Abstract—This paper presents a novel flexible control strategy for Unified Power Quality Conditioner (UPQC), which achieves more flexibility in compensation of power quality disturbances as compared to the existing methods. The proposed control strategy provides priority-based compensation as well as full and standard-based compensation considering the rating of series and shunt parts of a UPQC. The priority-based compensation is done based on the compensation priority among different power quality disturbances. In this control strategy, an on-line estimation of different voltage and current disturbances is required. For this purpose, a Unified Adaptive Power Quality Estimator (UAPQE) has been developed with simple structure. The proposed control strategy provides a new alternative for power quality compensation when the rating limit of the UPQC is reached. The performance evaluation of this control strategy was carried out by different simulation in PSCAD/EMTDC. The simulation results show the effectiveness of the proposed flexible control strategy for a UPQC.

Index Terms—Power quality, unified power quality conditioner, flexible compensation, PSCAD/EMTDC.

I. INTRODUCTION

With increasing application of nonlinear and electronically switched devices in distribution systems and industries, power quality problems such as harmonics, unbalance, and flicker have become serious concerns. In addition, lightning strikes on transmission lines, switching of capacitor banks, and various network faults can also cause power quality problems such as transients, voltage sag/swell and interruption. On the other hand, the use of sensitive loads involving digital electronics and complex process controllers requires a clean sinusoidal supply voltage for proper load operation [1].

Regulatory organizations have increased their efforts towards establishing standards which limit the power quality disturbances in power systems [2], [3]. In order to meet the power quality standard limits, it may be necessary to include some sort of compensation. Modern solutions can be found in forms of active rectification or active filtering [4]. A shunt active power filter is suitable for suppression of negative influence of non-linear loads on the supply network, but if there are supply voltage imperfections, series active power filter may be needed to provide full compensation [5].

In recent years, solutions based on Flexible AC Transmission Systems (FACTS) have appeared. The application of FACTS concepts in distribution systems has resulted in a new generation of compensating devices [6]-[8]. A Unified Power Quality Conditioner (UPQC) [6] is the extension of the Unified Power Flow Controller (UPFC) [9] concept at the distribution level, and multi-converter UPQC (MC-UPQC) [7] and also OPEN UPQC [8] are its new configurations for multi-bus/multi-feeder systems. A UPQC consists of combined series and shunt converters for simultaneous compensation of voltage and current imperfections in a supply feeder [6]. The general power circuit configuration of a UPQC is shown in Fig. 1.

The control strategy of the UPQC is the key element for its successful performance in mitigating the voltage and current disturbances. The control system processes both the instantaneous values of load current and bus voltage signals in order to determine the compensation priority among different disturbances.

The UPQC may encounter a power limitation for the following reasons:

1) In the design step, the rating of the UPQC is not designed for full compensation of all power quality disturbances, due to the fact that:
   - As the switch rating is increased, the switching frequency and consequently the compensation capability will be decreased.
   - With the increase of switch rating, the application of the UPQC may not be economically feasible.

2) The level of the power quality disturbances is
increased because of the changes in the distribution system configuration and also because of increasing application of power electronics devices.

In this paper, a new flexible control strategy for a UPQC is presented which is capable of compensating power quality disturbances in a flexible way considering the rating of the UPQC. In this control strategy, instantaneous values of the load current and bus voltage are continuously and adaptively processed by two Unified Adaptive Power Quality Estimators (UAPQE). The UAPQE works based on adaptive linear neurons (ADALINE) which can provide fast and accurate estimation of different power quality disturbances [13]. By using the estimated power quality disturbances, according to the rating of the series and shunt parts of the UPQC, the appropriate compensation scheme can be selected on-line. Finally, based on the selected scheme, the voltage and current reference signals are calculated and passed to the inverter controllers to produce and inject the required compensating signals.

