A new innovative current controller for selective harmonic compensation using active power filters in a microgrid with renewable energy source

Mohammad Firoozian[1], Seyyed Hossein Hosseinian[2], Mehrdad Abedi[2]
[1]Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[2]Department of Electrical Engineering, Amirkabir University, Tehran, Iran

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ABSTRACT

In this paper, a novel current controller for selective compensation with active power filter (APF) in a microgrid (MG) is proposed. Power generation with sinusoidal voltage and high quality is essential in the microgrid. Hence, a current control-based method for shunt active power filters aiming to compensate the selective harmonic is proposed. Also, voltage source converter is used in the APF to improve MG power quality. Using the suggested control method can reduce total harmonic distortion (THD). The obtained results from the MATLAB simulations proved the superior of our method than other methods to decrease the current harmonic in a microgrid to an admissible area. Additionally, the practical results obtained from the implementation of the proposed control approach on an actual microgrid confirm the efficacy of the proposed method.

Corresponding Author:

Mohammad Firoozian
Department of Electrical Engineering, Science and Research Branch, Islamic Azad University
Tehran, Iran
Email: m.firoozian@iau.ac.ir

1. INTRODUCTION

Power quality in microgrids is one of the most important issues extensively taken into consideration by the researchers in recent years. Many new electrical devices utilize microprocessor controllers and power electronics while these devices are sensitive to many kinds of distortions in the microgrid [1]. In this context, the renewable energy based distributed generations (DGs) embedded in microgrid often use an inverter for supplying the AC loads [2]. Voltage amplitude and phase control to determine the amount of active and reactive power delivered to the load is one of the main tasks of the inverter. Also, power quality indicators correction is possible by inverter control. Shunt active power filter (APF) can be a proper choice for voltage and current harmonic compensation in the output of renewable DGs [3]–[5]. The APF can simultaneously solve the problem of the harmonics and lack of the reactive power [6]. Additionally, the APF has the specific ability of adjusting the voltage of the inverter by using sinusoidal pulse width modulation (PWM) or DC link voltage control. The shunt APF can simultaneously compensate the current harmonic and improve the MG power factor better than the conventional methods (i.e., passive filters and capacitors). One of the most practical methods to remove harmonics and improve power quality indexes is using APF [7].

Tahri *et al.* [8] describe the fuzzy logic with a great deal of dynamic complexity is proposed to control the APF. In the design and control of the APF, instantaneous power theory is usually considered as a basis for computing the compensation flow. In this theory, it is assumed that the main voltages are ideal. However, in most cases and in most industrial plants, the main voltages may be unbalanced. In this situation, the mentioned theory not applicable. For the three-phase filters, the p-q theory can be used but the voltage is not ideal. Additionally, the traditional p-q theory is not so appropriate for controlling the harmonic voltages. In order to modify APF efficiency, a new control method based of fuzzy logic is presented in [9]. Generally, the APF control is performed in fundamental frame like sliding mode control [10] and equivalent PI and PID control [11], [12], stationary frame such as dead-beat control [13], hysteresis control [14] and eventually integral proportional (PI) controller with selective harmonic compensation capability [15], [16]. In the selective control in harmonics frame, each harmonic is controlled in its own reference frame. Despite the computation-time expensive harmonics frame method, it has an acceptable performance in controlling the APF. Terriche *et al.* [17] describe a PI control with fundamental reference frame is proposed for an active power filter. A comprehensive literature review for APF controller to decrease harmonics is done in [18], [19].

This paper proposes a new control strategy based on Pole-zero removal and decreased the current harmonic in a microgrid to an acceptable level. Additionally, the practical results obtained from the implementation of the proposed control approach on an actual microgrid. Harmonic reference frame method for selective control of the active power filter is chosen where all the harmonic components are selected separately. In the case of the harmonic current amplitude is higher than the active power filter capability, the proposed control system eliminates more destructive harmonics and thus provides APF with the ability to protect against overload in harmonic polluted system. In order to examine the performance of the proposed controller, it is implemented on the standard 12 buses micro-grids having some nonlinear loads connected to a distribution network. Moreover, the effectiveness of the control method has also been evaluated via practical experiments.

