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Power Compensation with Bi-directional Inverter in DC-Micro Grid Applications

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Abstract : *This paper presents a single-phase bi-directional inverter with dc-bus voltage regulation and power compensation in dc-microgrid applications. In dc-microgrid applications, a power distribution system requires a bi-directional inverter to control the power flow between dc bus and ac grid, and to regulate the dc bus to a certain range of voltages, in which dc load may change abruptly. This will result in high dc-bus voltage variation. In this paper, we take into account this variation and propose an on-line regulation mechanism according to the inductor current levels to balance power flow and enhance the dynamic performance. Additionally, for power compensation and islanding protection, the bi- directional inverter can shift its current commands according to the specified power factor at ac grid side. Simulated and Experimental results obtained from a 5 kW single-phase bi-directional inverter have verified the analysis and discussion.*

Keywords - *Bi-directional Inverter, DC-Bus, DC-Micro grid Applications*

I. INTRODUCTION

A dc-microgrid power distribution system combining renewable distributed generators (DG) with utility grid to supply power more efficiently has attracted a lot of attention. In dc-microgrid applications, a bi-directional inverter has to fulfill real power injection (sell power or grid connection) and rectification (buy power) with power factor correction (PFC) to regulate the dc bus within a certain range of 380 20 V [1],[2]Additionally, utility companies require reactive power compensation from the DG systems. The systems need to achieve the specified power factor. The overall system configuration is shown in Fig. 1.

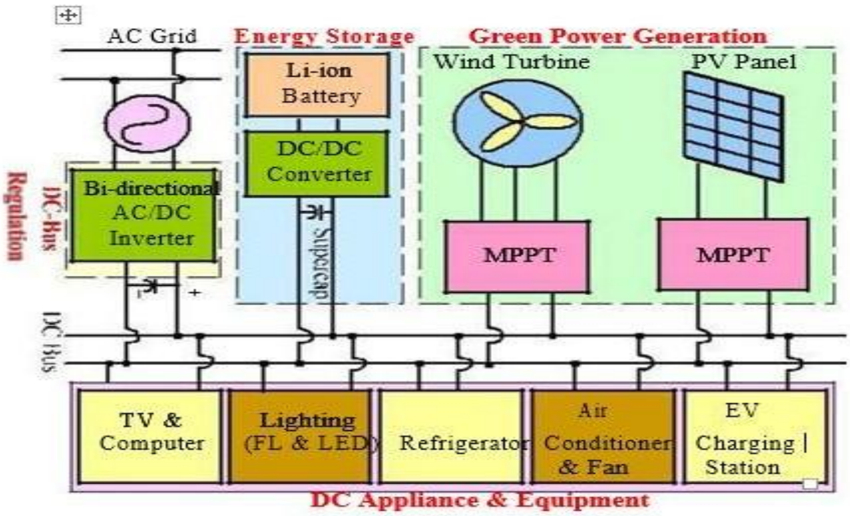


Fig. 1. Configuration of a dc-microgrid application system.

For regulating the dc-bus voltage of a dc-microgrid system, the bi-directional inverter must operate in either grid-connection mode or rectification mode. In literature, a robust dc-bus voltage control scheme with a window average

and an adaptive PI-like fuzzy logic controller [4] for regulating a constant dc-bus voltage were proposed. However, a heavy step load change will cause high dc-bus voltage variation and fluctuation, and the system might run abnormally or drop into under or over voltage protection. Bulky dc-bus capacitors can be adopted to increase the hold-up time and can suppress the fluctuation of dc-bus voltage, but it will also increase the size and the cost of a PV inverter system significantly. For reducing the dc-bus capacitor size, reference [5] uses an H-bridge in series with a bi-directional SR dc-dc converter. To operate the system more efficiently while without need of bulky dc-bus capacitors, an on-line regulation mechanism according to the inverter current levels is proposed in this paper. The bi-directional inverter can adjust its inductor current command and change its operational mode instantaneously to balance the power and tune the dc-bus voltage. It can enhance the dynamic. performance on dc-bus voltage response but induce high current harmonic components. On the other hand, the current command can be updated at the zero-crossing of every line cycle to reduce harmonic currents, while it will result in high dc-bus voltage variation. A trade off between the current harmonic components and dc-bus fluctuation are also investigated in this paper.Moreover, for meeting the requirement of reactive power compensation, the bi-directional inverter will adjust its output power factor and change the operational mode correspondingly. Experimental results from the designed 5 kW single-phase bi-directional inverter are presented to verify the analysis and discussion.

