Autonomous Harmonic Compensation in a Multi-Bus Micro-Grid Interfacing Converters through Fuzzy Logic Control

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Abstract
This paper proposes a novel approach to compensate buses voltage and current harmonics through distributed generation (DG) interfacing converter in a multi-bus micro-grid. The control approach of each individual DG unit was designed to use only feedback variables of the converter itself that can be measured locally. In the proposed approach, the adjacent bus voltage is indirectly derived from the measured DG converter output voltage, DG line current and line impedance. A closed-loop fuzzy controller is designed to achieve harmonics compensation. Therefore, the traditional harmonic measurement devices such as APF's installed at the bus as well as the long distance communication between the bus and the DG converter are not required. The proposed approach can compensate the current harmonics, mitigate the buses voltage distortion and enable the customer devices to be operated in normal conditions within the multi-bus microgrid, and meanwhile relieve the burden of power quality regulator installed at the point of common coupling. Matlab simulations and experimental results are presented to show the operational effectiveness of the proposed approach.

Keywords—Multi-bus microgrid, Distributed generation, Grid-tied converter, Harmonic compensation control, Fuzzy logic control.

1.INTRODUCTION

The microgrid as a new concept has been brought about due to the development of renewable energy systems, storage devices and coordinate converter control scheme. It has been an important role in electric industry restructure due to the increasing attentions on environmental, economical, and social interests [1–4]. With the increasing penetration of DG units and rapid growth of distributed loads, the single bus microgrid to some extent cannot satisfy the demand of power supply system construction. The multi-bus microgrid consisted of several buses is a practical solution to connect the wide area distributed DG units and loads, which can realize the objective of optimizing network operation, minimizing the distribution network losses and maintaining the voltage profiles [5–7]. The proliferation of nonlinear loads in power systems has been increasing in an unprecedented pace in recent years due to the advance of power electronics technologies. As a result, the power quality issue, induced by the nonlinear loads, has become a crucial factor that may affect the normal operation of both customer devices and power systems [8, 9]. As a conventional approach, ancillary devices, such as passive filters and active power filters (APF), can be installed in the grid to overcome the distribution network harmonic problems. These ancillary devices, however, are undesirable because of their high installation costs. In the multi-bus microgrid, the DG interfacing converters can be considered as active cells for control and management purposes [10, 11]. Although the DG interfacing converters may introduce harmonics into the power network, and cause power quality issues, they are also able to improve system efficiency and power quality if designed and controlled properly. Thus, DG units have the ability to enhance the power quality as well as the reliability of microgrids. Using DG units as harmonics compensators can reduce the need for adding extra devices in multi-bus microgrids. This leads to the result that a significant growth of DG penetration in multi-bus microgrids will require new control scheme in order to exploit the power quality improvement capability of DG units. Therefore, a merging concept is to use these power electronic interfaced DG systems to simultaneously realize real power generation and harmonic compensation functions.

A shunt resistive active power filter (R-APF) control scheme based on voltage detection for the purpose of
harmonic compensation has been proposed in [12, 13]. The APF was controlled as a small virtual resistance at selected harmonic frequencies, and therefore it is possible to damp out harmonic propagation. But this control scheme is affected by the location of APF, the detection point and the network characteristics. Therefore, the value of the virtual resistance should be chosen carefully, otherwise, other buses' voltage distortion may be deteriorated. Further, a cooperative control of two APFs with communication was proposed in [14] to damp out harmonic propagation within the power distribution system, where a central controller regulates the virtual resistance value according to the voltage distortions at each APF installation position. However, the mutual communication increases the investment cost and reduces the operational reliability. In [15], the compensation approach for PCC harmonics is derived by setting the DG unit to work as an R-APF. The DG system works as a small resistance at selected harmonic frequencies. Therefore, the harmonic currents of nonlinear loads installed at the PCC can be absorbed by DG system, resulting in an improved PCC voltage and line current quality with low total harmonic distortion (THD). Nevertheless, the prerequisite of implementing this control function is that additional measurement devices, e.g. voltage and current transducers and communication channels, are required to provide the PCC distortion information since the DG units normally locate far away from PCC. Similarly, the virtual resistance should be chosen carefullyto attenuate the harmonic distortion. In [16], a harmonic impedance synthesis technique was presented for voltagecontrolled distributed generation inverters in order to damp harmonic voltage distortion in a distribution network. Negative harmonic inductances and positive harmonic resistances are synthesized at the dominant harmonic frequencies. Thus, the harmonic voltage drop on the grid-side inductance can be effectively attenuated. Nevertheless, the synthesized harmonic impedance should be designed carefully, which will affect the harmonic damping performance and the operational stability. Also in [17], a selective