The performance of the proposed control strategy is found to be quite satisfactory in mitigation of power quality disturbances based on the compensation priority among disturbances while keeping the rating of the UPQC. The theoretical expectations are verified by software simulation using PSCAD/EMTDC software package.

II. UPQC CONFIGURATION WITH THE PROPOSED FLEXIBLE CONTROL STRATEGY

The basic blocks of the proposed flexible control strategy for the UPQC connected to an electric distribution system are shown in Fig. 2. The proposed control strategy requires an on-line estimation of individual power quality disturbances of the bus voltage and load current such as harmonic components. Therefore, the time domain approaches such as instantaneous power theory [14] is not appropriate and the frequency domain approaches must be used. For this purpose, two UAPQEIs are used and the values of the voltage and current disturbances are estimated.

In this unit, first, the possibility of full compensation is investigated. The required power of the series and shunt parts of the UPQC for full compensation of all disturbances are calculated and compared with their rated values. If there is no power limitation in using the series or shunt parts, the full compensation is performed. In this case, the reference signals are produced in a manner that all disturbances are fully compensated.

If there is a power limit for a full compensation, the possibility of the standard-based compensation is investigated. By calculating the series and shunt parts power for this scheme and comparing with the UPQC rating, if there is no power limitation, the standard-based compensation is done. In this case, all power quality disturbances are compensated up to the standard limits determined by the regulatory organizations [2], [3].

Finally, if there is a power limit for the standard-based compensation, the priority-based compensation is performed. In this case, the reference signals are produced based on the compensation priority among different power quality disturbances considering the rating of the UPQC.

The voltage and current reference signals \((v_{ref}, i_{ref})\), which are produced by the proposed flexible control strategy, are applied to the gating signal generation unit. This unit uses the SPWM voltage control and hysteresis current control methods for the series and shunt converters in the UPQC configuration respectively.

III. UNIFIED ADAPTIVE POWER QUALITY ESTIMATOR (UAPQE)

In the proposed flexible control strategy, an on-line estimation of different power quality disturbances is required. For this purpose, a UAPQE, which has a simple structure, was developed by the authors [15]. The UAPQE consists of three Adalines and one Multi-Output Adaline (Mo-Adaline).

Artificial Neural Networks (ANN) are extensively used in power systems for classification and control purposes. Adaline is a multi-input/single-output neuron which can be trained on-line based on on-line inputs and the target response. The internal structure of the Adaline is shown in Fig. 3.

Its output is a linear combination of its inputs with a weighting vector as in (3). \(W\) is the weighing vector and \(X\) is the input vector

\[
X = [x_1 \ x_2 \ x_3 \ \ldots \ x_{n-1} \ x_n]
\]

\[
W = [w_1 \ w_2 \ w_3 \ \ldots \ w_{n-1} \ w_n]
\]

\[
y = W \times X^T
\]

In the training process, the weights are adjusted such that...
Fig. 4. Internal structure of the Unified Adaptive Power Quality Estimator (UAPQE).

the error between the output of the Adaline ($y$) and the desired output ($y_d$), which its parameter must be estimated, is minimized. The Widrow-Hoff rule, which works based on the least square error method, is used for training. The Widrow-Hoff rule is given by [16]

$$ W(k+1) = W(k) + \alpha \frac{e(k)X(k)}{X^T(k)X(k)} $$

(4)

where

$W(k)$: Weight vector in $k$'th time step

$W(k+1)$: Weight vector in $(k+1)$'th time step

$X(k)$: Input vector in $k$'th time step

$y(k)$: Adaline's output in $k$'th time step

$y_d(k)$: Desired output in $k$'th time step

$e(k) = y_d(k) - y(k)$: Prediction error in $k$'th time step

$\alpha$: Learning rate

After the training process, the estimated parameters are calculated using the weighting vector elements. Adaline has been used for individual power quality disturbance estimation such as harmonics [16] and flicker [17]. Also, the Mo-Adaline is an adapted version of Adaline for online estimation of symmetrical components of an unbalance signal [18].