II. ANALYSIS OF THE PROPOSED PV INVERTER SYSTEM

The proposed PV inverter system is shown in Fig. 2, which can fulfill grid-connection (sell power) and rectification (bus power) modes. The inverter senses inductor current *iL*, dc-bus voltage *vdc* and line voltage *vs*, and uses the tabulated variable inductance to determine a control for operating the inverter stably. When the output power from PV panels is higher than load requirement, the dc-bus voltage increases; thus, the inverter is operated in grid-connection mode. On the other hand, the inverter is operated in rectification mode with PFC to convert ac source to replenish the dc bus. Since the load may change abruptly and cause dc-bus voltage varying beyond the operating range, it requires a regulation mechanism to control the dc-bus voltage to a certain range. In [6], [7], the control laws of grid-connection and rectification modes have been derived and are re-written as follows:

$$d_{gc} \quad \frac{i_L \cdot L_s(i_L)}{vdc \cdot Ts} \quad \frac{|vs|}{v_{dc}} \quad \text{(for grid-connection mode)} \qquad (1)$$

and

$$d_{rs} \quad \frac{iL \cdot Ls\,(iL)}{vdc \cdot Ts} \quad \frac{v_{dc} - |vs|}{v_{dc}}. \quad \text{(for rectification mode)} \qquad (2)$$

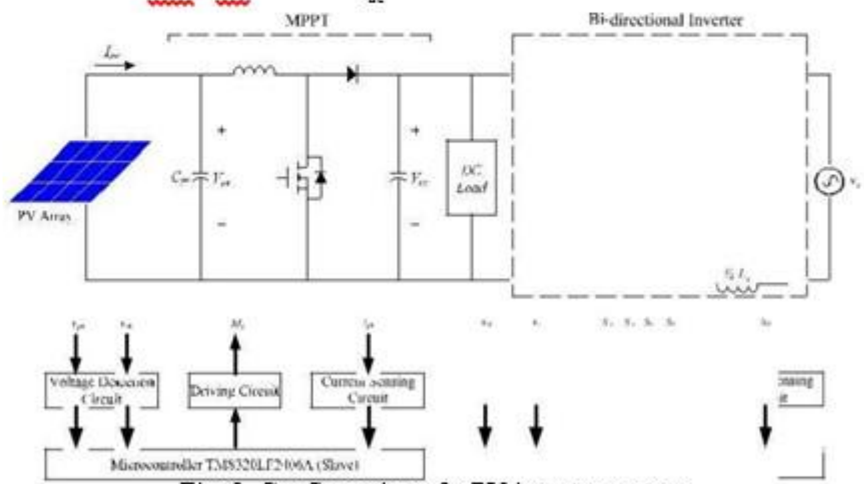


Fig. 2. Configuration of a PV inverter system.

A. DC-bus Voltage Regulation

In the proposed dc-microgrid configuration, there is a battery charging/discharging converter which can help to regulate dc-bus voltage for a short time period. In case, the battery has been fully charged, discharged or there is even no battery, the bi-directional inverter has to be responsible for dc-bus regulation. For reducing dc-bus capacitance and mode change frequency, a linear dc-bus voltage regulation mechanism is proposed, as illustrated in Fig. 3, in which the dc-bus voltage is regulated according to the inductor current linearly. When the bi-directional inverter sells higher power, which means less load power requirement, the dc-bus voltage will be regulated to a higher level. If there is a heavy step load change suddenly, this mechanism can avoid a voltage drop below 380 V abruptly and it will not change the operation mode from grid connection to rectification, or can even avoid under voltage protection. On the other hand, when the bi-directional inverter buys higher power, the dc-bus voltage is regulated to a lower level, reducing the frequency of mode change.