The rest of the article is continued as, the flow control method for APF is explained in section 2. The proposed harmonic current control for selective compensation is introduced in section 3. The simulation results are discussed in section 4 and then experimental results are explained. Eventually this paper concluded and plan for future studies in section 5.

2. FLOW CONTROL METHOD FOR AN APF

In Figure 1 an APF control diagram is illustrated. As depicted in Figure 1, the control system is consisted of voltage control, fundamental current control, harmonic current control high pass filter (HPF) for harmonic detection blocks [20]. The APF works like a current harmonic source and injects similar amplitude current harmonics and the opposite phase into the distribution network. In this method, the line current is measured to determine the current harmonic to be injected [21].

$$i^*_{F1d} = \left(K_{pdc} + K_{idc}\frac{1}{2}\right)(V^*_{dc} - V_{dc}) \tag{1}$$

The controller gains K_{pdc} and K_{idc} are constant parameters usually between 0.1 and 1. The current control intended for APF is performed separately for all harmonics [22]. System inductance in vector method is calculated as follow:

$$\underline{v}_F - \underline{e}_{dq} = R\underline{i}_F + L\frac{d\underline{i}_F}{dt} + j\omega_e L\underline{i}_F \tag{2}$$

where, L is line inductance, R is line resistance, $\underline{i}_F$ and $\underline{v}_F$ are filter current and voltage respectively and also $\underline{e}_{dq}$is system voltage in d-q framework. In this model, Pole-zero cancellation is done the fundamental current controller block which is a proportional–integral (PI) controller [23].

$$\underline{v}^*_{F1} = \left(K_P + (K_i + j\omega_e K_P)\frac{1}{S}\right)\left(\underline{i}^*_F - \underline{i}_F\right) + \underline{e}_{dq} \tag{3}$$

Where K_p is proportional gain and $Ki+j\omega_e K_p$ is integral gain. The block diagram of fundamental current controller with RL plant model is shown in Figure 2. The current control model can be formulated as follow [24]:

$$T_1 = \frac{\underline{i}_F}{\underline{i}^*_{F1}} = \frac{K_p s + K_i + j\omega_e K_p}{Ls^2 + (K_p + R + j\omega_e L)s + K_i + j\omega_e K_p} \tag{4}$$

If $K_P/K_i = L/R$ is considered, the (4) will be a low-pass filter as follow:

$$T_1 = \frac{\underline{i}_F}{\underline{i}^*_{F1}} = \frac{K_p}{Ls + K_p} \tag{5}$$

The fundamental controller’s function is to recognize the sinusoidal current which needs a relatively low bandwidth. If the reactive current reference is non-zero, the controller will be able to compensate the reactive power. Moreover, when the unbalanced load compensation is required, the same topology and extra negative sequence controller must be added.

