Parameters Extraction of Unified Power Quality Conditioner on the Calculation of a Membership Function

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Abstract: The Unified Power Quality Conditioner (UPQC) has the capability of improving power quality in the industrial distribution systems. It is a combination of shunt and series active power filters, both joined together by a common Direct current (DC) bus. The major issue when utilizing the UPQC is the determination of the optimal parameters. The traditional method used to determine the optimal parameters of the UPQC is a daunting task, because the system requires greater computational and simulation efforts. This paper proposes a faster approach using the concept of a Membership Function (MF) in which a Weight Factor (WF) is utilized. In the proposed technique, a range of values is specified for each parameter of the filters. These values are used to design a membership function for each parameter, and the choice of the optimal parameter is extracted by the aid of a WF. In this study, the effectiveness of the UPQC was tested at various system conditions to verify the performance of the proposed technique. The presented results show that the obtained parameters of UPQC using the proposed technique can provide fast dynamic response.

Keywords: Voltage sag, Harmonic distortion, Membership Function, UPQC, Series and shunt active power filters

1. Introduction

Power quality is an important issue to the Electricity distribution companies, as they are obliged to supply consumers with desirable quality of power supply. In order to maintain the quality of power in the system, the existing level of disturbances such as harmonic, dip, surge, interruptions, flicker and signaling voltages should be determined. It is well known that the sensitive electronic equipment can strongly be impacted due to the disturbances in the voltage (harmonics and sag). Such disturbances may lead to overall tripping in the industrial plants [1]. In the modern power plants, power electronic devices are widely used. Generally, these technologies produce distortion in voltages and currents [2]. Therefore, mitigating equipment is often installed by industrial customers to protect their own plants and avoid high economic damage due to the loss of daily production. Since the power quality problems can also affect the distribution utilities and industrial customers, new trends have been initiated to install dual mitigating techniques in both sides. With such environment, sensitive equipment can be protected from voltage disturbances and thus reducing the injected distortion by this equipment to the network [3].

The decrease for a short duration in the Root Mean Square (RMS) of a supplied voltage is referred as voltage sag. This duration is in the range of 5 cycles to a minute [4]. Depending on the fault type and distribution system topologies, the voltage sag could have unbalanced behavior [5]. This occurs when voltage phasors differ in amplitude and the phase relationship becomes not equal to 120° [6]. Voltage sag is normally occurs due to a sudden change in the line current

flowing through the source impedance caused by faults, transitional events (similar starting time of motors) or increase in load demand [4].

The change in the waveform from the ideal sinusoidal waveform of a supply voltage is known as harmonic distortion. Total Harmonic Distortion (THD) is a term used to measure the harmonic distortion level. Usually, THD for voltage or current is defined as the total RMS value of individual harmonics divided by the RMS value of the fundamental, and then multiplied by 100% [7].

Active power filters (APFs) are the most promising solution for power quality issues in the distribution system. They are classified based on the implemented control techniques, the strategy of connecting the feedback signals and the design of power inverter. There are four types of these filters known as UPQC, shunt APF, series APF and hybrid APF. Given the multitude of problems concerning power quality improvement, UPQC has been proposed for voltage sag compensation and harmonic mitigation [2, 7, 8]. It is one of the most flexible techniques that can offer the advantages of both shunt APF and series APF, which are combined in one power quality enhancement device [2, 9]. The concept of active filtering in the UPQC is to maintain the load current distortion from a time domain instead of a frequency domain approach [10]. Here, the parameters and operating conditions may strongly affect the performance of UPQC.

While the performance of UPQC can be impacted by the components of converting system (soft switches, resistors, inductors, capacitors and DC link voltage), the process whereby the reference current is obtained and the control strategy (hysteresis, triangular carrier, periodical sampling) utilized in generating the Pulse Width Modulation (PWM) [5, 11, 12] play significant role in improving the power quality of the whole system. Intelligent control and optimization methods for the UPQC have been proposed in many articles, particularly in [4, 11, 13–17]. The applications of fuzzy logic to control the shunt and series active power filters are presented in [11, 14, 16]. Particle swarm optimization has been proposed in [4, 13] to optimize the feedback signals of UPQC. Genetic algorithm was applied to optimize the parameters of the UPQC as discussed in [17]. Other methods proposed for power quality improvement using conventional techniques are outlined in [2, 8, 10, 18, 19].

In the aforementioned studies, the methods of selecting the optimal parameters for shunt and series APFs have not received much attention. Though, the parameters of the UPQC have been optimized in [17], however, a comprehensive study is not provided and the model is simply focusing on the application of genetic algorithm. Basically, the parameters of the controlled signals are derived by the control circuit of UPQC. As the integral gain of controller corrects the steady state error of the voltage control, the increase in proportional gain can cause instability in the system [9, 18, 19]. Hence, optimal regulation of proportional controllers with accurate selections of the resistor, inductor and capacitor values is crucial for the DC voltage control.