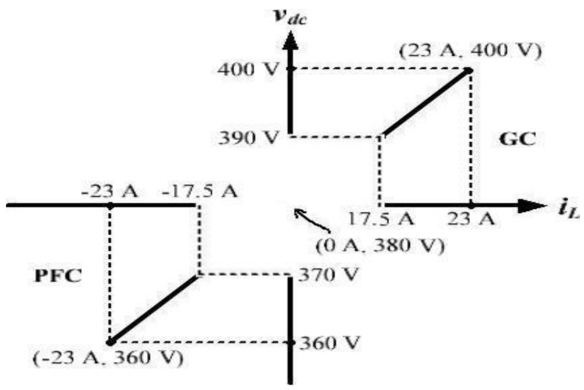


Fig. 3. Illustration of a dc-bus voltage regulation mechanism with a linear relationship between inductor current *iL* and dc-bus voltage *vdc*.

$$I \quad \frac{C_{dc}(v2 - v1)}{Tl} \; flC_{dc}(v2 - v1), \qquad (3)$$

where line frequency $f_l = 1/T_l$, C_{dc} is the dc-bus capacitance, and v_1 and v_2 are as indicated in Fig. 4. From the linear dc-bus voltage regulation relationship shown in Fig. 3, the new steady state voltage v_{set} can be obtained. Therefore, the adjustment current command I_A and steady state inductor current I_{set} can be determined. The control laws, which can adjust inductor-current command to a new set value I_{set} and can regulate the dc-bus voltage to its corresponding voltage v_{set} simultaneously, are derived as follows:

$$I_A \quad (1 \quad \frac{20V}{23A} f_l C_{dc} \quad) I_c \quad (380V - v_2) f_l C_{dc}$$
$$-[(v_2 - v_1) f_l C_{dc} \quad](1 \frac{20V}{23A} f_l C_{dc} \quad), \qquad (4)$$

$$I_{set} \quad I_c - I \quad I_c - f_l C_{dc}(v2 - v1), \qquad (5)$$

and

$$v_{set} \quad 380V \quad \frac{20V}{23A} I_{set}, \qquad (6)$$

where *Ic* is the current command given at *t1*, and *IA* is the adjustment current command given at *t2*. At *t2*, the inverter applies *IA* to control the system power flow, and the dc-bus voltage can be regulated to the corresponding voltage *vset* at next line cycle *t3* which achieves power balance on the dc side.At *t3*, the current command is changed to *Iset* and the dc-bus voltage can be regulated to *vset*, if there is no further load change. In (3) ~ (6), currents *Ic*, *IA* and *Iset* denote the average values of their full-wave rectified sinusoidal current waveforms.

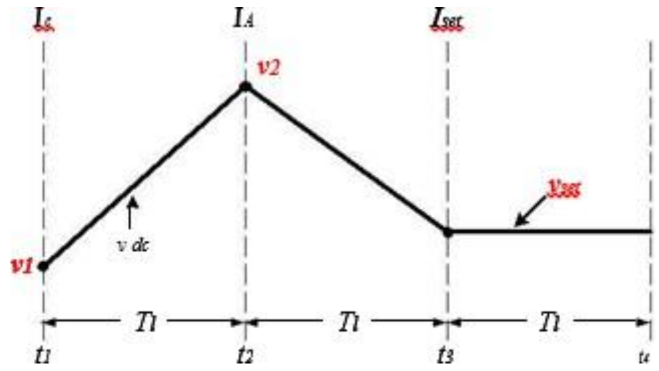


Fig. 4. Illustration of the one-line-cycle dc-bus voltage regulation mechanism for the inverter with power imbalance.