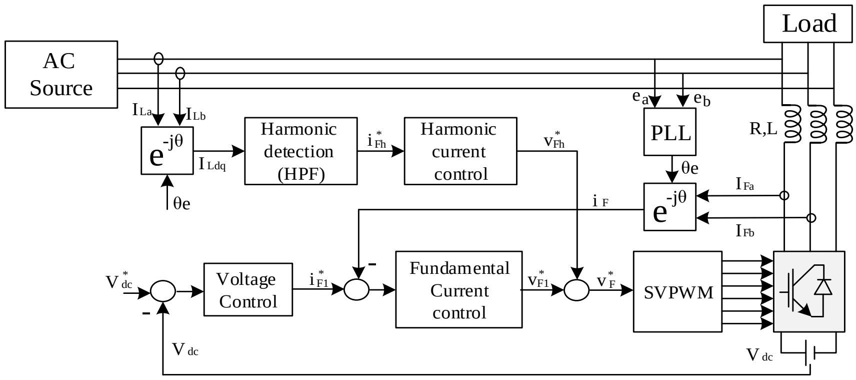

Figure 1. The active power filter control diagram

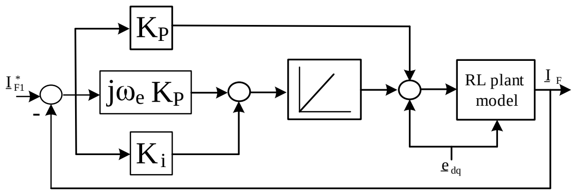

Figure 2. The fundamental current control

3. THE PROPOSED CONTROL METHOD

As proved is literature review the compensation methods based on selective harmonic have better performance than non-selective methods. When harmonic current amplitude is higher than active power filter endurance limit, the controller compensates the most destructive harmonic and also protect the system against overload. Another prominent feature of the proposed control method is its robustness uncertainty conditions. In the proposed control method, compensation is done by generating a harmonic current with equal amplitude and opposite phase of demand side harmonic current. The injected currents are based on k=6n±1 of harmonic sequence. The controller rotating framework is done with frequency ωe and frequency -ωe is selected for coordination. In this situation, the *k=6n±1* will transform to *k=6n*.Therfore, rotating reference frame can be demonstrated as below [25]:

$$\underline{v}_F^k - \underline{e} = R i_F^k + L(d\underline{i}_F^k)/dt + jk_e L\underline{i}_F^k \tag{6}$$

Using PI controller is necessary but it cannot remove pole and zero. Therefore, a current controller for the *kωe* via the following transfer function is needed.

$$T_{PIk}^k = K_{pk} + (K_{ik} + jk\omega_e K_{pk})\frac{1}{s} \tag{7}$$

Where, *K* represents the harmonic order. The positive sequence and negative sequence are in opposite directions to each other. The controller is transferred by considering $k\omega_e$ for negative sequence and $-k\omega_e$ for positive sequence. Because of frequency changes, T_{PIk}^k for positive and negative sequence harmonic T_{PIk-}^k and sequence harmonic T_{PIk+}^k is formulated as follows:

$$T_{\mathrm{PIk}+} = \frac{K_{pk}s + K_{\mathrm{ik}}}{s - \mathrm{jk}\omega_e} \qquad \mathrm{T}_{\mathrm{PIk}-} = \frac{K_{pk}s + K_{\mathrm{ik}}}{s + \mathrm{jk}\omega_e} \tag{8}$$

For simultaneously controlling of the negative sequence and positive sequence of the current harmonic with a controller, the T_{PIk}^{k} consists of T_{PIk+}^{k} and T_{PIk-}^{k} should be as follow:

$$T_{PIk} = T_{PIk+} + T_{PIk-} = 2\frac{K_{pk}s^2 + K_{ik}s}{s^2 + (k\omega_e)^2} \tag{9}$$

The *k*th harmonic order resided in the fundamental reference frame is as follows:

$$T_k = \frac{i_{Fk}}{i_{Fk}^*} = \frac{2(K_{pk}s^2 + K_{ik}s)}{Ls^3 + \left(2K_{pk} + R\right)s^2 + (2K_{ik} + L(k\omega_e)^2)s + R(k\omega_e)^2} \tag{10}$$

The current loop is a band-pass filter if assuming $K_p/K_i=L/R$.

$$K_k = \frac{i_{Fk}}{i_{Fk}^*} = \frac{2K_{pk}s}{Ls^2+2K_{pk}s+L(k\omega_e)^2} \tag{11}$$

In Figure 3, the H_k frequency response is depicted. The graphical results of Figure 3 are calculated for k = 6, L=10 mH, R=1π and also K_p is equal to 1 and 5.