The internal structure of the developed UAPQE is shown in Fig. 4. The UAPQE can be used for on-line estimation of different power quality disturbances in a three phase system. As shown in this figure, an Adaline is used for each phase signal which estimates the fundamental component, harmonic components, and flicker in each phase. Then, the three-phase fundamental components are processed by a Mo-Adaline and the symmetrical components are reachable compensation state is achieved. Finally, according to this compensation state, the reference voltage and current signals are calculated for the series and shunt converters.

The flowchart of the proposed flexible control strategy is shown in Fig. 5. As shown in this flowchart, the following three compensation states are defined:

1. Full Compensation
2. Standard-based Compensation

At each time step, the required output power for the series and shunt parts of the UPQC for each compensation states in terms of different voltage and current disturbances are needed. In this paper, it is assumed that the source bus voltage contains harmonics, can be unbalanced and can be subjected to sags/swells, zero sequence components and flicker are not considered. Also, the load current contains harmonics, can be unbalanced and has a reactive component. Based on these assumptions, the source bus voltage and load current can be written as (5) and (6), respectively. For the sake of simplicity, all equations are shown for phase 'a', and the phase angle of the fundamental positive sequence voltage in phase ‘a’, which is set to zero, is assumed as the reference angle

$$ v_{sa}(t) = \sqrt{2}V_{sa} \sin(\omega t + \phi_{sa}) $$

(5)

$$ i_{sa}(t) = \sqrt{2}I_{sa} \sin(\omega t + \phi_{ia}) $$

(6)

where

$V_{sa}, \phi_{sa}$: RMS value and phase angle of the positive sequence component of the source bus voltage

$V_{ia}, \phi_{ia}$: RMS value and phase angle of the negative sequence component of the source bus voltage

$I_{sa}, \phi_{sa}$: RMS value and phase angle of the positive sequence component of the load current

$I_{ia}, \phi_{ia}$: RMS value and phase angle of the negative sequence component of the load current

$\omega = 2\pi f$: Fundamental frequency

The positive sequence of the load current can be decomposed into active and reactive components as in (7)

$$ i_{sa}(t) = \sqrt{2}I_a \cos \phi_{ia} \sin \omega t + \sqrt{2}I_r \sin \phi_{ia} \cos \omega t $$

(7)

$$ + \sqrt{2}I_{sa} \sin(\omega t + \phi_{ia}) $$

As shown in Fig. 2, the relation between the load voltage, the source bus voltage and the injected series voltage is given by (8), and the relation between the source current, load current and the injected shunt current is given by (9)

$$ v_i = v_s - v_{mj} $$

(8)

$$ i_s = i_j - i_{mj} $$

(9)
Fig. 5. Flowchart of the proposed flexible control strategy.

Where

\[ v_l, i_l \]: Load voltage and current
\[ v_s, i_s \]: Source bus voltage and source current
\[ v_{inj}, i_{inj} \]: Injected series voltage and shunt current by the UPQC

Now, each compensation state is defined and the power relations for the series and shunt parts of the UPQC are derived. It must be emphasized that the power calculation must be done for each phase individually, because the power system is assumed to be unbalanced. The single-
phase power is calculated by \( S = V_{ref} I_{ref} \) where \( V_{ref} \) and \( I_{ref} \) are per-phase rms values of the voltage and current. The power of the series and shunt parts of the UPQC can be calculated by using (10) and (11), respectively

\[
S_{Series-i} = V_{inj-i} I_{s-i} \quad ; \quad i = a, b, c
\]

\[
S_{Shunt-i} = V_{inj-i} I_{s-i} \quad ; \quad i = a, b, c
\]

where

\( V_{inj-i} \): RMS values of the injected series voltage and shunt current by the UPQC in phase ‘i’.

\( V_{inj-i} \): RMS values of the load voltage and source current in phase ‘i’.