virtual impedance loop is considered to improve the sharing accuracy of load harmonic currents among the DG units, which however needs low-bandwidth data communication signals among individual distributed generation systems. Unfortunately, the communication among DG units will increase the system complexity and reduce the operational reliability in a multi-bus microgrid.
In order to improve the power quality regulation capability and operational reliability of wide area distributed multi-bus microgrids, this paper proposes a novel approach to compensate bus voltage and current harmonics, which only requires the local information of DG units, i.e., the converter output voltage and current. The proposed controller has a cascaded structure, whose outer loop voltage controller regulates the distorted bus voltage without using the directly measured bus information and the accompaniedlong distance communication. An inner loop harmonic current compensator regulates the current harmonics. This control scheme enables the DG unit to absorb the harmonic currents introduced by the nonlinear loads, so that the current quality injected into the main bus is improved, and the sub-bus voltage distortion can be mitigated. Therefore, the burden of the power quality regulator installed at per level bus is relieved. The detailed illustration of the proposed control scheme will be elaborated in the following Sections. Matlab simulations and experimental prototype have verified the performance of the proposed power quality control approach in a multi-bus microgrid.

2.GENERAL ILLUSTRATION OF POWER QUALITY IN A MULTIBUS MICROGRID

The single-line diagram of a general multi-bus microgrid is shown in Fig. 1 as an example for illustration. Themulti-bus microgrid comprises one 10 kV bus, two 380 V buses and three feeders. Two 380 V buses are connected to the 10 kV bus through step-up transformers. Three combinations of linear and nonlinear loads are supplied by themulti-bus microgrid. Two DG units are equipped with a grid-interfacing converter and a hybrid energy resource which contains energy sources and energy storage system. Each DG unit is able to supply any amount of real powerwithin the pre-specified limits. ZLinen (n = 1,2,…, i) represents the line impedance which cannot be neglected in themulti-bus microgrid. As shown in Fig. 1,

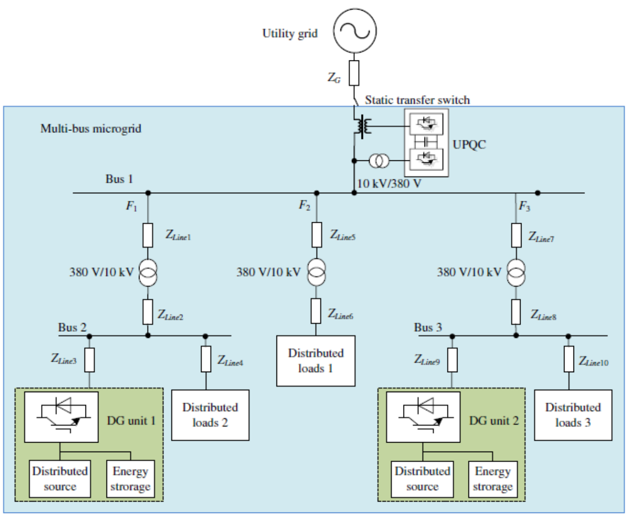

Fig. 1 General illustration of a multi-bus microgrid with power electronics interfaced DG systems

a static switch is inserted between the utility grid and the multi-bus microgrid to connect/disconnect the multi-bus microgrid during the online/offline operation. With the increasing applications of nonlinear loads, the power quality of the multi-bus microgrid would be significantly deteriorated due to the harmonics propagation. A unified power quality conditioner (UPQC) can be installed at the main bus to compensate harmonics. However, the complex structure of the multi-bus microgrid increases the difficulty of harmonics compensation. For example, the UPQC installed at Bus 1 as shown in Fig. 1 can improve the current and voltage quality of Bus 1, however, it cannot restraint the harmonic propagation within the multi-bus microgrid and guarantee the power quality of sub-buses (e.g. Bus 2 and Bus 3), which directly supply the distributed loads. With the harmonic current flowing in the multi-bus microgrid, the voltage of sub buses will be distorted due to the voltage drop on the line impedance. The distorted bus voltage will seriously affect the normal operation of distributed loads.

