Performance improvement of a system level harmonic using a harmonic power flow controller

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Abstract

Penetration of harmonics from downstream low voltage networks and resonance phenomenon has caused the level of harmonics to increase in transmission networks. Compensation of these harmonics at high voltage levels is neither recommended nor cost effective. This is due to the fact that there is no single large non-linear load which is causing these harmonics, yet filtering at low voltage non-linear load sites cannot completely compensate the harmonics and the remaining harmonic at standard levels still flow into the upstream networks. The idea of controlling harmonics at a medium/high voltage level caused by the remaining harmonics flown from low voltage networks and possibly amplified by resonance conditions with the use of series active power filters has been proposed by the authors in a published work. Since, this application of a series active filter was new, it was preferred to assign a new name for such device, i.e. harmonic power flow controller or simply HPFC. This work looks into the control strategies applicable to a HPFC in more details. The shortcomings of the previous methods are now removed resulting in better performance of a HPFC.

Keywords- Harmonic Voltage Control, Current Harmonic Flow, HPFC, ZAPI, MAPI, IZAPI, IMAPI, Harmonic Power Loss control

1. Introduction

Filtering at low voltage levels and at the non-linear load sites have been the most common solution to mitigate harmonics and prevent them from entering into upstream medium/high voltage networks [1-6]. However, due to several reasons this filtering cannot completely absorb the harmonics [7-8]. One can consider harmonics caused by distributed low-power loads such as residential customers which do not normally use any filtering equipment. It is also worth mentioning that all filtering techniques limit the levels of harmonics to the limits specified by standards such as IEEE-519. On the other hand, in several cases, it is observed the remaining harmonics at low voltage levels penetrate into the medium/high voltage networks and are amplified by resonance conditions.

In many cases, mitigating the remaining harmonics at a medium/high voltage networks is not easily possible due to the fact that the source of harmonics are not located at medium/high voltage, and there is no single large non-linear load at which site a filter can be installed. To tackle the issue, the authors proposed a new method of controlling harmonic currents at medium/high voltage networks by the use of series active power filters (SAPFs)[9-10]. The main idea in this reference [10] is to control the flow of
harmonic currents and redirect them into the paths which the outcome will be a better harmonic profile. In this method, the SAPF injects a harmonic voltage term into a line to create a change in harmonic flow [10]. This action can be compared to what a phase-shifter does at the main frequency. Since, the task performed be the SAPF in this application is different from what has been considered for a SAPF, the authors preferred to consider a new name for SAPF in this task, i.e. harmonic power flow controller or simply HPFC.

Principles of operation and the proof of concept of the HPFC were presented in [10]. Two primary control methods were also introduced in [10] for the operation of a HPFC. This work is a continuation of [10]. The authors in the current paper have tried to improve the control methods of a HPFC and alleviate the shortcomings of the proposed control strategies in. In order to have a complete work, the basics of the device principles of operation are again summarized in this work, and therefore, some of the figures are similar to those of [10].

The control methods proposed in [10] are named as zero active power injection (ZAPI) and minimum apparent power injection (MAPI) control methods. The improved methods in this work are named as improved ZAPI or IZAPI and improved MAPI or IMAPI.

The structure of this work is as follows. In section II, the structure and principles of operation of the HPFC are reviewed. ZAPI and MAPI control methods are briefly discussed and their shortcomings are described. Section III presents the IZAPI and IMAPI control methods. The performance of the proposed new control strategies are tested through simulation on the IEEE 14-bus test bed. Section IV, proposes a new control method based on cost-optimization technique. In section V, a HPFC is designed for real harmonic problem in Iran north-west HV transmission network. Finally, section VI summarizes the conclusions.

2. Structure and Control of HPFC

Figure 1 (a) shows a circuit diagram of an HPFC in a simple network which is composed of a voltage source converter (VSC), an energy storage element, and a series transformer [10]. In this configuration, a voltage harmonic term is created by the VSC and injected through the series transformer into the grid.

Depending on the control strategy, a HPFC may need to exchange active/reactive power with the grid. This property can be compared to that of a dynamic voltage restore (DVR)[11-15]. If an active power exchange occurs, an energy source at the DC link is required as (Figure 1(b)) [13].