### A. Full Compensation

Full compensation is the best compensation state because in this state all disturbances are fully compensated. If the ratings of the series and shunt parts of the UPQC are enough, the voltage and current reference signals are constructed such that all voltage and current disturbances are fully compensated as in (12) and (13), respectively

\[
v_{inj-k}(t) = \sum \sqrt{2} V_{v_{h_{k}}} \sin(h \omega t + \phi_{h_{k}})
\]

\[
i_{inj-k}(t) = \sum \sqrt{2} I_{h_{k}} \sin(h \omega t + \phi_{h_{k}})
\]

The voltage reference signal given in (12) contains three terms. The first term is for harmonic compensation, the second term is for sag/swell compensation and the third term is for negative sequence compensation. Also, as given in (13), the current reference signal contains four terms, which are for harmonic compensation, reactive power compensation, negative sequence compensation and finally DC-link capacitor voltage regulation.

In case of sag/swell compensation, there is a real power exchange between the series converter and the network. This causes DC-link capacitor voltage deviation from its reference value. The real power which is needed for the voltage regulation is provided by the shunt converter. The last term in (13) is added for this purpose. A PI controller is used for voltage regulation of the DC link capacitor. The input of the controller is the difference between the capacitor voltage and its reference value, and the output of the controller is equal to \( dv \) which is used in the last term of (13). By substituting (5), (6) and (12), (13) into (8) and (9), the load voltage and source current can be written as (14) and (15), respectively

\[
v_{inj}(t) = \sqrt{2} V_{ref-ref} \sin \alpha t
\]

\[
i_{inj}(t) = \sqrt{2} I_{s} \cos \phi_{s} + dv \sin \alpha t
\]

Finally, the required power (per-phase) of the series and shunt parts of the UPQC, are calculated by (16) and (17), respectively.

In the flowchart of the proposed control strategy, in the first step, the required power for the series and shunt parts of the UPQC are calculated based on (14) and (15) for each phase and compared with their ratings. If there is no power limitation for the series and shunt parts, \( V_{inj} \) and \( I_{inj} \) are calculated based on (12) and (13) and sent to the gating signal generation unit.

### B. Standard-Base Compensation

In this case, the series or shunt parts of the UPQC have limited power such that full compensation cannot be achieved. Therefore, the standard-based compensation is considered. In this compensation state, all power quality disturbances are compensated up to the standard limits determined by the regulatory organizations. For example, if the calculated Harmonic Factor \( HF = V_{s}/V'_{s} \) for a harmonic component is greater than its standard limit, then a compensation term is added to the voltage reference signal such that the resulted voltage harmonic component is limited to its standard limit, otherwise no compensation is needed for this component. The related if-then rule is given in (18)

\[
\text{if } V_{h_k} > HF_{k, limit} V'_{1k} \Rightarrow V_{inj-k} = V_{h_k} - HF_{k, limit} V'_{1k}
\]

\[
\text{else } k = a, b, c
\]

where

\( V_{h_k} \): RMS value of the \( h \)th order harmonic component in phase \( k \)

\( V_{s} \): RMS value of fundamental in phase \( k \)

\( V_{inj-k} \): RMS value of injected \( h \)th order harmonic component in phase \( k \)

\( HF_{k, limit} \): Standard limit of the HF for the \( h \)th order voltage harmonic component

In this condition, the voltage reference signal is given by (19). In this equation, the first term is added for harmonic compensation, the second term is added for sag/swell compensation and the third term is added for negative sequence compensation. In the second term the \( sag_{limit} \) and \( swell_{limit} \) are the limit values of the sag and swell. However, there is no standard values for these parameters and these limit values are dependent on the sensitivity of each load. Also \( U_{v} \) in the third term, is the standard limit of voltage unbalance factor.
the third term is added for current unbalance correction with $U_s$ being the limit value of the current unbalance factor. Finally, the last term is added for DC-link capacitor voltage regulation which $dv$, as in the case of full compensation, is the output of the PI controller. The load voltage and line current in this case are given in (23) and (24), respectively.