This work is an extension of that presented in Ref. [20], where the impacts of resistor, inductor and capacitor values on the performance of UPQC have been analyzed. This paper presents a technique to extract the optimal parameters of UPQC by calculating their Membership Functions (MFs) based on the Weight Factors (WFs). Initially, the values of parameters in the system are used to design the shape of MFs. Then, the MPs are calculated for each two variables, and combined together to produce the calculated membership of the selected criteria used to extract the parameters in each set. In the selected criteria, the optimal parameters are those showing a high value of the calculated MF. A comprehensive analysis was performed to validate the proposed method using the MATLAB environment. Section 2 formulates the parameters of series and shunt filters and presents the modeling and control of UPQC. The concept of parameters extraction using MFs with its application is explained in Section 3. Results and conclusion are given in Section 4 and 5 respectively.

2. Structure And Principal Operation

The UPQC is a combination of shunt and series active power filters installed at the secondary side of power distribution network. In this structure, the shunt active power filter (APF) is suitable to tackle the current related problems, whereas, the voltage related problems can be

handled by using series active power filter (APF). The concepts and principal operations of shunt and series APFs are explained in this Section.

The circuit diagram of Shunt APF is depicted in Figure 1. The principal operation of APF is to force the source current to be pure sinusoidal. This can be achieved by generating a current to be injected into the point of coupling, which is equal and opposite in polarity to the harmonic current drawn by the load [1, 9, 21]. To cancel the harmonics generated by the non-linear load and to make the source current sinusoidal, the injected current by the shunt inverter "$i_{Sh}(\omega t)$" is determined by the following equation,

$$i_{Sh}(\omega t) = i_S(\omega t) - i_L(\omega t) \tag{1}$$

where, $i_S(\omega t)$ and $i_L(\omega t)$ are the reference source current and the load current respectively.

Figure 2 shows the diagram of series APF illustrating the basic operation of this filter. The series inverter injects its generated voltage in such a way, so that the voltage at the load side would be at desired voltage magnitude [1, 18]. To maintain the voltage at the load terminal to be equal to the nominal voltage, the applied voltage by series inverter "$v_{Sr}(\omega t)$" is found as,

$$v_{Sr}(\omega t) = v_L(\omega t) - v_S(\omega t) \tag{2}$$

where, $v_L(\omega t)$ and $v_S(\omega t)$ are the desired voltage at the load bus, and the source voltage respectively. As seen from Eq. (2), to compensate voltage dip, a voltage (in-phase) should be applied by the series inverter so that the sum of the reduced source voltage and series voltage maintain the desired load voltage.
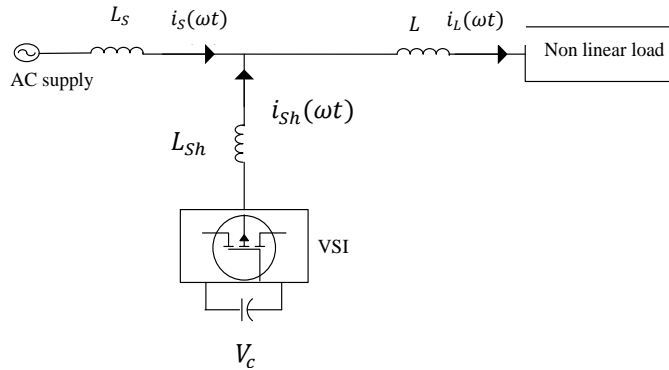

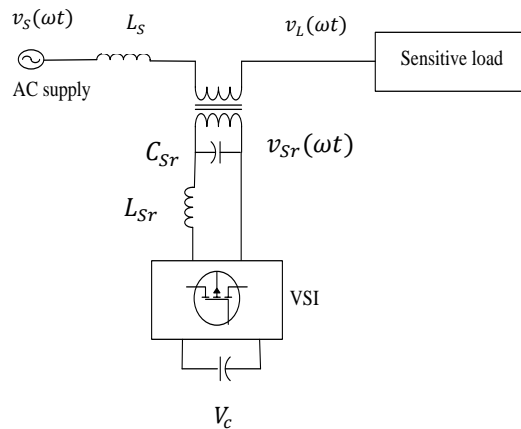
Figure 1. Shunt active power filter

Figure 2. Series active power filter

The generic structure of UPQC considered in this study is an integration of shunt and series active power filters connected through DC link as shown in Figure 3. In this configuration, the series APF is connected to the distribution network through transformer, while the shunt APF connection is made to the load through inductive link. The series and shunt APFs are operated with a classical PI (Proportional Integration) controllers. The control of series inverter is sinusoidal Pulse Width Modulation (PWM) and the shunt inverter is hysteresis current control [2, 7, 22, 23, 24]. The conventional configuration of UPQC with its dynamic control equations characterizing the feedback signals are well documented [1 – 4, 22, 23, 24, 25], and hence, are not presented in this paper. Normally, the UPFC employs two voltage source inverters (VSIs) connected to a common DC link formed by using capacitor. The DC link capacitor provides a power to the VSIs which inject the series voltages and shunt currents into the system. Referring to Figure 3, the series APF is voltage controlled, whereas the shunt APF is current controlled. The objective of the shunt APF is to regulate the DC link voltage between APFs, making the DC link voltage constant even during system disturbances. It is to be noted that in the normal condition, a change in the DC link voltage can be occurred due to power losses caused by the system and inverter operations (losses of soft-switching). Such losses should be compensated to maintain a constant DC voltage during the normal operation [25]. Here, the reference voltage is determined using the following equation,

