and mutation rate ($m(s)$)
2: $i = 1$ to $N_g$ for
3: Mapped species to Habitations: Using (24) probabilistically map parameters of PI controller to a habitats $P_s(t + \Delta T)$ $\rightarrow$ MapSpecies($\mu_k, \lambda_s, N_p$)
4: Compute HSI of the species: Compute fitness function by ITAE $\rightarrow$ Fitness ($f(K_p, K_i)$) for each PI controller
5: Update immigration and emigration rates: Using (25); revise $\lambda$ and $\mu$ that is $[\mu_{k+1}, \lambda_{s+1}]$ $\rightarrow$ Update($\mu_k, \lambda_s$)
6: Species migrate to other habitats: Using (24); migrate parameters of the PI controller with high immigration rate to the other habitat.
7: Mutation: Mutate the gains of PI controller with low HSI using (26) to advance controller performance $\rightarrow$ Mutation($K_p, K_i$)
8: end for

### 4 SIMULATION STUDY

In this section, UPQC is simulated in MATLAB/SIMULINK software tool with the proposed full order adaptive observer controller under different PQ conditions using ode 45 solvers with a fixed sampling time of 10 $\mu$s. The UPQC controller performance is verified by an exhaustive simulation study, as illustrated below. The PI controller and its parameter are optimized by BBO algorithm as analysis of UPQC has demonstrated. The
results for sag, swell, harmonics, and load unbalancing conditions are presented in this section to observe the performance of the full order adaptive observer controller on UPQC with non-linear load. Appendix A1 contains the detailed design values of UPQC for the simulation model.

4.1 Shunt section of UPQC ability analysis under unbalancing and load current harmonics

The dynamic behaviour of UPQC under unbalancing and load current harmonics is presented in Figure 4(a). The load unbalancing has been achieved during load injection in phase ‘c’ load at time 0.5 s. The balanced supply currents ($i_s$) have been observed during the imbalance in the load current ($i_l$) due to phase removal. Figure 4(a) indicates the dc-link voltage transient response to a load change. During load change, capacitor voltage increase to 716 V to absorb the additional energy. Controller responds for this change and brings the dc-link voltages
FIGURE 4 (a) Behaviour of Shunt APF under unbalancing and load current harmonics. (b) Behaviour of Series APF for sag, swell, and supply voltage harmonic. (c) Behaviour of UPQC in steady state and transient condition again to its reference value of 700 V. The overshoot and settling time can be optimized by optimizing the controller parameters $K_p$ and $K_i$. The self-supporting dc bus voltage ($V_{dc}$) profile is also shown here which is within the limit of 3% tolerances band. The $V_{dc}$ is settles down after variances of 16 V from its ideal controlled estimation of 700 V. There is an immaterial move of half cycle for the shunt APF to appraise important reference power ($P_{ref}$) estimations. This occurred because of the utilization of lower order channels (filters) in estimation dc bus voltage and active average power ($P_{Lavg}$) calculation. The load voltage ($v_l$) profile is maintained at its ideal level irrespective of unbalanced loading conditions. The FPSC of supply voltage in $\alpha$–$\beta$ frame signals ($\hat{v}_{\alpha}^{+}, \hat{v}_{\beta}^{+}$) is used to estimate balanced reference positive sequence currents ($i_{ref}^+$) under all power quality (PQ) conditions. During current harmonic as well as load unbalancing, $\hat{v}_{\alpha}$ and $\hat{v}_{\beta}$ are harmonic free with proper load current magnitude. It indicates that the observer control is providing FPSC sinusoidal in nature during all PQ issues. The outcome observed in the wave shape that the three-phase supply currents ($i_s$) consistently track the reference supply currents ($i_{ref}^+$) under dynamics disturbance. It should also be noted that supply voltage ($v_s$), load voltage ($v_l$), and supply current ($i_s$) are in phase with each other so it concluded that the shunt compensator of UPQC work as power factor correction mode during load dynamics. Figure 4(a) also shows the compensating current ($i_{com a}, i_{com b}, i_{com c}$) injected by the shunt APF containing all the harmonics, to make supply current sinusoidal. When the shunt APF supply these compensating currents, the current harmonics were compensated and $i_s$, total harmonic distortion.
4.2 Series section of UPQC ability analysis for sag, swell and supply voltage harmonics