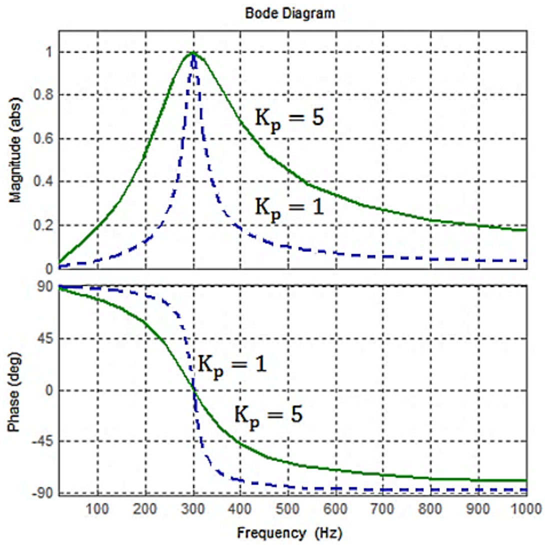

Figure 3. The H_k frequency response

The lower value is also selected for proportional gain of the PI controller ($K_p \leq 1$) for all controllers. The mathematical representation of the controller associated with every harmonic order is as follows:

$$H_{PI} = \sum_{n=1}^{7} \quad 2 \times \frac{K_{pk}s^2+K_{ik}s}{s^2+(k\omega_e)^2}, \qquad k = 6n \tag{12}$$

Due to the possible change in frequency, the inductance values are not exactly known. The (12), is virtually executed by K_{pk} and K_{ik}. Using this method for harmonic orders selection helps better compensation. The HPF is a high pass filter which its output is compensated by the active power filter harmonic current.

$$H_{\mathrm{HPF}} = \frac{i_{FH}^*}{i_L} = 1 - \left(\frac{\omega_0^2}{s^2+2\beta\omega_0 s+\omega_0^2}\right)^2 \tag{13}$$

Where the cut-off frequency ω_0 is *300 rad/s* and also $\beta=0.8$. The HPF is run in the main frame that the DC has no phase change.

4. RESULTS AND DISCUSSION

The power system selected for the simulation study of this paper is a 12-bus microgrid, shown in Figure 4, with two non-linear loads and two DG units connected to the main network. The first DG unit (DG1) is battery energy storage and the second (DG2), is photovoltaic. The photovoltaic is connected to the microgrid with a chopper and an inverter. The microgrid nominal voltage is 230 V and its frequency is 50 Hz [26]. Two nonlinear loads are connected at buses 4 and 11.

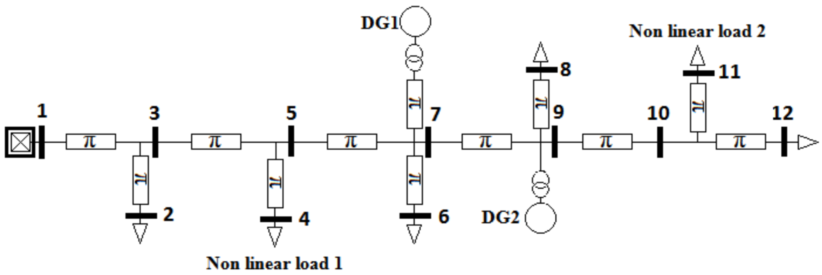

Figure 4. The single diagram of the 12-bus microgrid

The APF with the proposed harmonic current control is designed and located on the bus with the highest THD. The current THD before the compensation is calculated and presented in Table 1. The THD can be calculated by as follow [27].

$$THD_i = \frac{100 \times \sqrt{\sum_{h=2}^{N} I_{h,rms}^2}}{I_{1,rms}} \tag{14}$$

It is obvious that the buses 4 and 11 have higher THD than the other buses because of non-linear electrical loads. The pre- compensation current THD at bus 4 is 30.65% and 24.7% at bus 11. Thus, two active filters are installed on these buses. The harmonic spectrum consists of positive component ($k_+=6n+1$) and negative component ($k_-=6n-1$) of k order harmonic. The proposed controller is tuned for negative component and positive component which consequently converts the $k=6n\pm1$ to $k=6n$. The simulation results for k=12 and k=6, are accumulated in Table 1. The bus 4 current THD by selective compensation for k=6 and k=12, are reduced to 9.02% and 12.7%, respectively.