$$V_{Sh}^{Re} = K_P \Delta I_{Sh}^{Re} + K_I \int \Delta I_{Sh} dt \qquad (3)$$

$$\Delta I_{Sh} = I_{Sh}^{Re} - I_{Sh} \qquad (4)$$

where, I_{Sh}^{Re} is the reference current of the Shunt APF; K_P and K_I are the proportional gain and integral gain of the PI controller respectively. The ΔI_{Sh} is calculated using the PI controller, and the general expression of PI controller with complex Laplace variable "s" is,

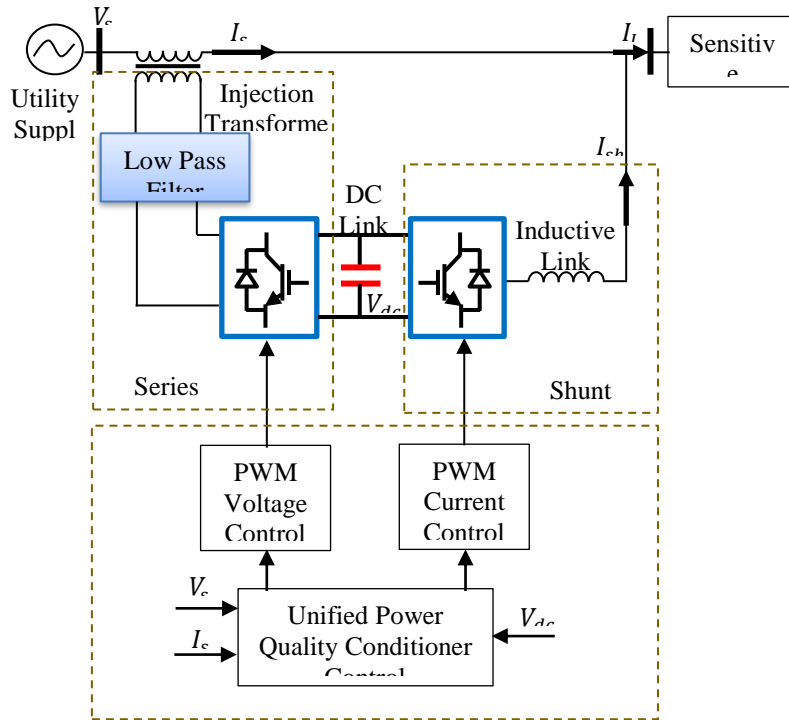$$G(s) = K_p + \frac{K_i}{s} \qquad (5)$$

Figure 3. Conventional UPQC structure

As seen from Figures 3 and 4, the control of UPQC is realized in three stages, in the first stage, the information of the system (voltage and current) is gathered from the measuring units. Using the sensed values of the voltage and current, the compensating commands are derived according to the control methods and configuration of the system. Commonly, the input variables to the controller are error defined as the difference between the desired and real signals. The derived error signal is then processed in a controller. In the last stage, the gating signals for the soft-switches of VSIs are generated. In the shunt APF, a closed loop is employed known as hysteresis control to generate the gate signals of the shunt VSI, while for the series APF an open lope is utilized known as SPWM to generated the gate signals of the series VSI. Referring to Figure 4, the control circuit of shunt APF calculates the compensating current for current harmonic and reactive power compensation. The control circuit of series APF compares the actual voltage and reference voltage to generate the difference to be injected into the system.
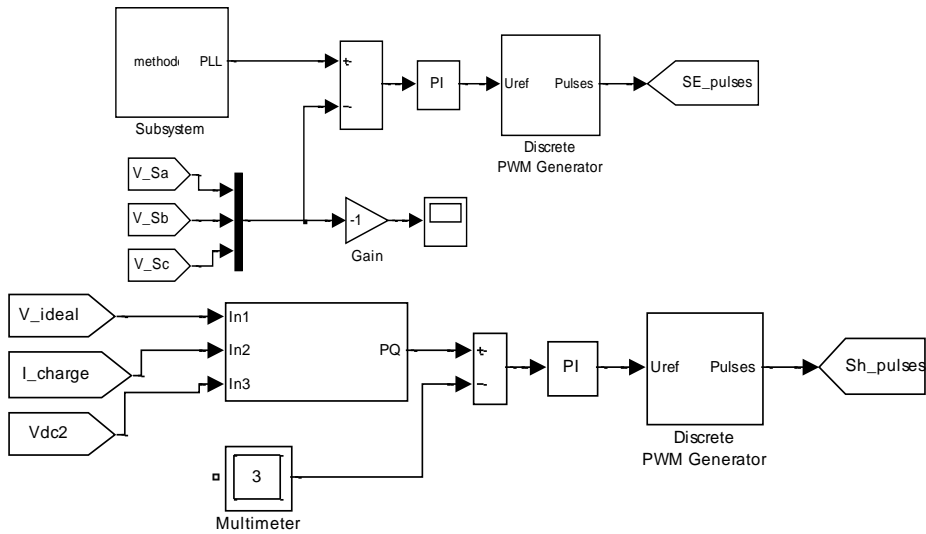