In order to illustrate the harmonic propagation within the microgrid, a two-bus network interconnected through an

isolation transformer is shown in Fig. 2 as a simple example. The DG unit and distributed loads are connectedto the sub-bus, and a diode rectifier with an RC load is considered as the nonlinear load to produce harmonic currents. For the conventional control method, the DG unit is controlled to generate real power and its output current iDG injected to the sub-bus is sinusoidal, as shown in Fig. 2a. Hence, the harmonic currents introduced by the nonlinear load mainly flow to the main bus due to the lower impedance of the utility grid. The harmonic propagation within the multi-bus network will unavoidably generate the voltage harmonics as expressed below:

$$\dot{V}_{Line} = Z_{Line\_h} \cdot \dot{I}_h \tag{1}$$

where _VLine is the harmonic voltage matrix; I_h is the harmonic current matrix and ZLine_h is the corresponding order harmonic impedance matrix, respectively. The harmonic voltage will lead to the sub-bus voltage distortion within the multi-bus microgrid. When the main bus is connected to many sub-buses with distributed nonlinear loads, as shown in Fig. 1, the current flowing to the utility grid is the sum of currents flowing from the sub-buses to the main bus, which can be expressed as:

$$i_G = \sum_{k=1}^{m} i_k \tag{2}$$

whereik is the current flowing from kth sub-bus to the main bus and m is the total number of sub-buses. Due to the nonlinear loads, the currents flowing to the main bus contain harmonics, and (2) can be rewritten as:

$$i_G = \sum_{h=1}^{n} i_{Gh} = \sum_{k=1}^{m} \sum_{h=1}^{n} i_{kh} \tag{3}$$

whereikh is the hth order component of the current flowing from kth sub-bus to the main bus. The total harmonic distortion of the current injected to the utility grid from the multi-bus microgrid can be expressed as:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{n} I_{Gh^2}}}{I_{G1}} \times 100\% \tag{4}$$

where IG1 and IGh are the rms values of the fundamental and hth harmonic components of the current injected to theutility grid, respectively. When the multi-bus microgrid contains many nonlinear loads, the harmonics propagation will lead to serious power quality problems within the multi-bus microgrid. Meanwhile, the harmonic currents flowing to the utility grid will aggravate the

THD of the grid current. In other words, the main bus handles all burdens of the harmonic currents introduced by the distributed nonlinear loads. This will increase the burden of the UPQC installed at the main bus. In contrast, the current iDG can be controlled to contain harmonics according to the distortion information of the bus voltage, and the DG unit can absorb the harmonic currents introduced by the nonlinear load as shown in Fig. 2b. Therefore, this can help compensate the harmonic currents flowing from the sub-bus to the main bus by dispatching the harmonic currents introduced by the nonlinear load. With the decreasing distortion of the current flowing to the main bus, the voltage quality of sub buses will be improved, and the burden of the harmonic compensation devices installed at the main bus can be relieved. This will benefit the customer devices, the multi-bus microgrid and the utility grid simultaneously.However, a reliable approach to acquire the information of voltage and current harmonics at any level buses is not straightforward. The communication between the bus and the DG will reduce the operational reliability of the whole system and increase investment to guarantee the bandwidth of communication channels. Especially, relying on communication is not practical when the communication distance is long. This paper thus proposes a new method to indirectly acquire the distortion information of the bus voltage without communication, and the DG units could accurately` compensate current harmonics. The details will be presented in the next Section.