For conceptual and steady-state analysis, a HPFC is modeled as a series harmonic voltage source whose amplitude and angle are controllable [16]. Figure 2 shows an equivalent model of the HPFC. In this model, the amplitude and the angle of line current harmonic (Ih) can be controlled by the amplitude (V_hpc) and angle (θh) of the HPFC output [10].

The same as a DVR [11-15], the size and complexity of a HPFC depends on the magnitude and phase angle of the series injected harmonic voltage. Therefore, several strategies of harmonic voltage injection can be considered, and depending on the active/reactive/harmonic power exchange between the line and the HPFC, the structure and size of the HPFC will change.

In [10], two control methods, MAPI and ZAPI were proposed. In Figure 3, the MAPI control vector diagram of a HPFC in a sample line is shown. In this diagram, Zh is the harmonic impedance of the line in which the HPFC is installed. Vsh, V_rh, Ih0 are bus-side, line-side harmonic voltage and the line harmonic current respectively before using the HPFC. By using the HPFC, the injected harmonic term of V_hpc will change V_rh0, Ih0 to V_rh, Ih.
In the MAPI control method, the injected harmonic voltage $V_{hpfc}$ is such that the rating of the HPFC is minimized. To achieve this, the injected harmonic voltage ($V_{hpfc}$) must be as low as possible. This results in an injection signal in-phase with $V_{rh}$.

In the ZAPI control method, the HPFC injected harmonic voltage ($V_{hpfc}$) is perpendicular to the harmonic current as shown in Figure 4. Therefore, no harmonic power is exchanged between the HPFC and the network.

MAPI and ZAPI methods are inaccurate methods because of controlling the HPFC by sampling of sending and receiving HPFC line parameters. In the MAPI method, the HPFC apparent power is not precisely minimized, and in the ZAPI method, the HPFC active power is not exactly zero, because injecting a series harmonic voltage, will also change the bus side harmonic voltage.

To show this concept, an HPFC is tested on the IEEE 14-busbar test system [17-18]. Figure 5 shows the system under study. The study is performed for only the $5^{th}$ harmonic which is normally the dominant harmonic in power networks.

As Figure 5 shows, an HPFC is placed in the feeder between buses 4 and 7. Table 1 lists the values of the linear and non-linear loads in the system.

The HPFC injects a $5^{th}$ harmonic voltage in the feeder between buses 4 and 7, and the outcome is studied. The angle of the injected voltage is changed from 0 to 360°.

Figure 6 shows the $5^{th}$ harmonic voltage variation at the bus side (bus 7) in the ZAPI/MAPI control method as the result of the HPFC operation. The study shows that the harmonic voltage of this busbar changes by the injected harmonic voltage by the HPFC. Therefore, it is necessary to keep this voltage, $V_{sh}$, unchanged.

### 3. Improved ZAPI and MAPI control methods

Using the sending/receiving line parameters results in accuracy of MAPI/ZAPI methods. In other words, in MAPI method, the HPFC apparent power is not precisely minimized, and in ZAPI method, the HPFC active power is not exactly zero.

To increase the accuracy of these methods, it is essential to incorporate other parameters of the network into the HPFC control algorithm. For this purpose, the IMAPI and IZAPI methods are proposed as the improved versions of MAPI and ZAPI.

#### 3.1. Improved Minimum Apparent Power (IMAPI) Method

Figure 7 shows an installed HPFC in a typical line, e.g. k-m. In this figure, $V_h$-harmonic voltage of network buses- can be calculated as:

$$V_h = V_{h0} - Z_h * Y_{HPFC,h} * V_{HPFC,h},$$

$$V_{h0} = Z_h * I_{h0}.$$  \hspace{1cm} (1)

$$V_{h0}: \text{initial harmonic voltage vector without HPFC},$$

$$I_{h0}: \text{initial harmonic current vector without HPFC},$$

$$Z_h : \text{impedance matrix of network, i.e:}$$

Paper-Scientia Iranica-6-SCI-TEMP-2021-1401-02-26-1
The complex, active/reactive and apparent powers of the HPFC can be calculated as:

\[
S_{\text{HPFC}} = \left[ V_{\text{HPFC},h}^* I_{\text{km,h}} \right] = P_{\text{HPFC}} + j Q_{\text{HPFC}},
\]

\[
P_{\text{HPFC}} = \left| V_{\text{HPFC},h}^* I_{\text{km,h}} \right| \cos \left( \theta_{\text{HPFC},h} - \theta_{\text{km,h}} \right) + \left| V_{\text{HPFC},h} \right|^2 \left| A_{\text{km,h}} \right| \cos \left( \theta_{\text{km,h}} \right),
\]

\[
Q_{\text{HPFC}} = \left| V_{\text{HPFC},h}^* I_{\text{km,h}} \right| \sin \left( \theta_{\text{HPFC},h} - \theta_{\text{km,h}} \right) - \left| V_{\text{HPFC},h} \right|^2 \left| A_{\text{km,h}} \right| \sin \left( \theta_{\text{km,h}} \right),
\]

\[
| S_{\text{HPFC}} | = \left( P_{\text{HPFC}}^2 + Q_{\text{HPFC}}^2 \right)^{1/2} = \left| V_{\text{HPFC},h} \right|^2 \left| A_{\text{km,h}} \right|^2 + \left| V_{\text{HPFC},h} \right|^2 \left| A_{\text{km,h}} \right|^2 +
\]
2|I_{km,0}|*|V_{HPFC,h}|*|A_{km,h}|*\text{Cos} (\theta_{Ak,m,0} + \theta_{HPFC,h} - \theta_{lm,0})^{(1/2)}.

(8)

To minimize the apparent power (HPFC Capacity), the derivative of (8) with respect to $\theta_{HPFC,h}$ is calculated and set to zero, i.e:

$$\frac{d}{d\theta_{HPFC,h}} S_{HPFC} = K_{const} * \left[ V_{HPFC}^2 + 2 |I_{km,0}| * |V_{HPFC,h}| * |A_{km,h}| * \text{Sin} (\theta_{Ak,m,0} + \theta_{HPFC,h} - \theta_{lm,0}) \right] = 0.

(9)

By solving (9), the angle of the HPFC for minimizing the HPFC capacity can be derived as (10).

$$\theta_{HPFC,h} = k\pi \left( \theta_{I_{km,0}} - \theta_{Akm,h} \right)

(10)

This relation shows that the HPFC angle depends on the HPFC line current angle and the angle of an equal impedance $A_{km,h}$ (This value is constant).

To study the effect of IMAPI Control method, an HPFC is placed in the feeder between buses 4 and 7 of the IEEE 14-busbar test system. Figure 8 shows the harmonic apparent, active and reactive powers of the HPFC and the optimum angle of the HPFC. Figure 9 shows the harmonic voltages at all buses with and without the HPFC. It can be seen from Figure 9 that the harmonic voltage values have changed by the HPFC.

3.2. Improved Zero Active Power (IZAPI) Method

The harmonic active power of the HPFC can be calculated by equation (6). In IZAPI control method, no harmonic power is exchanged between the HPFC and the network.

The HPFC harmonic current and voltage magnitude are obtained from the following equations:

$$|I_{km,0}| * \text{Cos} (\theta_{HPFC,h} - \theta_{I_{km,0}}) + |V_{HPFC,h}| * |A_{km,h}| * \text{Cos} (\theta_{Ak,m,0}) = 0

(11)

$$|V_{HPFC,h}| = - \left| I_{km,0} \right| \left| A_{km,h} \right| \left( \frac{\text{Cos} (\theta_{HPFC,h} - \theta_{I_{km,0}})}{\text{Cos} (\theta_{Ak,m,0})} \right)

(12)

Figure 10 shows the locus of the amplitude of the HPFC versus its angle in IZAPI control method (HPFC is installed in line 4-7). This figure shows that for IZAPI control method, the amplitude and the angle of the HPFC depend on each other.

Figure 11 shows the harmonic apparent, reactive and active power of the HPFC in IZAPI control method. Simulation results show that by using this method, no harmonic active power is exchanged between the HPFC and the network.

Figure 12 shows the HPFC line harmonic current variations and the HPFC harmonic reactive power versus the HPFC amplitude in IZAPI control method. This graph shows that the HPFC amplitude is limited by the level of harmonic current control and the HPFC capacity.