Figure 4. Conventional control of UPQC

3. Parameters Extraction Using MF

As it was concluded in the previously published work [20], the classical technique requires great efforts to acquire the actual parameters of the UPQC. Therefore, such technique may not be effective to find the optimal parameters of the system. To overcome this issue, the principle of membership calculation incorporated with the utilization of WF is used to help in extracting the best values of the main parameters, considering the mutual relationship between these parameters. More details about the proposed method are described in this Section.

A. The Concept Of Parameters Extraction

The approach to parameters extraction of UPQC is achieved based on mapping these parameters into MFs in order to determine the membership of each given input. The values of the parameters involved in the system are used to design the membership functions. These functions are calculated for each parameter in the power circuit using a trapezoidal MF. In other words, the fundamental concept behind membership function is that, the extracted parameter based on the calculation of the designed function incorporated with the WF should have the higher value of membership. In this work, Trapezoidal function was chosen as it is more adapted for such application, where simple formulas and computational efficiency are required. It should be noted that the design of MFs for other topologies can be different depending on the system topology and the applied control technique.

A trapezoidal MF is specified by four parameters (a,b,c,d) that determine the "x" coordinates of the four corners as seen in Figure 5, and expressed mathematically as,

$$\mu(x) = \max\left(\min\left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}, 0 \right) \right) \tag{6}$$
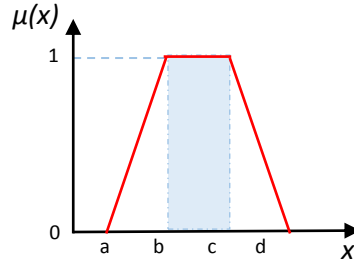

Figure 5. Selected trapezoidal MF for parameters extraction

The shape of the MF is normally representing the fuzziness of the variables describing the Fuzzy systems [26]. While the approach for parameters extraction as proposed is based on the shape of MF, table of fuzzy sets and defuzzification (including Fuzzy inference system) are not applied in this work. The technique of selecting the best values of the parameters is based on mapping the input data into MFs. The configuration of UPQC with the controlled PWM converters as shown in Figures 3 and 4 was simulated by considering different scenarios to generate a range of values for each parameter of the system. These values are used to design the MFs. The approach for using the proposed technique is summarized by the following steps:

1. The system is analyzed by considering different scenarios to determine a range of values used to design the MF for each parameter.
2. The values of MFs for the parameters involved in the power circuit are calculated using Eqs. (7) – (15) as presented in the next subsection.
3. Finally, from the calculated sets with each WF, the memberships that show maximum values are extracted as the optimal parameters of UPQC.

B. Application Of The Concept: A Case Study
The parameters of the system are selected depending on the scope of study. In this work, the considered parameters to design the MFs are: THD of load voltage, THD of source current, voltage mitigation (VoltM), resistor and inductor. Figures 6 (a, b) and 7 (a, b, c) show the trapezoidal MFs which have been designed from the simulation of the system given in Figures 3 and 4. Note that the range of values are selected based on the capacity of the power filters, the desired input source and the output voltage. Mapping these values through the designed membership functions as seen in the Figures 6 and 7, is used to define how each point in the input space represented by the values of system components is mapped to a degree of membership between 0 and 1 [27]. In the next step, the MFs are calculated, in which the WFs are employed as demonstrated for each set in the following examples. Here, extracting the best values of the sensitive parameters utilized in the UPQC, can be achieved using the selected criteria of the highest membership

Example for Set 1:
The optimal parameter values are found through the calculation of MF for each parameter using the WF. First, for resistor with inductor, then THD of the load voltage (THDVL) with THD of the source current (THDIS), these relationships can be written as,

$$\mu_1 = \lambda(i)\min(\mu_r,\mu_l)+\frac{1-\lambda(i)}{2}(\mu_r+\mu_l) \tag{7}$$

$$\mu_2 = \lambda(i)\min(\mu_{THDVl},\mu_{THDIs})+\frac{1-\lambda(i)}{2}(\mu_{THDVl}+\mu_{THDIs}) \tag{8}$$

$$\mu_{cr1} = \lambda(i)\min(\mu_1,\mu_2)+\frac{1-\lambda(i)}{2}(\mu_1+\mu_2) \tag{9}$$

where, $\lambda(i)$: Weight Factor; (i =0-1) is the length of the WF; μ_r: MF of the resistor; μ_l: MF of the inductor; μ_{cr1}: MF of the selected criteria for the extracted parameters in the first set; μ_{THDVl}: MF of THD for the load voltage; μ_{THDIs}: MF of THD for source current.