Table 1. The results of harmonic compensation

Buses	Before compensation	Selective compensation for k=6	Non-selective selective compensation for k=12
1	6.43	2.97	4.51
2	1.34	1.03	1.31
3	9.15	3.76	5.85
4	30.65	9.02	12.7
5	3.52	1.3	2.33
6	5.17	3.92	5.01
7	4.06	1.8	3.02
8	6.55	4.84	6.31
9	7.87	3.65	6.11
10	7.87	3.65	6.11
11	24.7	6.81	12.85
12	8.31	6.5	7.78

The results of Table 1 show the decrease of current THD after using APF. Moreover, it is evident that the harmonic compensation is performed in the best way. The 5 and 7 order current harmonics before and after using APF on bus 4 are depicted in Figure 5 and Figure 6, respectively. Additionally, in Figure 7 and Figure 8, 11th and 13th current harmonics at bus 4 before and after the selective compensation with k=12 are shown, respectively.

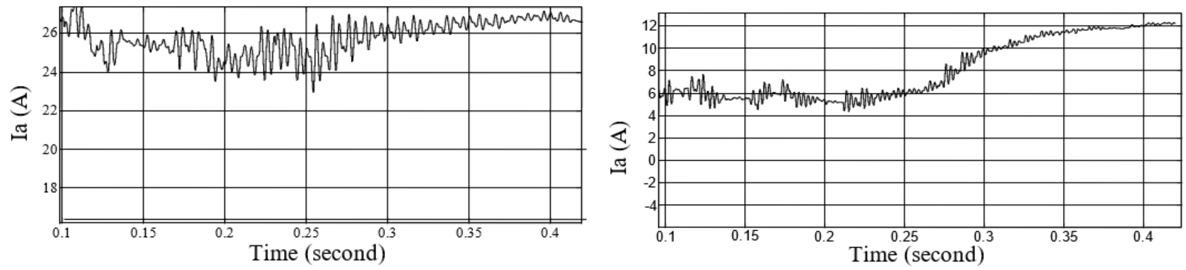

Figure 5. 5th and 7th current harmonics at bus 4 before the selective compensation

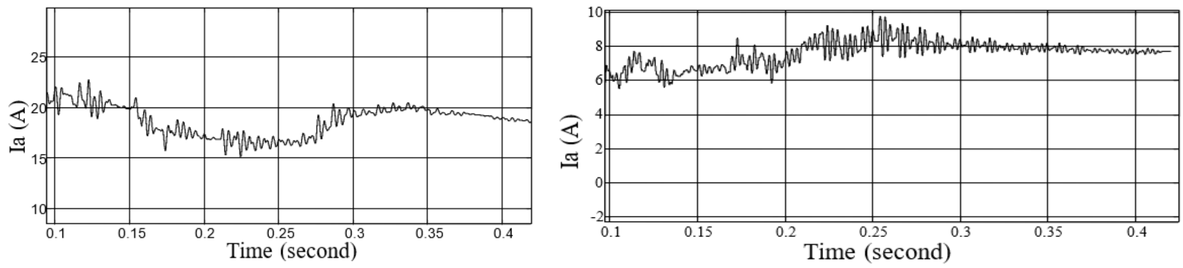

Figure 6. 5th and 7th current harmonics at bus 4 with selective compensation (k=6)