4. Cost Function Control Algorithm Method

In previous subsections, IMAPI/IZAPI methods were considered to control the HPFC parameters based on the buses harmonic voltages and series line/transformer harmonic current values. In these methods, the injected harmonic voltage is such that the rating of the HPFC is minimized or no harmonic
power is exchanged between the HPFC and the network. In these methods, there is no control on the network parameters such as harmonic power losses and other bus-bars harmonic voltage values. It is essential to define a cost function for an HPFC to control the network parameters such as harmonic power losses and harmonic voltage variations.

4.1. Harmonic Voltage Minimization

Harmonic voltage at bus \( j \) can be determined as:

\[
V_{j,h} = V_{j,h0} + (Z_{jk,h} - Z_{jm,h})*Y_{km,h}*Y_{HFPC,h} = V_{j,h0} + C_{j,h}*V_{HFPC,h}
\]  

where \( C_{j,h} \) is:

\[
C_{j,h} = (Z_{jk,h} - Z_{jm,h})*Y_{km,h}
\]  

For this purpose, the cost function is defined as follows.

\[
\text{Cost function} = \sum_{j=1}^{M} \left( |V_{j,h}|^2 - |V_{j,h0}|^2 \right) K_j
\]  

\[
= \sum_{j=1}^{M} \left( K_j \left( |V_{j,h0}|^2 + |C_{j,h}|^2*|Y_{HFPC,h}|^2 + 2*|V_{j,h0}|*|C_{j,h}|*|Y_{HFPC,h}|*\cos\left(\theta_{HFPC,h} + \theta_{C,h} - \theta_{V,h0}\right) \right) - |V_{j,h0}|^2 \right)
\]

\[
= \sum_{j=1}^{M} \left( K_j \left( |C_{j,h}|^2*|Y_{HFPC,h}|^2 + 2*|V_{j,h0}|*|C_{j,h}|*|Y_{HFPC,h}|*\cos\left(\theta_{HFPC,h} + \theta_{C,h} - \theta_{V,h0}\right) \right) \right)
\]

\[
\theta_{V,h0} = \leq V_{j,h0}, \theta_{HFPC,h} = \leq V_{HFPC,h}, \theta_{C,h} = \leq C_{j,h}
\]  

where \( K_j \) is the weighting factor of the \( j \)th bus harmonic voltage variation.

In the cost function, all the parameters are constant values, and the HPFC angle is controlled to optimize the cost function. To achieve this, it is necessary to solve the following equation:

\[
\frac{d\text{CostFunction}}{d\theta_{HFPC,h}} = \sum_{j=1}^{M} \left( -2*K_j \left( |V_{j,h0}|*|C_{j,h}|*|Y_{HFPC,h}|*\sin\left(\theta_{HFPC,h} + \theta_{C,h} - \theta_{V,h0}\right) \right) \right) = 0
\]

To investigate the effect of this control method, an HPFC is installed in different lines in IEEE 14-bus test system. Table 2 shows the HPFC angle to minimize harmonic voltage by installing the HPFC at different lines.

Simulations show that, when the voltage harmonic decreases, harmonic power losses will increase by about 17.9% when the HPFC is installed in line 5-6. Therefore, for the optimum control of harmonic voltages, it is necessary to consider harmonic power losses in the cost function as well.

4.2. Harmonic Power Loss Minimization

Harmonic power losses can be determined as:

\[
P_{\text{Loss,h}} = 3*\sum_{j=1}^{M} \left( |R_{j,h}|*|I_{j,h}|^2 \right)
\]  

\[
I_{pq,h} = \left( V_{p,h} - V_{q,h} \right) / Z_{pq,h}
\]  

\[
\]
\[ I_{km,h} = \left( V_{k,h} - V_{m,h} - V_{HPFC,h} \right) / Z_{km,h} \]  

where \( I_{pq,h}, I_{km,h} \) are the harmonic currents of the lines p-q and k-m respectively.