Finally, the required power of the series and shunt parts of the UPQC, are calculated by (10) and (11), respectively.

### C. Priority-Based Compensation

If the ratings of the series or shunt parts of the UPQC are limited for applying the standard-base compensation, the priority-based compensation is performed. In this case, power quality disturbances are compensated based on the predefined compensation priority among different power quality disturbances. The compensation priority is determined based on the evaluation of economical impacts of different power quality disturbances. For example, the economical impacts of short duration sag/interruption are about 0% of total economical impacts of low power quality in European countries, and thus, it has the highest compensation priority in the series compensation [19].

If the limited rating is related to the series part of the UPQC, then the series compensation must be restricted. If it is related to the shunt part of the UPQC, then the shunt compensation must be restricted. Finally, if it is related to both parts then series and shunt compensation must both be restricted.

For restriction of the series or shunt compensation based on the compensation priority among disturbances, in each step of the algorithm the compensation of the lowest priority disturbance is restricted in a predefined step. For example the predefined step for the unbalance factor is assumed to be 1%. This means that when we want to restrict the voltage unbalance compensation, in each step its corresponding term in the reference signal is decreased so that the unbalance factor to be increased 1%. When the compensation term for the lowest priority disturbance is reduced to zero, which means that there is no compensation term for this disturbance in the reference signal, and still the power rating is not enough, then the compensation of the next low priority disturbance will be restricted.

For this manner, finally, based on this innovative optimization scheme, the best compensation state can be selected.
Fig. 6. Series compensation, (a) distorted source bus voltage, (b) injected series voltage, and (c) load voltage.

TABLE I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source voltage</td>
<td>380 V (L-L) (rms)</td>
</tr>
<tr>
<td>Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Injection transformer ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>2000 μF</td>
</tr>
<tr>
<td>Shunt side filter</td>
<td>$R = 3 \Omega$, $C = 60 \mu F$, $L = 2 \text{mH}$</td>
</tr>
<tr>
<td>Series side filter</td>
<td>$R = 10 \Omega$, $C = 60 \mu F$, $L = 2 \text{mH}$</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>Nonlinear/sensitive load</td>
<td>3-phase diode rectifier with RL load ($R = 10 \Omega$, $L = 20 \text{mH}$)</td>
</tr>
<tr>
<td>Rating of series part of UPQC</td>
<td>20 kVA</td>
</tr>
<tr>
<td>Rating of shunt part of UPQC</td>
<td>20 kVA</td>
</tr>
</tbody>
</table>

V. SIMULATION RESULTS

The proposed flexible control strategy for the UPQC has been tested through extensive case study simulations using PSCAD/EMTDC. A 3-phase 3-wire distribution system, which is connected to a UPQC, with the proposed control strategy, is considered as in Fig. 2. System parameters are provided in Table I. In this section, simulation results are presented, and the performance of the proposed control strategy is shown.

Let us consider that the source BUS voltage ($v_s$) contains the fifth order harmonic with an HF of %45, and the seventh order harmonic with an HF of %23. An input fundamental voltage sag with variable amplitude is simulated in different time intervals. The simulation results are shown in Figs. 6-13.

The distorted source bus voltage, injected series voltage, and the load voltage are shown in Fig. 6. Also the RMS values of the fundamental load and source voltages are shown in Fig. 7 and HF associated with individual load voltage harmonic components are shown in Fig. 8. The load current, injected shunt current, source current, and DC-link capacitor voltage are shown in Fig. 9, and HF associated with individual source current harmonic components are shown in Fig. 10. Fig. 11 shows the source Power Factor (PF) and finally, for better comparison of different compensation schemes the Total Harmonic Distortions (THD) of the load and source voltages are shown in Fig. 12 and the THDs of the source and load currents are shown in Fig. 13.