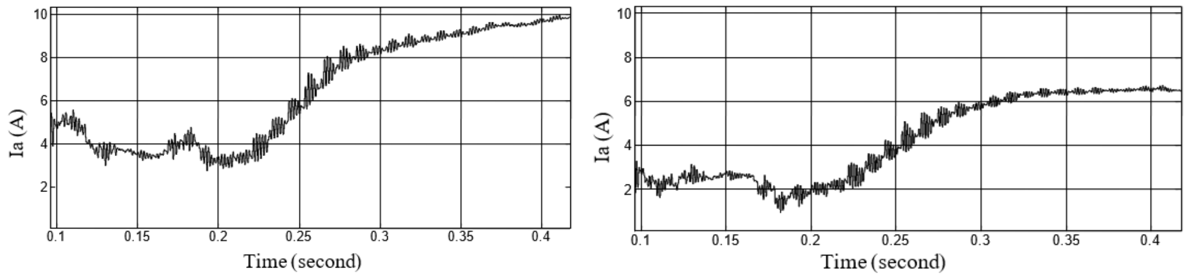

Figure 7. 11th and 13th current harmonics at bus 4 before the selective compensation

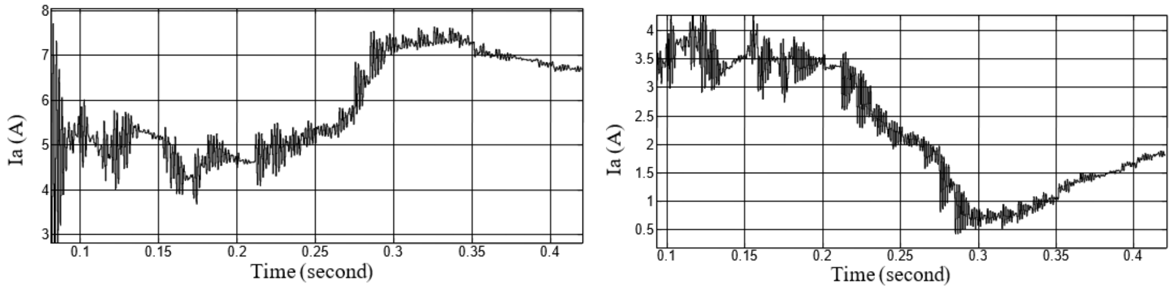

Figure 8. 11th and 13th current harmonics at bus 4 with selective compensation (k=12)

The Figures 9, 10, 11 and 12 depict the current with and without the selective compensation. The results evidently demonstrate the improvement in the current waveform. Also, the bus 11 current THD by selective compensation, with *k=6* and *k=12*, are reduced to 6.81 and 12.85, respectively. In addition, the current THD at all the other buses are decreased justifying the effective performances of the proposed APF in the microgrid.

4.1. Experimental results

The performance of the proposed current controller for selective compensation with active power filter is evaluated by some practical experiments. In Figure 12, the experimental setup is illustrated consisting of a rectifier, a three-phase inverter, grid inductance, PWM and sensor boards, resistive load and the proposed APF.

In the case of APF absence in the setup, the current THD is about 26%. Therefore, according to the standards, the compensation is necessary in this situation. In Figure 13, the current wave forms before and after compensation is depicted. By using the proposed APF in the setup, the current THD had decreased to less than 4%.