Example for Set 2:
In this considered set, the calculation of MF is made first for resistor with THD of the source current (THDIS), then, the inductor with the THD of the load voltage (THDVL). It can be written for each MF as,

$$\mu_3 = \lambda(i)\min(\mu_r,\mu_{THDIs})+\frac{1-\lambda(i)}{2}(\mu_r+\mu_{THDIs}) \tag{10}$$

$$\mu_4 = \lambda(i)\min(\mu_{THDVl},\mu_l)+\frac{1-\lambda(i)}{2}(\mu_{THDVl}+\mu_l) \tag{11}$$

$$\mu_{cr2} = \lambda(i)\min(\mu_3,\mu_4)+\frac{1-\lambda(i)}{2}(\mu_3+\mu_4) \tag{12}$$

where, μ_{cr2} is the MF of the selected criteria for the extracted parameters in the second set.

Example for Set 3:
The MF is determined in this considered set for resistor with THD of the load voltage (THDVL), and then for inductor with THD of the source current (THDIS). The calculated MFs can therefore be expressed by,

$$\mu_5 = \lambda(i)\min(\mu_r,\mu_{THDVl})+\frac{1-\lambda(i)}{2}(\mu_l+\mu_{THDVl}) \tag{13}$$

$$\mu_6 = \lambda(i)\min(\mu_{THDIs},\mu_l)+\frac{1-\lambda(i)}{2}(\mu_{THDIs}+\mu_l) \tag{14}$$

$$\mu_{cr3} = \lambda(i)\min(\mu_5,\mu_6)+\frac{1-\lambda(i)}{2}(\mu_5+\mu_6) \tag{15}$$

where, μ_{cr3} is the MF of selected criteria for the extracted parameters in the third set.
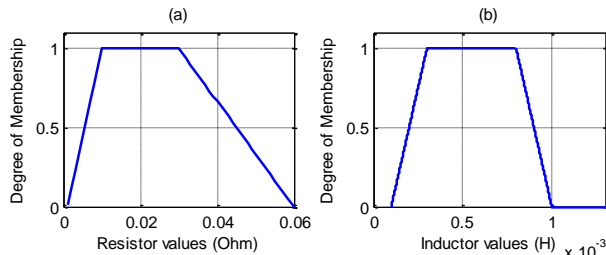

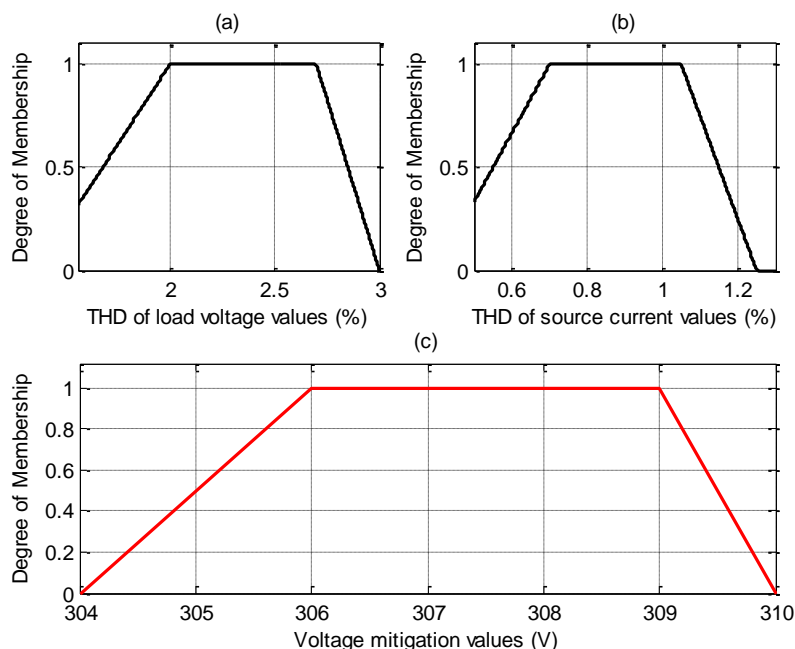Figure 6. Trapezoidal MFs, a) for resistor values, b) for inductor values

Figure 7. Trapezoidal MFs, a) for THD of load voltage, b) for THD of the source current, c) voltage mitigation

4. Results and Verification

The proposed approach as present in this paper has been implemented and verified using the simulation module shown in Figure 8. The standard values of the parameters used in the simulation are given in Table 1. The power circuit part in Figure 8 is modeled as a 3-phase system with a nonlinear load (diode bridge with RL). The reference signals for PWM switching frequencies of UPQC are obtained from the modeled proportional control using MATLAB/Simulink. The simulation steps started with the generation of the data for designing the shape of the MFs as explained in details in Section 3. The simulation time was set for 1 sec, and during this time, voltage sag and harmonic distortion were applied into the system. The assumed starting time for the operation of series APF is 0.2 sec, while the shunt APF starts at 0.4 sec to operate. Several simulations were carried out in which the values of capacitor for the shunt APF and the values of the resistor and inductor for series APF were varied. In order to avoid the initial transient state in the simulation, the data is collected from 0.08 sec. After the next step which is explained in the next paragraph, the optimal parameters values are found, these values are tested to ensure that UPQC can maintain a desired voltage level and free from distortion at the load bus.