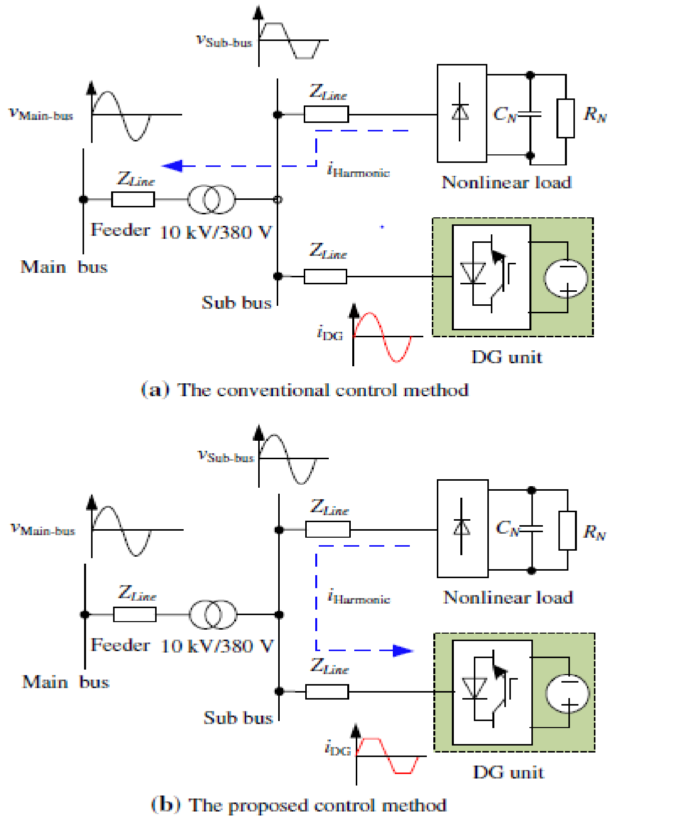

Fig. 2 Comparison of harmonic currents flow

3.Proposed control principle

In order to illustrate the control principle, a two-bus network is derived from Fig. 1. In specific, the configuration of two buses network and its control block diagram are shown in Fig. 3.It can be seen that Bus 2 is connected to Bus 1 through a step-up transformer. The DG unit 1 and the distributed loads 2 composed of linear and nonlinear loadsare connected to Bus 2. The nonlinear load represented by a rectifier circuit with an RC load could introduce currentharmonics.The DG unit 1 connects to Bus 2 through a distribution line represented by ZLine3.

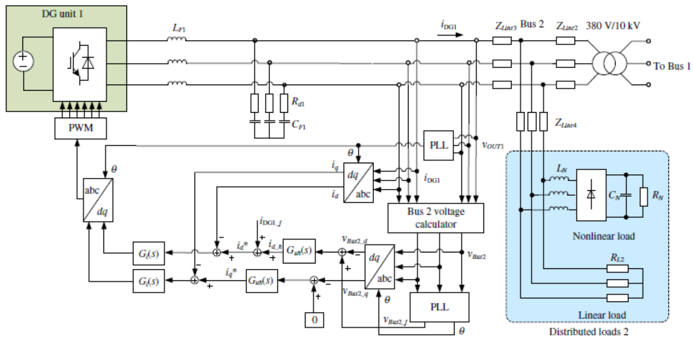

Fig. 3 Overall illustration of the circuit configuration and control diagram

When properlycontrolled, the DG unit can compensate the harmonic currents, and in consequence, improve the voltage qualityof Bus 2, as shown in Fig. 2b. The main control blocks include bus voltage calculation, phase locked loop (PLL)and cascaded voltage and current controller, which will be next illustrated in detail.

3.1 Bus voltage calculation

It should be noted that the proposed control scheme is to deal with power quality issues in a multi-bus microgrid,where the DG converter is installed far away from the ac bus. To well illustrate this scenario, a single line representation is drawn in Fig. 4, where ZLine3 represents the impedance between DG unit 1 and its adjacent Bus 2,whose value can be easily obtained by calculating the known cable or line parameters. In practice, the DG unitsand distributed loads will at times locate far apart, and then the line impedance cannot be neglected. As a result, theharmonic propagation in the multi-bus microgrid will lead to the Bus 2 voltage distortion, which is definitely
unwanted for both loads supplied by Bus 2 and the multibusmicrogrid. Compared with the traditional control scheme that directly measures the Bus 2 voltage and delivers the distortion information to the DG units via acommunication system, the proposed approach indirectly obtain the Bus 2 voltage by only measuring the DG unit 1line current injected into the ac bus and the converter output voltage. The Bus 2 voltage depicted in Fig. 4 can then be calculated as:

$$\begin{bmatrix} \dot{V}_{Bus2\_1} \\ \dot{V}_{Bus2\_5} \\ \dot{V}_{Bus2\_7} \\ \vdots \\ \dot{V}_{Bus2\_n} \end{bmatrix} = \begin{bmatrix} \dot{V}_{DG1\_1} \\ \dot{V}_{DG1\_5} \\ \dot{V}_{DG1\_7} \\ \vdots \\ \dot{V}_{DG1\_n} \end{bmatrix} - \begin{bmatrix} Z_{Line3\_1} & 0 & 0 & \cdots & 0 \\ 0 & Z_{Line3\_5} & 0 & \cdots & 0 \\ 0 & 0 & Z_{Line3\_7} & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 0 & 0 & 0 & \cdots & Z_{Line3\_n} \end{bmatrix} \times \begin{bmatrix} \dot{I}_{DG1\_1} \\ \dot{I}_{DG1\_5} \\ \dot{I}_{DG1\_7} \\ \vdots \\ \dot{I}_{DG1\_n} \end{bmatrix} \quad (5)$$