With the proposed regulation mechanism, it takes only one line cycle to adjust the dc-bus voltage to a new set point. In next iteration, current *Iset* is treated as a new *Ic* command and time *t3* is a new *t1*. However, if at *t3*, dc-bus voltage *vdc* is not close to *vset* enough (due to new power imbalance), current *IA* is treated as a new *Ic*, time *t2* is *t1* and a new *IA* can be determined at *t3* based on (4), achieving one-line-cycle regulation mechanism. Moreover, if the load changes very often over one line cycle, it will result in high dc-bus voltage fluctuation, and even cause dc-bus voltage varying beyond the operating range. Without increasing the dc-bus capacitors, this paper proposes a fast dc-bus voltage regulation mechanism, as illustrated in Fig. 5, where the bi-directional inverter might have to adjust its current command every quarter line period (*Tl/*4), as shown in Fig. 5(a), and/or change its operational mode, as shown in Fig. 5(b), instantaneously to balance the power and regulate the dc-bus voltage. The current command updated mechanism at each *Tl*/4 can be expressed as follows:

$$Ic\left(\frac{Tl}{4}\right) \quad \frac{4Cdc\, v1}{T_l} \quad Ic(0) \quad , \tag{7}$$

$$Ic\left(\frac{2Tl}{4}\right) \quad \frac{4Cdc \quad v2}{T_l} \quad Ic\left(\frac{Tl}{4}\right), \tag{8}$$

and

$$Ic\left(\frac{3Tl}{4}\right) \quad \frac{4Cdc \quad v3}{Tl} \quad Ic\left(\frac{2Tl}{4}\right), \tag{9}$$

where

$$v_1 \quad v_{dc}\left(\frac{Tl}{4}\right) - v_{dc}(0) \quad I_c(0) \cdot \frac{Tl}{8Cdc} - (vset - vdc(0)) / 4, \tag{10}$$

$$v_2 \quad vdc\left(\frac{2Tl}{4}\right) - vdc\left(\frac{Tl}{4}\right) - Ic\left(\frac{Tl}{4}\right) \cdot \frac{Tl}{8Cdc} - \left(vset - vdc\left(\frac{Tl}{4}\right)\right) / 3, \tag{11}$$

and

$$v_3 \quad vdc\left(\frac{3Tl}{4}\right) - vdc\left(\frac{2Tl}{4}\right) \quad Ic\left(\frac{2Tl}{4}\right) \cdot \frac{Tl}{8Cdc} - \left(vset - vdc\left(\frac{2Tl}{4}\right)\right) / 2. \tag{12}$$

Note that current command *Ic(0)* can be equal to either *IA* or *Iset*. For grid-connection mode, current *Ic(t)* is positive, while for rectification mode, *Ic(t)* will be negative. To reduce current distortion, the fast regulation mechanism cannot be activated too often until $v1 \geq 2V$, $v2 \geq 4V$ or $v3 \geq 6V$ in the designed 5 kW inverter Capacitance *Cdc* can vary with the dc appliances and power converters which are connected to the dc bus. In the developed dc-microgrid system, all of their bulky capacitors are removed from their power processers and installed into a box. Thus, capacitance *Cdc* can be either measured off-line or learned on-line, and substituted into (4) ~ (12) for determining *IA*, *Iset* and *Ic(kTl/4)*, where k = 0, 1, 2 and 3. Again, current *Ic(kTl/4)* denotes the average value over the time interval between *kTl*/4 and *(k+1)Tl*/4. *Ic* ($^{T}4^{l}$)