Initially, the MFs for each set as presented in section 3 (subsection 3.2) have been calculated. Ten subsets were considered in each set, where the value of the WF was changed (0 to 1). In other words, for each subset of the same set, deferent WFs were utilized. The extracted parameters in each subset related to each WF, are those values representing higher MFs in the subsets. These chosen values are used to adjust the components of UPQC. Tables 2–4 demonstrate only the selected values based on the higher membership found from the calculation of MFs, in which the WFs were employed.
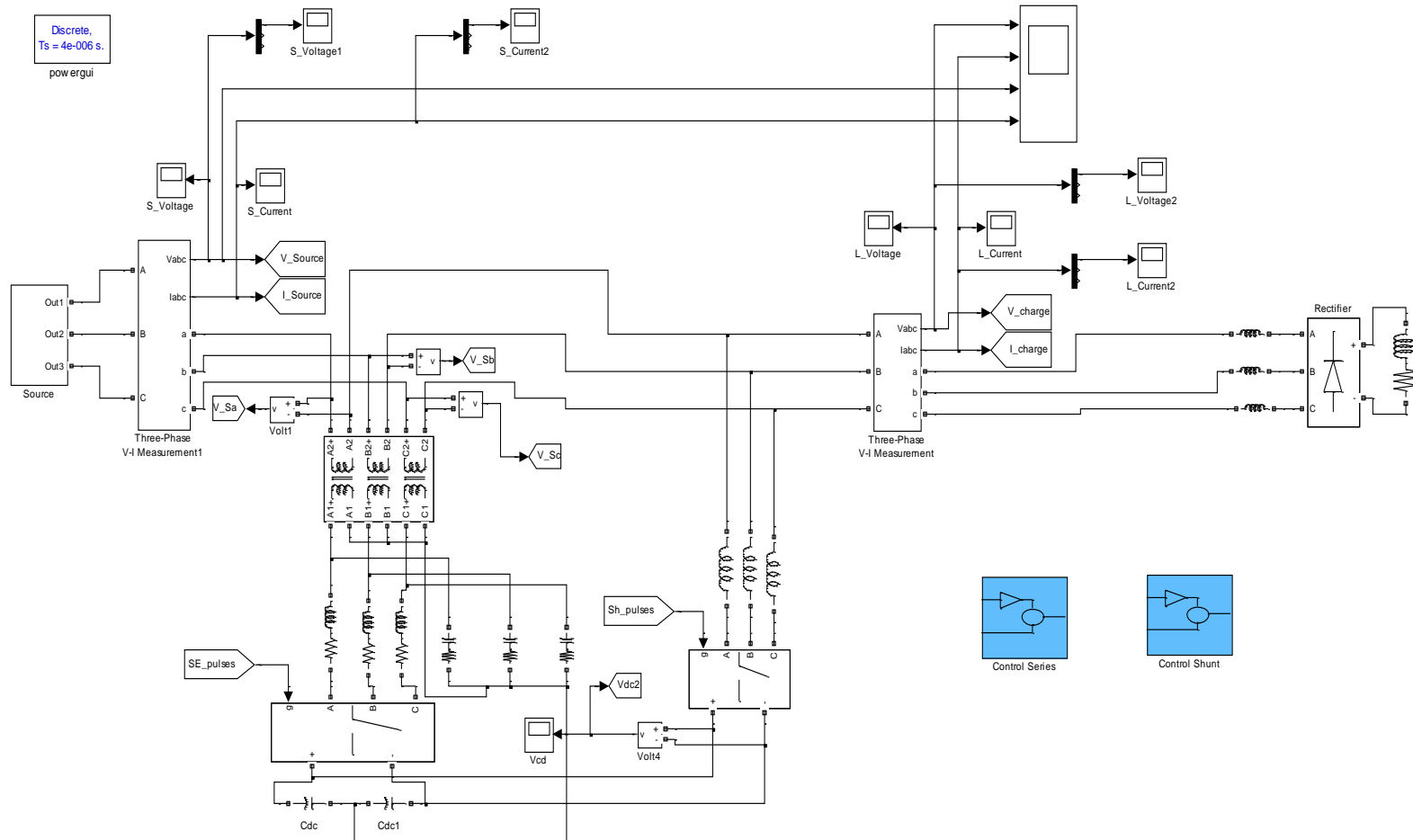
Figure 8. Detailed Simulink module of the UPQC using MATLAB environment

Table 1. The values of the parameter used in the simulation

The component of UPQC	Used values
Source voltage (line to line)	312 V
Fundamental frequency	50 Hz
Transformer ratio	1
Network inductance (L)	0.1 mH
DC link capacitors (C1, C2)	8.8 mF; 8.8 mF
DC reference voltage	850 V
Switching frequency	12 KHz
PI controller	Kp=300; Ki=35
Series APF (R C)	0.5 Ω; 220μF
Shunt APF inductive link (L)	1 mH
Load side (diode bridge rectifier with R L load)	3.4 Ω; 60 mH