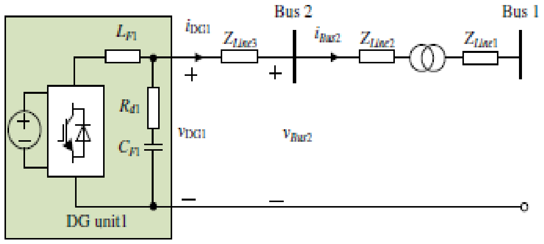

Fig. 4 Single-line illustration of the DG system in the multi-bus microgrid

where _VBus2 is the Bus 2 voltage vector; _VDG1 is the converter output voltage vector; ZLine3 is the line impedancevector; I_DG1 is the output current vector of DG unit 1; n isvthe highest harmonic order, respectively. The information of line impedance between the DG and the Bus can be obtained through the following methods.The first one is that the line information can be obtained from the power network design and construction parameters. The line impedance value is generally designed in accordance with the requirement of microgrid stability and the requirement of power sharing. The parameters of the line impedance can be relatively accurate. Other methods discussed in literature [18–20], inject a perturbation into the grid and then measure the PCC voltage and current to analyze and calculate line impedance at each frequency, these methods can accurately and rapidly measure the line impedance at each frequency, and it is suitable for the applications which need to measure harmonic impedance rapidly. For instance, the real resistance and inductance of feeder in [20] are 1 X and 6.1 mH, meanwhile, the measured values are 1.05 X and 6.01 mH. The measurement error is below 5%. It can be seen that the estimated values are very close to the real values of the feeder impedance. Further discussion on detailed line impedance estimation schemes is out of the scope of this paper. It is noted that both voltage and current are the sum of weighted fundamental and harmonic components. Hence, the Bus 2 voltage can be rewritten as (6).

$$v_{Bus2} = \sum_{h=1}^{n} v_{Bus2\_h} \qquad (6)$$

where h = 1,2,…,n, represents the harmonic order. The Bus 2 voltage calculated by (6) will be next used for PLL calculation as shown in Fig. 5.

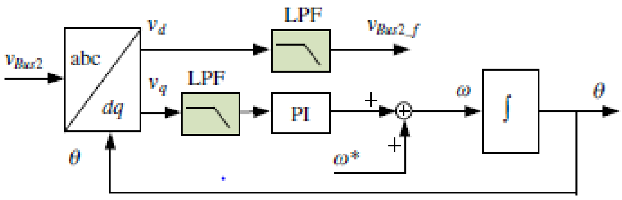

Fig. 5 Block diagram of the SRF-PLL

3.2 Phase locked loop

In the proposed approach, the voltage and current controller are designed in the rotating dq reference frame. Theestimation of ac voltage parameters, such as voltage amplitude and phase angle, will act as a crucial role in theoverall performance of the synchronization algorithm. With a low pass filter used to eliminate the harmonics, a synchronous reference frame phase locked loop (SRF-PLL)[21–23] as shown in Fig. 5 is used in the proposed controlstrategy. In spite of the good behavior of the SRF-PLLunder sinusoidal conditions, its performance is deterioratedwhen the three phase input signal becomes distorted. Whenthe three-phase instantaneous voltage waveforms aretransformed from the abc reference frame into the rotatingdq reference frame by means of the Park transformation[24, 25], the fundamental and (6n±1)th harmonics in theabc reference frame are represented by DC component and6nth harmonics in the rotating dq reference frame. In therotating dq reference frame, two low pass filters (LPFs)with high cutoff frequency, e.g. 150 Hz, implemented inthe control scheme can easily eliminate the 6th and higherorder harmonics to obtain the DC components of vd and vq.The LPFs have few affects to the DC components of the vdand vq. Therefore, the SRF-PLL with LPFs in the rotatingdq reference frame can provide a good performance of thephase angle and magnitude estimation under distortedcondition. In the rotating dq reference frame, the DCcomponent of the vd represents the amplitude of the fundamentalcomponent of Bus 2 voltage, which is subsequentlyset as the voltage reference in the nextsubsection. A feedback control loop is used to control theangular position by forcing the vq component to be zero. Asdepicted in Fig. 5, the estimated grid frequency is x. As afeed forward signal, the nominal angular frequency isconventionally adopted to improve the dynamics of thephase estimation h derived by integrating x.

3.3 Control scheme based on bus voltage calculation

After obtaining the phase angle of Bus 2 voltage from the SRF-PLL, the three-phase instantaneous Bus 2 voltage
calculated in the above subsection can be transformed from the abc reference frame into the rotating dq reference frame by means of the Park transformation. The d- and q-axis components of Bus 2 voltage should be incorporated into a voltage control loop to achieve proper harmonic voltage tracking performance as depicted in Fig. 3. In order to provide voltage harmonic compensation, the d-axis voltage component should be subtracted from the amplitude of fundamental voltage derived from the SRF-PLL and the q- axis voltage reference should be set to zero simply, as
illustrated in (7).