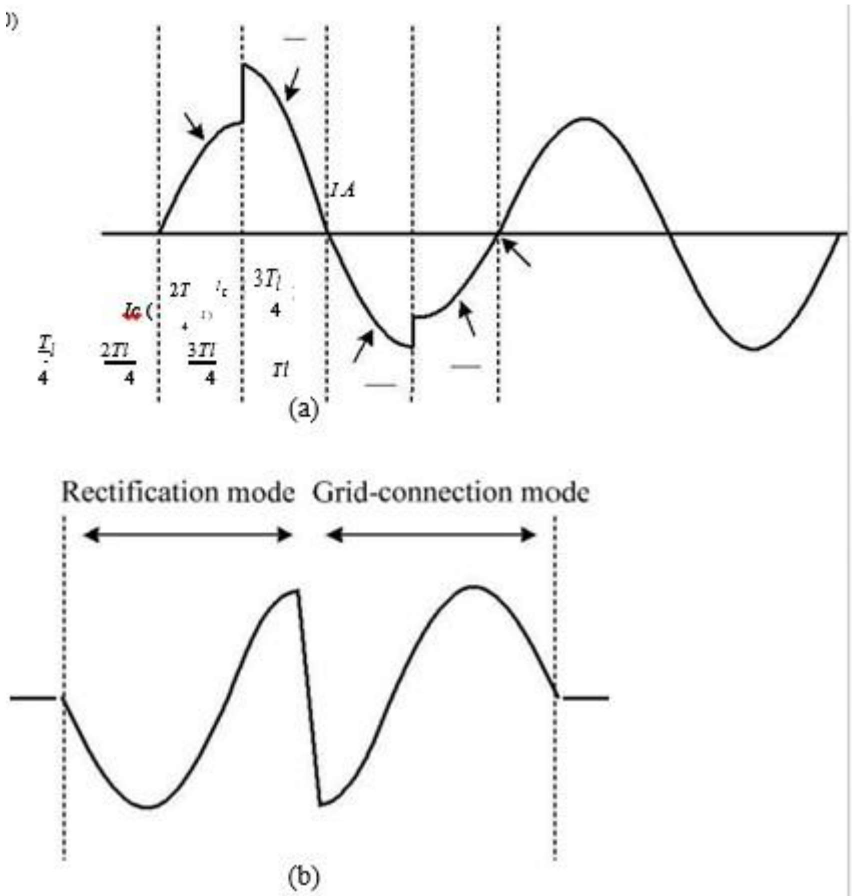


Fig. 5. Illustration of the fast dc-bus voltage regulation mechanism for the inverter operation: (a) current updated every *Tl*/4, and (b) abrupt mode change.

B. *Power Compensation*

The proposed PV inverter systems can inject real power and compensate reactive power for the ac grid simultaneously. The inverter controls the power factor according to the grid demands: real or reactive power. For power compensation, the bi-directional inverter can shift its current command according to the desired power factor at ac grid side, as shown in Figs. 6 and 7.In case the electric equipment is a capacitive load, the inverter shifts its inductor current command *iL* lagging line voltage *vs*. For a positive power (+P) injection, as indicated in Fig. 6, the inverter is operated in grid-connection mode which is divided into positive half cycle (PHC) and negative half cycle (NHC). On the other hand, it will be changed to rectification mode, including PHC and NHC, to buy power (-P) from the grid. While, if the electric equipment is an inductive load, the inverter shifts its inductor current leading line voltage, as shown in Fig. 7.

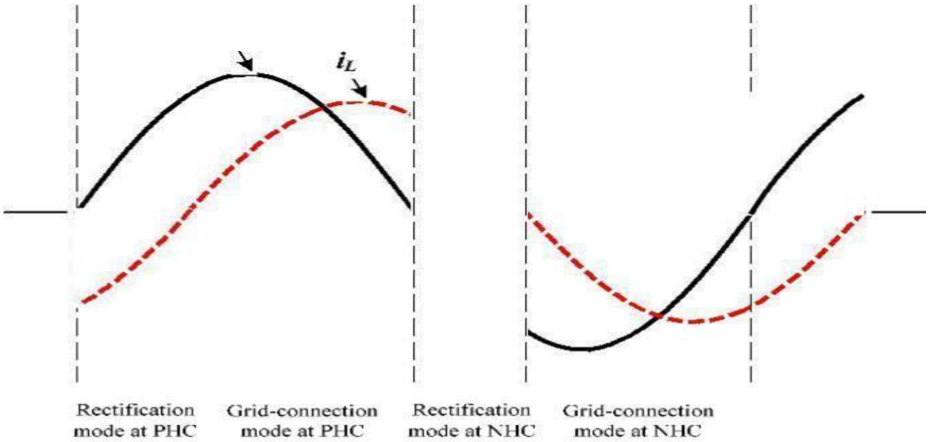


Fig. 6. Illustration of current *iL* lagging line voltage *vs* and their corresponding operational modes.