Table 2. Results of the extracted parameters for set 1

MF	Resistor (Ω)	Inductor (H)	THDVL (%)	THDIS (%)	VoltM (V)
			$\lambda=0.1$		
0.0040	3×10-3	0.1×10-3	3.55	1.13	305.5
			$\lambda=0.25$		
0.0029	5×10-3	0.2×10-3	2.83	1.19	307.58
			$\lambda=0.50$		
0.0019	5×10-3	0.2×10-3	2.83	1.19	307.58
			$\lambda=0.75$		
0.0010	5×10-3	0.2×10-3	2.83	1.19	307.58

Table 3. Results of the extracted parameters for set 2

MF	Resistor (Ω)	Inductor (H)	THDVL (%)	THDIS (%)	VoltM (V)
			$\lambda=0.1$		
0.0040	3×10-3	0.1×10-3	3.55	1.13	305.5
			$\lambda=0.25$		
0.0023	5×10-3	0.2×10-3	2.83	1.19	307.58
			$\lambda=0.50$		
0.0014	10×10-3	0.4×10-3	2.04	1.07	308.5
			$\lambda=0.75$		
0.0010	10×10-3	0.4×10-3	2.04	1.07	308.5

Table 4. Results of the extracted parameters for set 3

MF	Resistor (Ω)	Inductor (H)	THDVL (%)	THDIS (%)	VoltM (V)
			$\lambda=0.1$		
0.0040	3×10-3	0.1×10-3	3.55	1.13	305.5
			$\lambda=0.25$		
0.0023	5×10-3	0.2×10-3	2.83	1.19	307.58
			$\lambda=0.50$		
0.0014	30×10-3	0.6×10-3	1.77	1.07	309.1
			$\lambda=0.75$		
0.0010	30×10-3	0.6×10-3	1.77	1.07	309.1

Referring to Tables 2–4, it is seen that the selected values of the parameters involved in the UPQC are directly related to the changes in the system components. For instance, in a real system, the values of resistor and inductor are determined based on the design of the UPQC. Therefore, when evaluating the effectiveness of the UPQC by increasing the values of resistor or inductor or even capacitor, it is crucial to take into account the cost and weight including the physical size of the converting system. It is worth to mention here that adding extra components to the UPQC for achieving effective sag compensation and fast harmonic mitigation, these achievements should compensate the extra cost, size and volume due to adding the extra components. As a result, the designer will need to select from the listed parameters in the above Tables those values that have less THD and acceptable voltage mitigation, avoiding the high cost and weight due to unnecessary increase in the size of resistor or inductor.

In order to verify the performance of UPQC with the optimal parameters found using the proposed technique, simulations were carried out on the test system as shown in Figure 8 to validate the effectiveness of the extracted parameters. The selected results for system evaluation and verification are shown in Figures 9 (a, b) and 10 (a, b) respectively. To minimize paper length, the results of all extracted parameters listed in Tables 1–3 are not included here as there are only slight changes compared with the selected verified results. The sag at the source voltage is assumed to be occurred at time = (0.2–0.3) sec, and at time = (0.4–0.3) sec, this voltage assumed to be distorted. The voltage and current profiles are shown in Figure 9 (a, b), the disturbances are also indicated in this figure. The UPQC should maintain the voltage and current. As seen from Figure 10 (a, b). The series APF injects the required compensating voltage through the transformer, making the load voltage at desired level. Similarly, the Shunt APF injects the required compensation, making the load current free from distortion. These results show the performance of the UPQC with the optimal parameters obtained using the proposed technique.
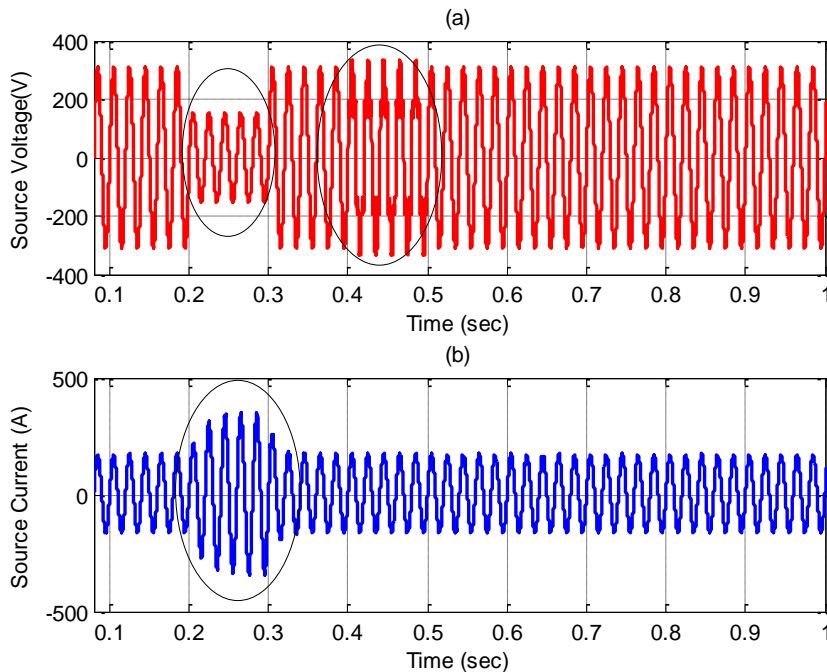