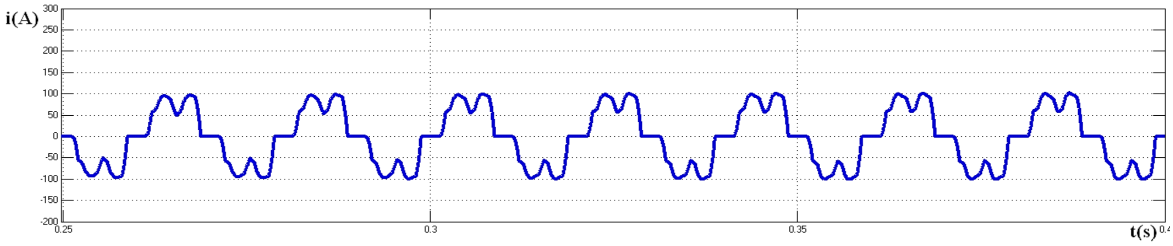

Figure 9. The bus 4 current before compensation

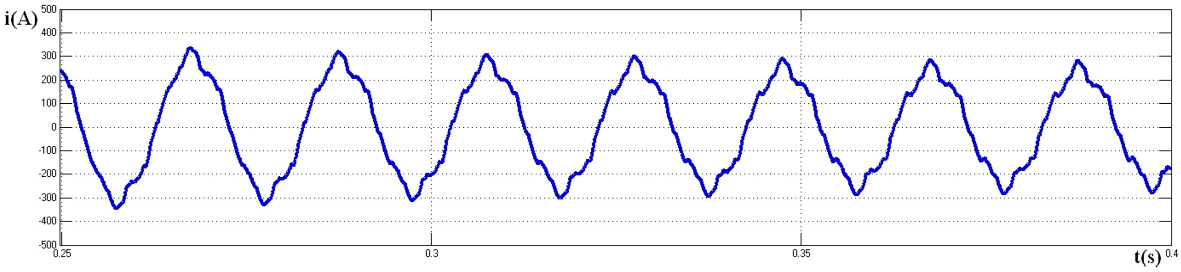

Figure 10. The bus 4 current by selective compensation (k=12)

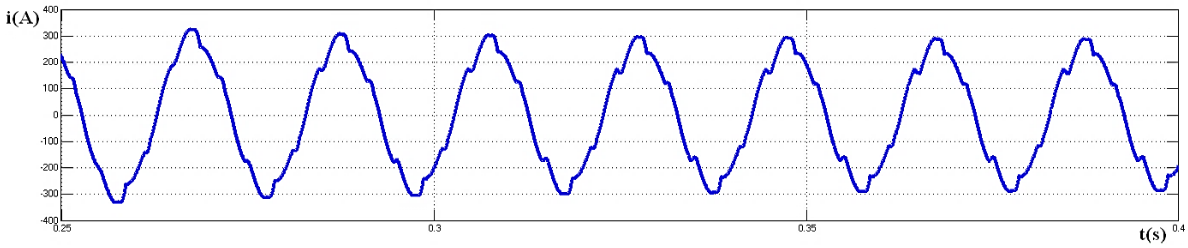

Figure 11. The bus 4 current by selective compensation (k=6)