\[ V_{p,h} = V_{p,h0} + (Z_{pk,h} - Z_{pm,h}) * Y_{km,h} * V_{HPFC,h} \]  

\[ V_{q,h} = V_{q,h0} + (Z_{qk,h} - Z_{qm,h}) * Y_{km,h} * V_{HPFC,h} \]  

Finally, the cost function (harmonic power losses) is defined as:

\[ \text{Cost function} = P_{Loss,h} = P_{Loss,h0} + K_{A,h} * |V_{HPFC,h}|^2 + K_{B,h} * |V_{HPFC,h}| \]  

where \( P_{Loss,h0}, K_{A,h}, K_{B,h} \) are as follows:

\[ K_{A,h} = 3 * \sum_{j=1}^{M} \left( R_{j,h} * |A_{j,h}|^2 \right) \]  

\[ K_{B,h} = \sum_{j=1}^{M} 6 \left( R_{j,h} * |I_{j,h0}| * |A_{j,h}| * \cos \left( \theta_{j,j0} - \theta_{HPFC,h} - \theta_{A,j,h} \right) \right) \]  

\[ \theta_{j,j0} = < I_{j,h0} >, \theta_{HPFC,h} = < V_{HPFC,h} >, \theta_{A,j,h} = < A_{j,h} > \]  

Where, \( A_{j,h} \) is a constant value which depends on the line impedances, which is calculated using (25).

\[ A_{j,h} = \left( (Z_{pm,h} - Z_{pk,h}) - (Z_{qm,h} - Z_{qk,h}) \right) * Y_{mk,h} / Z_{j,h} \]  

If the line is an HPFC-installed line, \( A_{j,h} \) must be determined from the following relation:

\[ A_{j,h} = \left( 1 + Y_{mk,h} * (Z_{mn,h} + Z_{kk,h} - 2 * Z_{mk,h}) \right) / Z_{j,h} \]  

In the cost function, all the parameters are constant values, and the HPFC angle is changed to optimize the cost function. To minimize the harmonic power, Eq. (27) must be met.

\[ \frac{d \text{Cost function}}{d \theta_{HPFC,h}} = |V_{HPFC,h}| * \frac{K_{B,h}}{d \theta_{HPFC,h}} = 6 * |V_{HPFC,h}| * \sum_{j=1}^{M} \left( R_{j,h} * |I_{j,h0}| * |A_{j,h}| * \sin \left( \theta_{j,j0} - \theta_{HPFC,h} - \theta_{A,j,h} \right) \right) = 0 \]  

Because of the complexity of (27), bi-section method is used to find \( \theta_{HPFC,h} \). Table 3 shows the HPFC angle to minimize the harmonic power losses by installing an HPFC in different lines.

Simulation shows when harmonic power losses decrease, harmonic voltages will increase or decrease when the HPFC is located in line 5-6 (Figure 13).

4.3. Harmonic Voltage and Power Loss Minimization

Because of the dependency of harmonic voltages and harmonic power losses, it is essential to define a more complete cost function that includes both quantities. This cost function is defined as:
\[
\text{Cost function} = \text{Cost function}(\Delta V_h^2) + \text{Cost Function}(P_{\text{loss}, h}) = \\
\sum_{j=1}^{N} \left( |V_{j,h}|^2 - |V_{j,0}|^2 \right) K_j + P_{\text{loss}, h0} + K_{A,h} \left| V_{\text{HPFC}, h} \right|^2 + K_{B,h} \left| V_{\text{HPFC}, h} \right| \\
(28)
\]

To minimize the cost function, it is necessary to solve the following equation which can be done using the bi-section method:
\[
\frac{d\text{Cost Function}}{d\theta_{\text{HPFC}, h}} = \sum_{j=1}^{N} \left( -2 * K_j * \left| V_{j,0} \right| C_{j,h} \left| V_{\text{HPFC}, h} \right| \sin \left( \theta_{\text{HPFC}, h} + \theta_{V,j,h} - \theta_{V,j,0} \right) \right) \\
+6 \left| V_{\text{HPFC}, h} \right| \sum_{j=1}^{M} \left( R_{j,h} \left| I_{j,0} \right| A_{j,h} \sin \left( \theta_{I,j,0} - \theta_{V,j,0} - \theta_{A,j} \right) \right) = 0 \\
(29)
\]

Table 4 shows the HPFC angle for minimizing the cost function by installing an HPFC in different lines. Simulation shows that by using this cost function, the harmonic voltage (Figure 14) and harmonic power losses (Figure 15) can be reduced simultaneously when the HPFC is located in line 5-6.