The dynamic behaviour of UPQC under various voltage fluctuations are represented in Figure 4(b). The series APF of UPQC starts its operation at the moment any voltage based PQ fluctuations occur in the system, in which the load voltage \((v_l)\) is compensated to be balanced and sinusoidal after compensation, as shown in Figure 4(b). Thus, to observe the voltage compensation of series APF sag in the supply voltage \((v_s)\) having magnitude of 0.70 pu is considered from 0.5 to 0.56 s. Similarly, a swell in supply voltage \((v_s)\) having magnitude of 1.30 pu is considered from 0.6 to 0.66 s. During voltage sag and swell conditions, the series APF is giving that vital voltage by series inductors to mitigate voltage sags and swells in the supply. This injected voltage is an in-phase compensating voltage \((\hat{v}_{inj_a}, \hat{v}_{inj_b}, \hat{v}_{inj_c})\) which is acquired by the distinction of reference load voltage \((\hat{v}_{lref}^+)\) and supply voltage \((v_s)\). Now at 0.4 to 46 s–11th and +13th harmonics with amplitude of 1/15th and 1/20th of supply voltage are introduced in the system. The source current \((i_s)\) waveform is also represented in Figure 4(b). It is observed that the source currents are larger/lesser during voltage sag/swell, respectively, in order to provide active power for the series APF to compensate power demanded by load. Since the load voltage \((v_l)\) depicted in Figure 4(b) is compensated from all PQ perturbations and it is sinusoidally balanced in nature with desired magnitude. The FPSC of supply voltage in \(\alpha-\beta\) frame signals \((\vec{I}_s^\alpha, \vec{I}_s^\beta)\) is also depicted during all PQ conditions. During harmonic \(\vec{I}_s^\alpha\) and \(\vec{I}_s^\beta\) is harmonic free while during sag and swell its magnitude decreases in accordance with the nature. It is further used to estimate the balanced reference positive sequence voltages \((\vec{V}_s^\alpha)\) under all PQ disturbances. According the in-phase unit templates \((\hat{u}_s^{+\alpha,\beta})\) is obtained to construct required reference load voltage \((\hat{v}_{lref}^+)\) for series APF.

The injected voltage \((\hat{v}_{inj_a}, \hat{v}_{inj_b}, \hat{v}_{inj_c})\) injected by series transformer is also shown in Figure 4(b) during voltage sag (at time 0.5–0.56 s), swell (at time 0.6–0.66 s), and voltage harmonics (at time 0.4–0.46 s) conditions with respective magnitude. It keeps the load voltage at desired reference level at load side. The result also indicates that, the load voltage \((v_l)\) consistently flows the reference load voltage \((\hat{v}_{lref}^+)\) under all dynamic disturbances. Similarly, from Figure 4(b) it can be seen that there is no phase difference between the fundamental positive sequence supply voltages \((\vec{V}_s^\alpha)\) and the load voltage \((v_l)\), so these two voltages are also in-phase in the UPQC system. Basically, the series part of UPQC is compensate, voltage harmonics, sag, swell and make the supply current in phase with load voltage in the distributed system at load side.

4.3 Ability analysis of UPQC in steady state and transient condition

The UPQC dynamic response with full order adaptive observer control is depicted in Figure 4(c) during transient and steady state conditions. The signals expressed in Figure 4(c) are supply voltages \((v_s)\), supply currents \((i_s)\), load voltage \((v_l)\), load currents \((i_l)\), DC bus voltage \((V_{dc})\), shunt APF compensation currents \((i_{com_a}, i_{com_b}, i_{com_c})\), and series APF compensation voltages \((\hat{v}_{finj_a}, \hat{v}_{finj_b}, \hat{v}_{finj_c})\) for each phase. Time instant 0.4–0.46 s, the supply voltage is deteriorated through −11th and +13th harmonics with 1/15th and 1/20th of fundamental voltage magnitudes. Similarly, at 0.5–0.56 s a voltage sag of 0.70 pu magnitude; 0.6–0.66 s a voltage sag of 1.70 pu amplitude are introduced in supply voltages \((v_s)\). In time 0.46–0.56 s, the load is changed from three phase to two phase when the phase c is disconnected from the supply. Therefore, it creates load unbalanced condition in the system as shown in the figure. It is evident from the results that the shunt APF mitigates the load unbalancing effectively by providing sinusoidally compensating current \((i_{com_c})\) in phase c during unbalanced loading condition.