As referred in previous section, the compensation priority between power quality disturbances is determined based on the evaluation of economical impacts of different disturbances. In this paper, the predefined compensation priorities between the current disturbances are:

1) Reactive power
2) Harmonic components (as the order of harmonic component is decreased its compensation priority is increased)
3) Unbalance factor

Also, the predefined compensation priorities between
the voltage disturbances are:
1) Sag/Swell
2) Harmonic components
3) Unbalance factor
A. Full Compensation

In the time interval of $0 < t < 0.2$ s, there is no sag/swell but during time interval of $0.2 < t < 0.4$ s, a 20% voltage sag occurs. In these time intervals, there is no power limitation in the series or shunt parts of the UPQC and all power quality disturbances are compensated.

As shown in Fig. 7 the voltage sag is fully compensated and thus the fundamental load voltage is equal to its nominal value. The reactive power of the load is fully compensated and the source unity power factor is realized as shown in Fig. 11. Also it can be seen in Figs. 8 and 10 that all harmonic components of the load voltage and source current are fully compensated. Also, the THDs of the load and source voltages and the THDs of the source and load currents which are shown in Figs. 12 and 13, respectively, confirmed this subject.

B. Standard-Based Compensation

During time interval of $0.4 < t < 0.6$ s, a 35% voltage sag is applied. In this condition, the rating of the series part of the UPQC is not enough for a full compensation, and the standard based compensation is performed.

As shown in Fig. 7 in this time interval although there is 35% sag, the fundamental component of the load voltage $\text{VL}$ is equal to 200 v and the sag is compensated to its standard value (10%). Also as shown in Figs. 8 and 12 the HF of the individual load voltage harmonic components and THD of the load voltage are increased because the harmonic compensation is not fully done. In this time interval power quality disturbances are compensated such that the standard limits are met.

C. Priority-Based Compensation

Finally, to evaluate the system behavior during a heavy sag condition which results in UPQC series part power limitation, a 50% voltage sag is applied during time interval of $0.6 < t < 0.8$ s. In this condition, the rating of the series part is limited such that full compensation and standard based compensation cannot be performed.

As shown in Fig. 7 in this time interval although there is 50% sag, the fundamental component of the load voltage $\text{VL}$ is approximately equal to 200 v and the sag is compensated to its standard value (10%) because the sag compensation has the highest priority in series compensation. Also as shown in Fig. 6, in this time interval, the load voltage is disturbed by harmonic components because the harmonic compensation has lowest priority than voltage sag. The HF of individual load voltage harmonic components and THD of load voltage which are shown in Figs. 8 and 12 also verified these results.

In shunt compensation the reactive power compensation has the highest priority and thus the source PF is approximately equal to unity as shown in Fig. 11. By increasing the harmonic content of the load voltage, the harmonic content of the source current is also increased as shown in Figs. 9 and 13.

VI. CONCLUSION

In this paper, a flexible control strategy for a UPQC is proposed. Compared to the conventional control strategies, the proposed control strategy is capable of flexible compensation of power quality disturbances in case of UPQC power limitation. If there is any power limitation in the series or shunt parts of the UPQC for full or standard-based compensation, the compensation will be performed based on a compensation priority among disturbances. This priority is determined based on the evaluation of economical impacts of different power quality disturbances. Based on the on-line estimation of different power quality disturbances and the rating of the series and shunt parts of the UPQC, one of the three compensation schemes is applied:

1. Full compensation
2. Standard-based compensation
3. Priority-based compensation

The performance of the proposed flexible control strategy is evaluated under various disturbance conditions. It is shown that the proposed control strategy detects and performs the best compensation scheme at different conditions. Although, the proposed control strategy is applied during operation stage of the UPQC, it can also be applied at the design step of the UPQC. Using of this approach at the design step reduces the rating of the UPQC, thus leading to cost savings.

REFERENCES


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