5. Simulation for a Real Network

In this section, the effect of the HPFC is evaluated in a real network, i.e. Iran north-west transmission system. Harmonic measurements have been performed at different locations in Iran NW transmission system (Figure 16) using HIOKI-3196 power quality analyzer. Figure 17 and Figure 18 show the harmonic measurement at buses 1 and 3 for a one-day period which is recorded by 10-minute sampling intervals. Figure 19 shows the harmonic voltage value at all buses at about 20:00 o’clock. As it can be seen, the 5th harmonic level is above IEEE 519 Std. limit (i.e. 1 %) during most of the measurement period. The objective in this case is to use an HPFC to change the harmonic impedance and accordingly alter harmonic flows such that the 5th harmonic level at bus 3 is decreased.

To design the HPFC, first the system model must be derived. The network is modeled at 400 kV and 230kV voltage levels with 28 buses (Figure 16).

The harmonic voltage at bus No. 3 is 4.3% which has caused complications in the network. To overcome the complications, the harmonic voltage needs to be decreased to a level below 2% (IEC 61000-2).

Table 5 shows the HPFC signal magnitude and angle using IZAPI and IMAPI control methods and minimizing the different cost functions by installing an HPFC in an optimum line.

Figure 20 shows harmonic voltage values of all buses for the control methods and their corresponding injected harmonic voltage given in

Table 5. Table 6 summarizes the network harmonic power loss, HPFC exchange apparent and active and reactive powers.

These simulations indicate that the network parameters cannot be controlled by IZAPI and IMAPI methods alone. The harmonic power loss is increased if Harmonic voltage minimization control method is used. Harmonic voltage of some buses is increased if only the power-loss minimization method is employed. Harmonic voltage and harmonic power losses can be reduced simultaneously if the last proposed method is used.
In Table 6 exchange power by HPFC and network is shown. By these values the capacity and structure of HPFC (with and without power supply) is obtained.

6. Conclusion

In this paper, the performance of a recently introduced harmonic conditioner, i.e. harmonic power flow controller or HPFC, has been improved by introducing new control strategies for the HPFC. It is shown that by employing the IMAPI/IZAPI control methods; one can more effectively reduce the size of the HPFC as compared to the previously MAPI/ZAPI control algorithms. Furthermore, two operating performance parameters, i.e. harmonic profile of the network and the harmonic losses cost function are considered and incorporated in the design and control of the HPFC. It is shown that HPFC can effectively achieve harmonic environment in places where no absorption harmonic filter can be installed.

7. References


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List of Figures

Figure 1-HPFC Circuit Diagram on a sample line, a) without active power exchange, b) with active power exchange [10]

Figure 2-HPFC equivalent model with no active power exchange with the network [10]

Figure 3- HPFC controlling vector diagram (Vrh is constant) in the MAPI control method [13]

Figure 4- HPFC controlling vector diagram (Vrh is constant) in the ZAPI control method [13]

Figure 5-The 14 bus-bar test system, an HPFC, and the harmonic source [8]

Figure 6- Harmonic voltage variation of bus side respect to no-HPFC in MAPI/ZAPI control method when HPFC is located between buses 4 and 7

Figure 7- Network model, a) HPFC on line k-m, b) Line p-q without HPFC

Figure 8-Harmonic apparent, active and reactive power of the HPFC in IMAPI control method (Bold line: Optimum angle of the HPFC)

Figure 9-Harmonic Voltage of Bus-bars with and without HPFC in IMAPI control method

Figure 10-Locus of HPFC output amplitude / angle in IZAPI control method

Figure 11-Harmonic apparent (a), reactive (b) and active (c) power of HPFC in IZAPI control method

Figure 12- HPFC line harmonic current variation (a) and HPFC harmonic reactive power (b) versus HPFC value in IZAPI control method (I0 is HPFC current before HPFC installation)

Figure 13- Effect of harmonic voltage minimization algorithm control on the voltage harmonic of different buses when the HPFC is located in line 5-6

Figure 14- Effect of HPFC cost function algorithm control on voltage harmonic of different buses when the HPFC is located in line 5-6

Figure 15- Effect of different cost function algorithm controls on active harmonic power losses of network variation when the HPFC is located in line 5-6

Figure 16- Iran north-west transmission system single-line diagram

Figure 17- 5th harmonic voltage measurements at bus 1.