The compensation currents \((i_{com_a}, i_{com_b}, i_{com_c})\) injected by shunt APF is also depicted in Figure 4(c) during load unbalancing (at time 0.46–0.56 s) and current harmonics (at time 0.4–0.47 s) conditions with respective magnitude which make the source current \((i_s)\) balanced, sinusoidal in nature, and it is in-phase with the source voltages \((v_s)\). The series part of UPQC gives mitigation to voltage distortion as well as sag/swell and causes load voltages \((v_l)\) distortions free as presented in Figure 4(c). It also depicts the injected voltage \((\hat{v}_{inj_a}, \hat{v}_{inj_b}, \hat{v}_{inj_c})\) injected by series transformer during voltage sag (time 0.5–0.56 s), swell (at time 0.6–0.66 s), and voltage harmonics (at time 0.4–0.46 s) conditions with respective magnitude which ensure that load voltage \((v_l)\) is free from all PQ perturbations and it is sinusoidally balanced in nature with desired magnitude. Subsequently it manages steady voltage regulation at PCC. The shunt part of UPQC gives compensation from the current harmonics and makes the supply currents \((i_s)\) sinusoidal as shown in Figure 4(c) irrespective of wave shape of the load current. Thus, it additionally kept up the power factor at unity and makes the supply current sinusoidally balanced. The full order adaptive observer control maintains the self-supporting dc-link voltage close to reference level under any current and voltage perturbation.

The percentage harmonic of load current \((i_l)\), load current \((i_s)\), supply current \((i_s)\), and load voltage \((v_l)\) are described in Table 3. Due to symmetrical three phases, the only line to line signals of Phase ‘a’ for harmonics compensation are analysed here. Although, the results are practically equivalent for other two phases. It can be observed that source current THD effectively compensated and THD decreased from 27.10% to 4.13%. Nature of the current is pure sinusoidal and balanced. Similarly, the load voltage THD effectively compensated and THD decreased from 16.38% to 3.45%. So, the nature of the voltage is pure sinusoidal and balanced. The harmonic spectrums supporting the restriction of harmonics frequency below 5% for
TABLE 3 Performance of UPQC under harmonic compensation

| Waveform distortion | Parameters       | Percentage of harmonics and magnitude |
|---------------------|-----------------|---------------------------------------|
| Harmonics level     | Source voltage ($v_{sa}$) | 16.38%, 582.9 V                      |
|                     | Supply current ($i_{sa}$)   | 4.13%, 31.3 A                         |
|                     | Load voltage ($v_{la}$)     | 3.45%, 585.8 V                        |
|                     | Load current ($i_{la}$)     | 27.10%, 30.56 A                       |

medium voltage implementation of IEEE guidelines by the proposed controller on UPQC system.

5 | TEST RESULTS DISCUSSION

The simulation results are verified by the experimental performance of the proposed full order adaptive observer control scheme on the UPQC system. This control scheme is implemented using the OP-5142 real-time simulator platform equipped with multi-core processor. The sampling time 70 μs is taken for 10 kHz switching frequency which can be easily implemented by this real-time processor. The dynamic performance is evaluated with abovementioned PQ disturbances on RL load connected to three phase bridge rectifier. While for the steady state performance during harmonic is evaluated with FLUKE-43B power quality analyser. All internal signals of the control algorithm during dynamic conditions are measured in ‘phase to ground’ while steady state analysis is measured in ‘phase to phase’ values. Since the power supply and the non-linear load are symmetrical in all three phases, ‘Phase a’ is only shown in all the waveforms. The detailed UPQC system parameter and full order control algorithm are given in Appendix section -9.2.