Figure 9. System evaluation during disturbances, (a) Source voltage (b) Source current
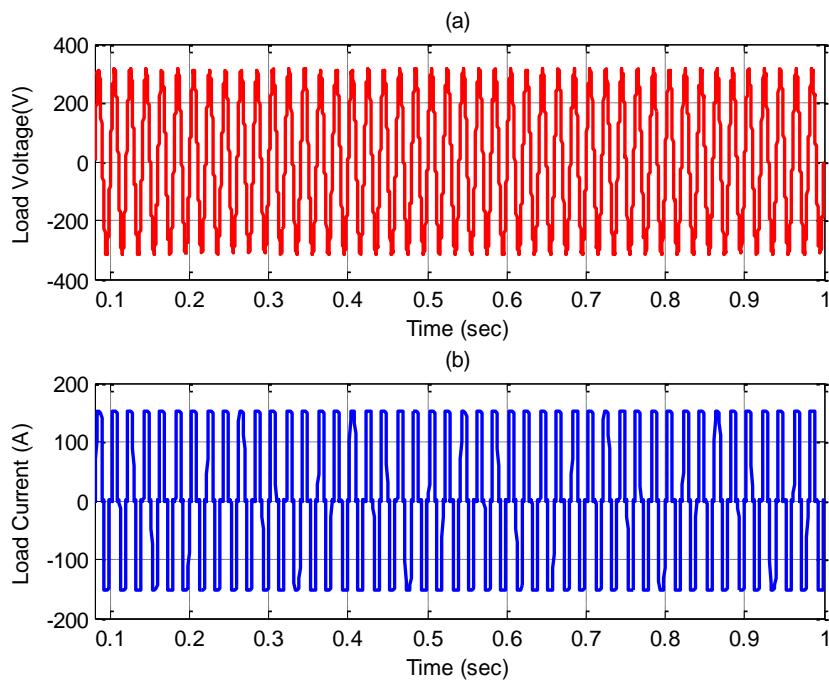
Figure 10. UPQC operation with the extracted parameters, (a) Load voltage (b) Load current

Furthermore, the system stability has been investigated when using different optimized and non-optimized values of resistors, inductors for the shunt and series APFs. The results of the control response are depicted in Figures 11. It can be observed from this figure the impact of the resistor and inductor values on the DC link voltage. It can also be seen the change in the system response with various values. It is to be noted that the selected optimal values of the parameters should not impact the system during the normal operation, as the stability of the DC voltage depends on the optimal parameters values of UPQC.
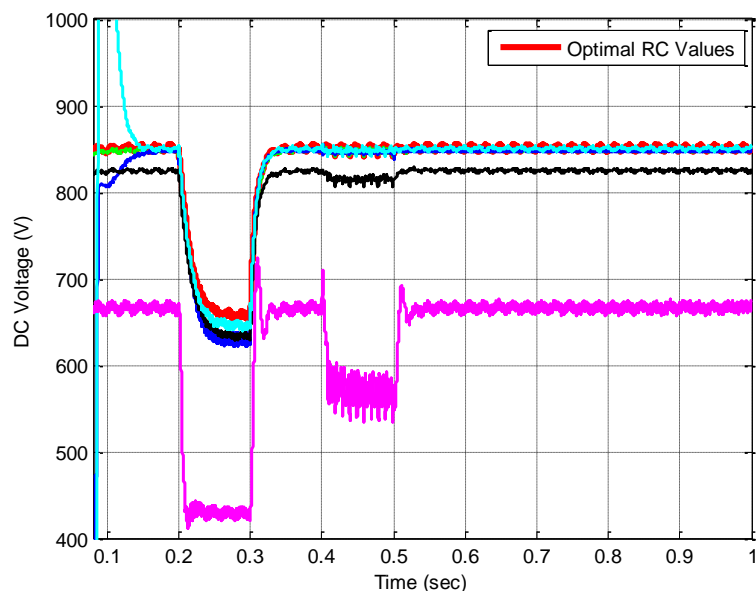

Figure 11. Control response of the DC voltage during voltage sag with different RL values

5. Conclusion

A simplified mathematical approach to extract the optimal parameters of UPQC has been proposed in this paper. This proposed technique would be very useful to determine the actual values of the parameters with less effort. Conceptual analyses of the extracted parameters using the controlled UPQC are also presented in this paper. Furthermore, different operating conditions were considered to evaluate the performance of UPQC with the extracted parameters during voltage sag and harmonic distortion. It is revealed from the results that the proposed approach is an effective in identifying the actual parameters of UPQC implemented on a three-phase distribution system.

6. Acknowledgement

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