Figure 18- 5th harmonic voltage measurements at bus 3.

Figure 19- 5th harmonic voltage measurements at all busses.

Figure 20- Ratio of harmonic voltage at Iran northwest bus-bars after installation of an HPFC in optimum line with ZAPI, MAPI control methods and harmonic voltage and power loss control methods.
Figures

Figure 1-HPFC Circuit Diagram on a sample line, a) without active power exchange, b) with active power exchange [10]

Figure 2-HPFC equivalent model with no active power exchange with the network [10]

Figure 3- HPFC controlling vector diagram (Vrh is constant) in the MAPI control method [13]
Figure 4- HPFC controlling vector diagram (\(V_rh\) is constant) in the ZAPI control method [13]

Figure 5- The 14 bus-bar test system, an HPFC, and the harmonic source [8]

Figure 6- Harmonic voltage variation of bus side respect to no-HPFC in MAPI/ZAPI control method when HPFC is located between buses 4 and 7
Figure 7 - Network model, a) HPFC on line k-m, b) Line p-q without HPFC

Figure 8 - Harmonic apparent, active and reactive power of the HPFC in IMAPI control method
(Bold line: Optimum angle of the HPFC)

Figure 9 - Harmonic Voltage of Bus-bars with and without HPFC in IMAPI control method
Figure 10-Locus of HPFC output amplitude / angle in IZAPI control method

Figure 11-Harmonic apparent (a), reactive (b) and active (c) power of HPFC in IZAPI control method
Figure 12- HPFC line harmonic current variation (a) and HPFC harmonic reactive power (b) versus HPFC value in IZAPI control method ($I_0$ is HPFC current before HPFC installation).

Figure 13- Effect of harmonic voltage minimization algorithm control on the voltage harmonic of different buses when the HPFC is located in line 5-6.

Figure 14- Effect of HPFC cost function algorithm control on voltage harmonic of different buses when the HPFC is located in line 5-6.
Figure 15- Effect of different cost function algorithm controls on active harmonic power losses of network variation when the HPFC is located in line 5-6

Figure 16- Iran north-west transmission system single-line diagram

Figure 17- 5th harmonic voltage measurements at bus 1.
Figure 18- 5th harmonic voltage measurements at bus 3.

Figure 19- 5th harmonic voltage measurements at all busses.
Figure 20- Ratio of harmonic voltage at Iran northwest bus-bars after installation of an HPFC in optimum line with ZAPI, MAPI control methods and harmonic voltage and power loss control methods.
Table 1- Specification of the loads under study [8]

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Static Load Spec.</th>
<th>5th order Harmonic Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P(MW)</td>
<td>Q(MVAr)</td>
</tr>
<tr>
<td>4</td>
<td>47.79</td>
<td>-3.9</td>
</tr>
<tr>
<td>5</td>
<td>7.6</td>
<td>1.6</td>
</tr>
<tr>
<td>8</td>
<td>29.5</td>
<td>16.6</td>
</tr>
<tr>
<td>9</td>
<td>29.5</td>
<td>16.6</td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>5.8</td>
</tr>
<tr>
<td>11</td>
<td>3.5</td>
<td>1.8</td>
</tr>
<tr>
<td>12</td>
<td>6.1</td>
<td>1.6</td>
</tr>
<tr>
<td>13</td>
<td>13.5</td>
<td>5.8</td>
</tr>
<tr>
<td>14</td>
<td>14.9</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2- HPFC angle for minimum harmonic voltage