5.1 | Dynamic performance of UPQC

The analysis of dynamic response of UPQC for mitigating the aforementioned PQ disturbances using full order adaptive observer control is explained from Figures 5 and 6. Figure 5(a-d) depicts the information about the supply voltage ($v_{sa}$ in trace 1), supply current ($i_{sa}$ in trace 2), load voltage ($v_{la}$ in trace 3), and load current ($i_{la}$ in trace 4) during voltage swells, sags, harmonics distortions, and load unbalanced, respectively. The Figure 5(a-c) illustrates the experimental results for 30% swell, 30% sag, and 11th and 13th orders harmonic distortions are superimposed on source voltage. Despite the supply voltage disturbances, the load voltage is able to keep a 230 V reference voltage as expressed in Figure 5(a-c). The current compensation capabilities are also shown in Figure 5(a,b) (in trace 2) under voltage swell and sag conditions. The magnitude of the source current ($i_{sa}$) during voltage sag compensation time increased from the normal operation. It is because whenever the sag occurs on the supply voltage, the shunt APF draws more power from the source to support series APF for voltage sag compensation.

FIGURE 5 Dynamic behaviour of UPQC during (a) swell, (b) sag, (c) harmonic disturbances, (d) load unbalances
Around this moment, time load voltage is sustained of steady magnitude level by UPQC controller. The UPQC also mitigates harmonic disturbances and maintains distortion less load voltage as expressed in Figure 5(c). In all Figure 5 (in trace 4) the load current appears to be highly distorted. But the UPQC controller kept up source current sinusoidal wave shape. The phase ‘a’ of load is detached to show load removal conditions (in trace 4) which appeared in Figure 5(d). It also delights the sinusoidal characteristic of supply current, despite the consequences of load disturbance and load voltage is also maintained at desired sinusoidal level. From the close observation in Figure 5(a–d) during disturbances and nominal conditions the load voltage \( v_{la} \) in trace 3) are in-phase with the source current \( i_{sa} \) in trace 2) that shows the UPQC is kept up adjusting the load power factor at unity.

Figure 6(a–d) demonstrates about the behaviour of dc-link voltage \( V_{dc} \) in trace 4) with supply voltage \( v_{sa} \) in trace 1), load voltage \( v_{la} \) in trace 2), and compensating voltage of ‘phase a’ \( v_{ca} \) in trace 3) at the various power quality perturbations. It is indicated that the compensated voltage pumped by series transformer in Figure 6(a–c) is in-phase throughout the conditions of sag, swell, and harmonic distortions. Similarly, Figure 6(d) shows about supply current \( i_{sa} \) in trace 1), load current \( i_{la} \) in trace 2), compensating current of phase A \( i_{ca} \) in trace 3) injected during the unbalance condition and dc-bus voltage \( V_{dc} \) in trace 4). The source current is shown to stay sinusoidal in nature while the load becomes unbalanced and the compensator injects a sinusoidal current. The voltage of dc link is seen dropping from the reference value of 400 V and quickly recovered by the shunt APF control operation. The Figure 6(a–d) demonstrates the variation of the dc-link voltage \( V_{dc} \) in trace 4) on UPQC system to compensate different PQ disturbances successfully.

5.2 Steady state analysis of UPQC

The waveform of the source current \( i_{sa} \), load current \( i_{la} \), supply voltage \( v_{sa} \), load voltage \( v_{la} \), and compensating current \( i_{ca} \) are depicted in Figures 7 and 8 under non-linear loads. Their FFT analyses are also shown in respective figures. Such waveforms are studied with 11th and 13th harmonics disturbances in the source voltage line. Figure 7(a) displays the source voltage \( v_{sa} \) waveforms that have harmonics of the above-said situations, and source current \( i_{sa} \) after mitigation. Figure 7(b) contributes to the information that the source voltages have a 14.50% THD. The source current has THD of 4.6% after compensation as display in Figure 7(c) which is maintained against load current \( i_{la} \) possessing THD of 23.6% which is depicted in Figure 8(c). Figure 7(d) displays the load voltage \( v_{la} \) waveforms after mitigation and shunt APF compensator current of phase ‘a’ \( i_{ca} \). Similarly, the load voltage \( v_{la} \) after compensation and distortional load current \( i_{la} \) waveforms are displayed in Figure 8(a). The load voltage is mitigated in Figure 8(b) and has an RMS value of 226.0 V with 4.4% THD. However, a non-linear load having the THD 23.6%, and the load current’s harmonic spectrum contains harmonics of the order \( h = 6 \pi \pm 1 \), where \( n = 1, 2 \ldots \) as shown in Figure 8(c). The key feature of UPQC
is the load voltage ($v_l$) and source current ($i_s$) will be in-phase after the mitigation that is shown in Figure 8(d). Simultaneously, load voltage and source current in Figure 8(d) are close to sinusoidal wave shape at desired amplitude level. It is illustrated in Figure 7(c) and Figure 8(b) that $v_l$ and $i_s$ fall within reasonable THD limits of IEEE-519-2014 standards.