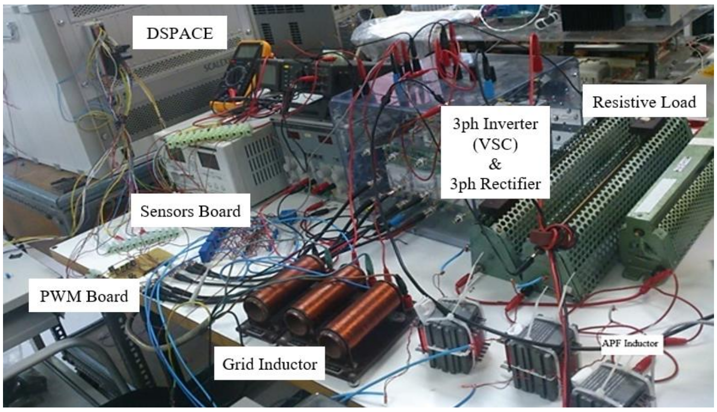

Figure 12. The experimental setup

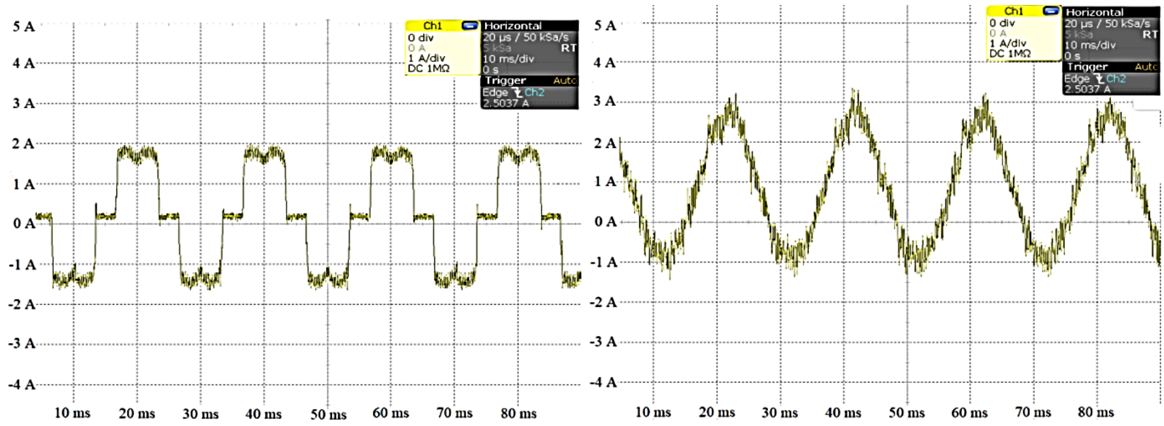

Figure 13. The current wave form before and after the selective compensation

5. CONCLUSION

In this paper, a cooperative harmonic filtering strategy throughout a grid-connected microgrid equipped with converter-based DGs is presented. A current selective harmonic method by installation and utilization of parallel active power filter is proposed. the power quality of the microgrid is improved by using proposed harmonic order method in the APF. Within the proposed controlling strategy, the number of used for the APF is reduced compared to traditional methods The proposed controlling approach is employed in a MG with the capability of decreasing the current THD. The performance of the proposed APF is evaluated by several simulations. According to the simulation results, with the installation of APF at the bus with the highest current THD, the harmonics is significantly reduced in all buses, especially in the bus where the APF is installed. Also, the efficacy of the proposed method was tested on an experimental setup. The practical results also confirmed the effectiveness of the proposed controller. The current THD has been significantly decreased after installing the proposed APF.

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BIOGRAPHIES OF AUTHORS

Mohammad Firoozian was born Sari, Mazandaran, Iran, in 1977. He received the Bachelor of Science (B.Sc.) degree from the Electrical Engineering Department, Mazandaran university, Babol, Iran, in 2000, and the Master of Science (M.Sc.) degree from the Electrical Engineering Department, Tehran Polytechnic, Tehran, Iran, in 2003, the Doctor of Philosophy (Ph.D.) degree in power system from the Department Electrical Engineering, Islamic Azad University, Tehran Science and Research Branch, Iran. He is currently a teacher with the Electrical Engineering Department, Islamic Azad University. His research interests include power system management, power quality improvement, energy Saving. He can be contacted at email: mohammadfirozian1@gmail.com.

Seyed Hossain Hosseinian was born Borujerd, Lorestan, Iran, in 1961. He received the Master of Science (M.Sc.) degree from the Electrical Engineering Department, Tehran Polytechnic, Tehran, Iran, in 1988, and the Doctor of Philosophy (Ph.D.) degree in power system from the Department Electrical Engineering, University of Newcastle, Newcastle upon Tyne, U.K. He is currently a Full Professor with the Electrical Engineering Department, Amirkabir University of Technology. His research interests include power system management, power quality improvement, energy pricing, frequency control and resilience improvement of microgrids, and deregulation in power systems. He can be contacted at email: hosseinian@aut.ac.ir.

Mehrdad Abedi was born in Tehran, Iran. He graduated from the University of Tehran with a degree in electrical engineering In 1970, he received an MS degree from Imperial College London in 1973 and a Ph.D from Newcastle University, both in electrical engineering with a specialty in electric machinery and power engineering. After graduation, he worked at General Electric Company plc as a researcher for one year and then returned to Tehran and began his work at Amirkabir University of Technology as an instructor. He is principally known as the author of some textbooks for undergraduate electrical engineering students (in Persian). He can be contacted at email: abedi@aut.ac.ir.