<table>
<thead>
<tr>
<th>Line</th>
<th>$\theta_{HPFC,h}$</th>
<th>Line</th>
<th>$\theta_{HPFC,h}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-7</td>
<td>256.98°</td>
<td>7-9</td>
<td>76.63°</td>
</tr>
<tr>
<td>5-6</td>
<td>276.57°</td>
<td>9-10</td>
<td>262.36°</td>
</tr>
<tr>
<td>6-11</td>
<td>107.71°</td>
<td>9-14</td>
<td>253.44°</td>
</tr>
<tr>
<td>7-8</td>
<td>256.77°</td>
<td>10-11</td>
<td>280.91°</td>
</tr>
</tbody>
</table>

Table 3- HPFC angle for minimum harmonic power loss

<table>
<thead>
<tr>
<th>Line</th>
<th>$\theta_{HPFC,h}$</th>
<th>$P_{Loss,h}(Pu)$</th>
<th>Line</th>
<th>$\theta_{HPFC,h}$</th>
<th>$P_{Loss,h}(Pu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-7</td>
<td>75.97°</td>
<td>0.1898</td>
<td>7-9</td>
<td>242.11°</td>
<td>0.2097</td>
</tr>
<tr>
<td>5-6</td>
<td>257.4°</td>
<td>0.1894</td>
<td>9-10</td>
<td>94.96°</td>
<td>0.2188</td>
</tr>
<tr>
<td>6-11</td>
<td>235.9°</td>
<td>0.2144</td>
<td>9-14</td>
<td>315.18°</td>
<td>0.2061</td>
</tr>
<tr>
<td>7-8</td>
<td>72.31°</td>
<td>0.1831</td>
<td>10-11</td>
<td>60.41°</td>
<td>0.2155</td>
</tr>
</tbody>
</table>

Table 4- HPFC angle for harmonic voltage and power loss minimization

<table>
<thead>
<tr>
<th>Line</th>
<th>$\theta_{HPFC,h}$</th>
<th>Line</th>
<th>$\theta_{HPFC,h}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-7</td>
<td>256.7°</td>
<td>7-9</td>
<td>75.42°</td>
</tr>
<tr>
<td>5-6</td>
<td>288.41°</td>
<td>9-10</td>
<td>265.62°</td>
</tr>
<tr>
<td>6-11</td>
<td>88.59°</td>
<td>9-14</td>
<td>221.15°</td>
</tr>
<tr>
<td>7-8</td>
<td>256.57°</td>
<td>10-11</td>
<td>266.75°</td>
</tr>
</tbody>
</table>
## Table 5- Optimum HPFC angle for harmonic voltage and power loss minimization

| HPFC Control Method                     | Line | \(|V_{HPFC}|\) | \(\theta_{HPFC}\) |
|----------------------------------------|------|---------------|------------------|
| IZAPI Method                           | 2-4  | 0.0315        | 208.7°           |
| IMAPI Method                           | 2-4  | 0.0304        | 37.4°            |
| Harmonic power loss minimization       | 5-6  | 0.03          | 145.7°           |
| Harmonic voltage minimization          | 2-28 | 0.03          | 127.8°           |
| Harmonic voltage and power loss minimization | 2-4  | 0.03          | 351.4°           |

## Table 6- Total harmonic power and HPFC harmonic apparent, active and reactive power for different HPFC control methods

<table>
<thead>
<tr>
<th>HPFC Control Method</th>
<th>(P_{Loss,h}) (kW)</th>
<th>(S_{HPFC,h}) (kVA)</th>
<th>(P_{HPFC,h}) (kW)</th>
<th>(Q_{HPFC,h}) (kVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without HPFC</td>
<td>522</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IZAPI Method</td>
<td>782</td>
<td>1005</td>
<td>0</td>
<td>1005</td>
</tr>
<tr>
<td>IMAPI Method</td>
<td>572</td>
<td>376</td>
<td>367</td>
<td>-82</td>
</tr>
<tr>
<td>Harmonic power loss minimization</td>
<td>425</td>
<td>684</td>
<td>510</td>
<td>-455</td>
</tr>
<tr>
<td>Harmonic voltage minimization</td>
<td>451</td>
<td>510</td>
<td>-25</td>
<td>-510</td>
</tr>
<tr>
<td>Harmonic voltage and power loss minimization</td>
<td>463</td>
<td>490</td>
<td>74</td>
<td>-484</td>
</tr>
</tbody>
</table>