6 CONCLUSION

The proposed full order adaptive observer control strategy is used for UPQC controller under various power quality (PQ) perturbations. The controlling of UPQC requires FPSC of the supply voltage and load currents. The full order observer based control algorithm is designed to extract the FPSC and eliminate harmonic components from the distorted PCC voltages. The proposed gains of the full order observer guarantee the local stability of the system, if parameters are unknown. The transient and steady state performance of UPQC system is made effective with this proposed control scheme. This paper also introduced an approach based on BBO algorithm for tuning the PI controller parameters in UPQC system. The results obtained through simulation on UPQC show that an efficient search for optimal tuning of PI controller gains can be carried out by the BBO method. Using BBO, the PI controller parameters’ tuning speed is enhanced from the traditional tuning process. After 11th iteration PI controller proportional parameter ($K_p$) and integral gain ($K_i$) are obtained as 125.43, 1.0 respectively, which maintains dc bus voltage level to desired magnitude. Now with these values it is provided better settling time ($t_s$), less peak over shoot, and tolerance band slightly less as compared to manual PI gains value. It is seen that the time taken to achieve stability for the BBO method on UPQC is less than that of manual PI controller. The THD is reduced to some extent of IEEE benchmarks. The performance of proposed full order adaptive observer control strategy along with optimized PI controller gains on UPQC is evaluated by MATLAB simulation and additionally validated through experimentation, which offers good tracing capabilities and dynamic response. Thus, the experimental performance is satisfactory in contrast to the simulation studies of the proposed control method for different PQ perturbations with different loading condition.

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APPENDICES
System parameter for simulation of UPQC
Supply PCC voltage (\(V_{dc}\)) = 415 V, 50 Hz; non-linear load, three-phase diode bridge rectifier (DBR) with \(L = 250 \text{ mH}, R = 20 \Omega\); dc-link voltage (\(V_{dc}\)) = 700 V; dc bus capacitor (\(C_{dc}\)) = 7000 \text{ mF}; series injection transformer = 120/120 V, 5kVA; source impedance (\(Z_s\)) = 0.060 \Omega, \(I_s = 1.5 \text{ mH}\); shunt interfacing inductance (\(L_{sh}\)) = 2.5 \text{ mH}\); series side interfacing inductance (\(L_{sh}\)) = 0.5 \text{ mH}; RC filter \(R = 3 \Omega, C = 30 \mu \text{ F}\); PI controller \(K_p = 125.43, K_i = 1.0\); LPF cut-off frequency = 10 Hz; switching frequency of both VSCs = 10 kHz, sampling time (\(T_s\)) = 10 \mu s. Full order adaptive observer gains \(O_\omega = [-6\omega; -9\omega^2]^T\), \(P_\omega = [1 \ 0; 0 \ 1]^T, \omega = 2\pi 50, \mu = 0.707\).
System Parameter for Test Performance of UPQC
Supply PCC voltage ($V_s$) = 230 V, 50 Hz; non-linear load three-phase DBR with $L = 250$ mH, $R = 20$ $\Omega$; dc-link voltage ($V_{dc}$) = 400 V; dc bus capacitor ($C_{dc}$) = 7000 $\mu$F; series injection transformer = 120/120 V, 5 KVA; shunt side interfacing inductance ($L_{sh}$) = 3.5 mH; series interfacing inductance ($L_{se}$) = 0.5 mH; RC filter $R_f = 5$ $\Omega$, $C_i = 200$ $\mu$F; PI controller $K_p = 65$, $K_i = 1$; sampling time ($T_s$) = 70 $\mu$s. Full order adaptive observer gains ($O_g$) = $[-6\omega; -9\omega^2]^T$, $P_k = [1 \ 0; 0 \ 1]^T$, $\omega = 2\pi 50$, and $\gamma = 0.707$. 