$$\begin{cases} v_{Bus2\_h\_d} = v_{Bus2\_d} - v_{Bus2\_f} \\ v_{Bus2\_h\_q} = v_{Bus2\_q} - 0 \end{cases} \quad (7)$$

where vBus2_h_d and vBus2_h_q are the d- and q-axis harmonic components of the Bus 2 voltage; vBus2_d and vBus2_qare the measured d- and q-axis components of the Bus 2 voltage and vBus2_f is the amplitude of the fundamentalcomponent of Bus 2 voltage, respectively. The voltage control loop uses a proportional controller plus multiple paralleled resonant controllers to achieve proper harmonic voltage tracking performance as expressed in (8).

$$G_{uh}(s) = K_{up} + \sum_{n=1}^{k} \frac{K_{uh}s}{s^2 + (6n\omega_0)^2} \quad (8)$$

whereKup is the proportional gain; k is the highest harmonics order selected for compensation; Kuh is the resonant
gain and x0 is the nominal angular frequency, respectively. It should be noted that the resonant controller in the synchronous reference frame is more effective than that in the stationary frame, since it represents two equivalent resonant terms in the stationary frame for compensating two adjacent odd harmonics [26–28].

Similarly, the three-phase instantaneous DG line current injected to Bus 2 can also be transformed from the abcreference frame into the rotating dq reference frame. The current reference can be obtained by combining the harmonic current reference and the fundamental current reference as illustrated in (9).

$$i_{\mathrm{DG1\_}ref} = i_{\mathrm{DG1\_}f} + i_h \qquad (9)$$

where iDG1_ref is the current reference; iDG1_f is the fundamental current command and ih is the currentharmonics reference to compensate. From (7), (8) and (9), the current reference iDG1_ref can be derived as:

$$i_{\mathrm{DG1\_}ref}(s) = i_{\mathrm{DG1\_}f}(s) + G_{uh}(s) v_{Bus2\_h}(s) \qquad (10)$$

For the inner current control loop, a proportional integral (PI) controller plus multiple paralleled resonant controllers as shown in Fig. 3 are used in the synchronous dq frame in order to force the DG line current to track the reference [29, 30], as expressed in (11).

$$G_i(s) = K_{pi}\left(1+\frac{1}{T_i s}\right) + \sum_{n=1}^{k} \frac{K_{ih} s}{s^2 + (6n\omega_0)^2} \qquad (11)$$

whereKpiis the proportional gain; Ti is the integral time constant; Kihis the resonant gain and x0 is the nominal angular frequency, respectively.

4 ANALYSIS OF HARMONIC COMPENSATION CAPABILITY IN A MULTI-BUS MICROGRID

In order to briefly illustrate the compensation capability of the proposed control method in a multi-bus microgrid, a comparison for three different scenarios is presented below. In detail, for the first scenario, the multibusmicrogrid only has one UPQC installed at the main bus to compensate harmonics. For the second scenario, additional APFs are installed at all sub-bus to compensate the current harmonics raised by the local nonlinear loads. For the third scenario, the distributed converters could perform as the active power filters to compensate the current harmonics by using the proposed method in this paper, while eliminating the APF installed at each subbus. For clear illustration, this section assumes that there are only 5th and 7th harmonic currents in the multi-bus microgrid as shown in Fig. 1, where, the 5th harmonic currents introduced by the distributed loads 1 to 3 are 0.02, 0.02 and 0.01 in per unit, and the 7th harmonic currents introduced by the distributed loads 1 to 3 are 0.01, 0.01 and 0.005 in per unit, respectively. In the first scenario, the DGs are controlled to inject real power, and only the UPQC installed at the main bus can compensate the harmonics introduced by all nonlinear loads. The maximum rms value of APF part compensation current can be calculated as:

$$\begin{aligned} I_{\mathrm{APF\_max}} &= \sqrt{\sum_{h=2}^{n} (I_{\mathrm{APF\_}h\mathrm{\_max}})^2} = \sqrt{\sum_{h=2}^{n}\left(\sum_{k=1}^{m} I_{kh}\right)^2} \\ &= 0.0557(\mathrm{p.u.}) \end{aligned} \qquad (12)$$

whereIkh is the rms value of hth harmonic current introduced by the kth distributed load; m is the total number ofdistributed loads and n is the highest harmonics order, respectively. In this scenario, the APF part of UPQC canguarantee the quality of current injected into the utility grid and the main bus voltage. However, it cannot attenuate the harmonic propagation within the multi-bus microgrid and guarantee the power quality of sub-buses. In order to improve the power quality within the multibusmicrogrid, the second scenario can be assumed, where the additional APF0 and APF00 are installed at Bus 2 and Bus 3, respectively. In this scenario, APF0 and APF00 compensate the harmonics introduced by the distributed loads connected to Bus 2 and Bus 3, respectively. The maximum rms value of APF0 and APF00 compensation current can respectively be calculated as:

$$\begin{cases} I_{\mathrm{APF'}\_\max} = \sqrt{\sum_{h=2}^{n} \left(I_{\mathrm{APF'}\_h}\right)^2} = 0.0224\,(\mathrm{p.u.}) \\ I_{\mathrm{APF''}\_\max} = \sqrt{\sum_{h=2}^{n} \left(I_{\mathrm{APF''}\_h}\right)^2} = 0.0112\,(\mathrm{p.u.}) \end{cases} \qquad (13)$$

Because of the compensation capability of APF0 and APF00, the APF part of the UPQC at the main bus only needs to compensate the current harmonics introduced by the distributed load 1, and the maximum rms value of APFpart compensation current reduces to 0.0224 p.u.. Compared to the first scenario, the power quality within the multi-bus microgrid can be significantly improved and the burden of the APF part is relieved. However, this scenario needs additional APF installed at each sub-bus, which would definitely increase the installation investment.

In the last scenario, the DGs are controlled to realize real power generation and harmonic compensation functions.

Being different from the above two scenarios, DG 1 and DG 2 are controlled to absorb the current harmonicsintroduced by the distributed loads. Therefore, they can perform like APF0 and APF00 to compensate the currentharmonics at Bus 2 and Bus 3. The maximum rms value of APF part compensation current is the same as the secondscenario. Therefore, the last scenario can guarantee the power quality within the multi-bus as well but reduce theinvestment for additional power quality devices. The comparison among these three scenarios is summarized inTable 1.

Table 1 Comparison of compensation capability of three scenarios

Scenario	APF capacity			Compensation performance		
	APF part of UPQC (p.u.)	APF′ (p.u.)	APF″ (p.u.)	Bus 1	Bus 2	Bus 3
1	0.0559	No	No	Well compensated	N.A.	N.A
2	0.0224	0.0224	0.0112	Well compensated	Well compensated	Well compensated
3	0.0224	No	No	Well compensated	Well compensated	Well compensated

When the grid voltage is distorted, a UPQC installed at the main bus can help guarantee the microgrid powerquality. The dynamic voltage restorer (DVR) part is used to compensate the harmonic voltages of the main bus voltage. Meanwhile, the APF part is used to compensate the harmonic currents injected to the grid. Doing so, the proposed control scheme can provide a good performance under the distorted gird voltage condition. In microgrid, the line impedance can be classified into three categories: resistive impedance, inductive impedance and capacitive impedance, respectively. In the proposed control scheme, the calculation accuracy of bus voltage and the harmonic compensation performance are not affected by the impedance type. However, the large error betweenthe real line impedance value and estimated value will affect the accuracy of the harmonic voltage calculation,and the complete compensation cannot be achieved. But when considering the closed control loop can achieveproper fundamental and harmonic current tracking performance and the estimated values are very close to the realvalues of the feeder impedance [18–

20], the proposed harmonic compensation scheme can still significantly improve the power quality of the microgrid.

5 SIMULATION AND EXPERIMENTAL VERIFICATIONS

To verify the performance of the proposed power quality control approach in a multi-bus microgrid, Matlab simulations were first conducted according to the configuration of multi-bus microgrid shown in Fig. 1. The detailed circuit and control parameters of the simulated multi-bus microgrid are listed in Table A1.

It can be seen that the bus voltage and bus current injected into the main bus are severely distorted because ofthe large current harmonics induced by the nonlinear load and the non-negligible line impedance. As a result, the THD of main bus current found to be 5.36%.

In contrast, when the harmonic compensation function is implemented, the DG will simultaneously inject real power to the microgrid and absorb most of the harmonics introduced by the nonlinear load. The corresponding experimental results are shown in Fig. 7. It can be seen that the power quality of both bus voltage and bus current are improved significantly, and the THD of main bus current is now reduced to 0.31%.

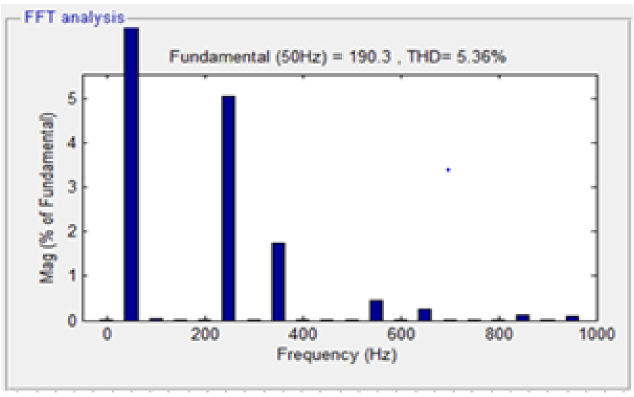

Fig.6 THD without compensation

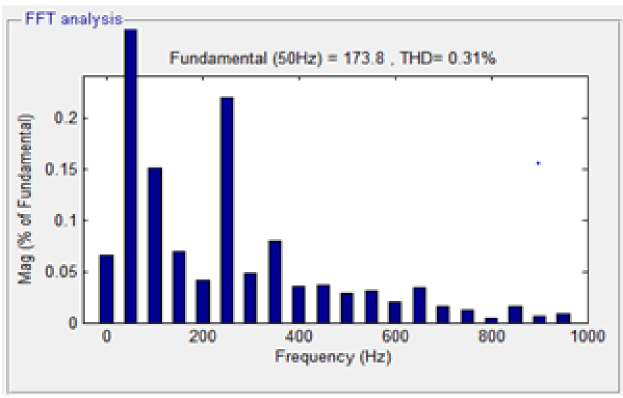

Fig.7 THD with compensation

6.CONCLUSION

This paper has proposed a novel control approach of DG interfacing converter for harmonic compensation in amulti-bus microgrid. The proposed control approach can simultaneously enable

the DG units to deliver real powerinto the multi-bus microgrid and compensate the harmonics appeared in the bus voltages and currents introduced by
nonlinear loads within the multi-bus microgrid without communication. It only requires local information of theDG unit, such as the converter output voltage and current and the line impedance, to derive the distortion information of its adjacent bus. As a consequence, the traditional measurement devices installed at the bus as well as the long distance communication between the bus and the converter can be eliminated. An outer voltage control loop and an inner current control loop are designed to guarantee the DGreal power generation and harmonics compensation functions. The proposed approach is suitable for a multi-busmicrogrid since the DG units can compensate the current harmonics, mitigate the buses voltage distortion, andensure the customer devices in normal operations within the multi-bus microgrid, while significantly relieve theburden of the power quality regulators installed at the PCC. Matlab simulations and experimental verifications arepresented to show the performance of the proposed control approach.

Table A1 Parameters of the multi-bus microgrid in simulations

Elements	Parameters	Values
Utility power grid	Grid voltage V_G	10 kV
	Grid frequency f_G	50 Hz
	Grid resistance Z_G	0.2+j0.31 Ω
DG converter	Switching frequency f_s	12.5 kHz
	Dead time	1 μs
	DC link voltage	700 V
LC filter	Inductor L_{F1}, L_{F2}	5 mH
	Capacitor C_{F1}, C_{F2}	1 μF
	Damping resistance R_{d1}, R_{d2}	30 Ω
Line impedance	Z_{Line1}	1.08+j1.34 Ω
	Z_{Line2}	0.5+j0.31 Ω
	Z_{Line3}	0.2+j0.31 Ω
	Z_{Line4}	1+j0.63 Ω
	Z_{Line5}	0.81+j1.01 Ω
	Z_{Line6}	1+j0.63 Ω
	Z_{Line7}	0.54+j0.67 Ω
	Z_{Line8}	0.5+j0.31 Ω
	Z_{Line9}	0.2+j0.31 Ω
	Z_{Line10}	1+j0.63 Ω
Three phase nonlinear loads	Three-phase diode rectifier	–
	AC smoothing inductor L_N	2 mH
	DC load capacitor C_N	550 μF
	DC nominal load R_N	50 Ω
Three phase linear loads	P_{Load1}	3 kW
	P_{Load2}	1.5 kW
	P_{Load3}	3 kW

Table A2 Parameters used in experiments

Elements	Parameters	Values
AC power grid	Grid voltage V_G	110 V
	Grid frequency f_G	50 Hz
	Grid resistance R_G	0.02 Ω
	Grid inductor L_G	2 mH
DG converter	Switching frequency f_s	12.5 kHz
	Dead time	1 μs
	DC link voltage	400 V
LC filter	Inductor L_F	5 mH
	Capacitor C_F	1 μF
	Damping resistance R_d	30 Ω
DG line impedance	Resistance R_L	0.01 Ω
	Inductor L_L	1 mH
Liner load	Real power P	1.2 kW
Nonlinear load	Three-phase diode rectifier	–
	AC smoothing inductor L_N	2 mH
	DC load capacitor C_N	550 μF
	DC nominal load R_N	50 Ω

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