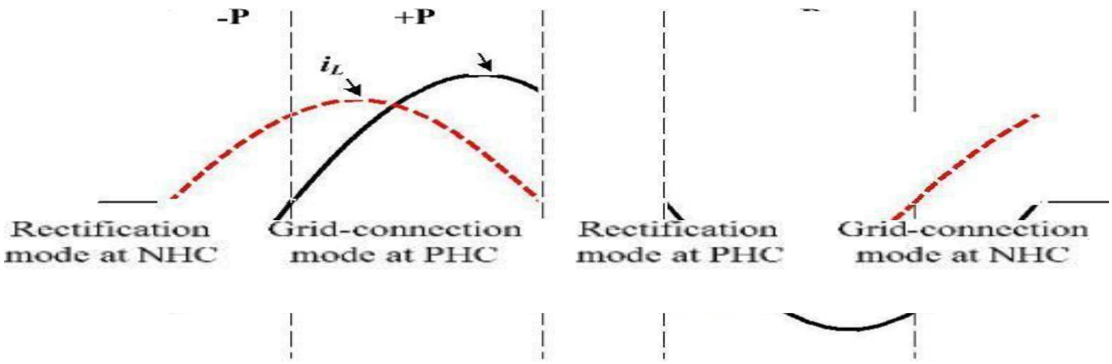
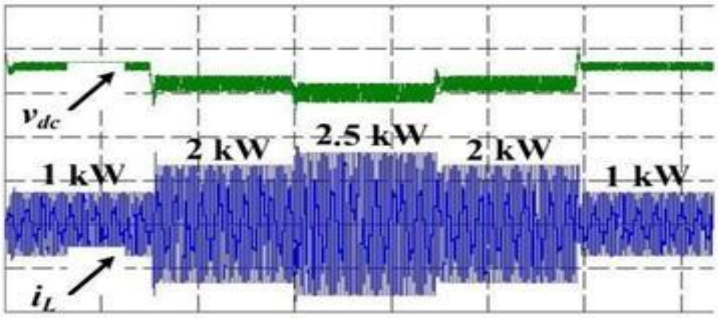


Fig. 7. Illustration of current *iL* leading line voltage *vs* and their corresponding operational modes

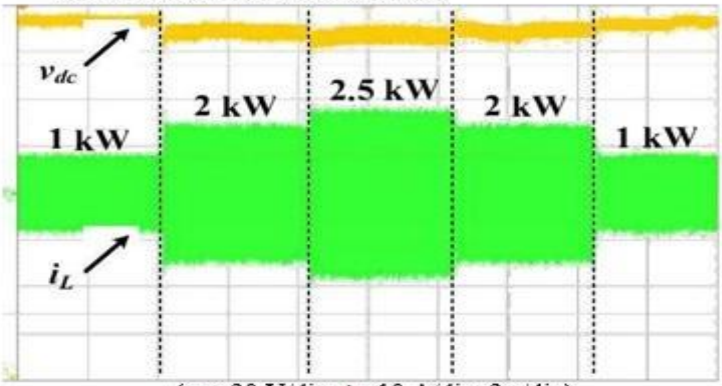
III. SIMULATION RESULTS

In this study, a 5 kW bi-directional inverter was simulated and implemented to verify its feasibility, of which the specifications and components are collected in Table 1. For dc-bus voltage regulation, Figs. 8 and 9 show the simulated and measured waveforms of dc-bus voltage and inductor current with load variation between 1 kW and 2.5 kW in rectification mode. The dc-bus voltage is adjusted to its corresponding voltage by following the *vdc-iL* linear relationship shown in Fig. 3. Figs. 10 and 11 show their expanded waveforms when the load condition varies from 1 kW to 2 kW. It can be observed that the inverter can regulate the dc-bus voltage to 372 V, which is corresponding to its current level of 8.4 A. Figs. 12~15 show the simulated and measured waveforms of dc-bus voltage and inductor current corresponding to the inverter operated in grid-connection mode.



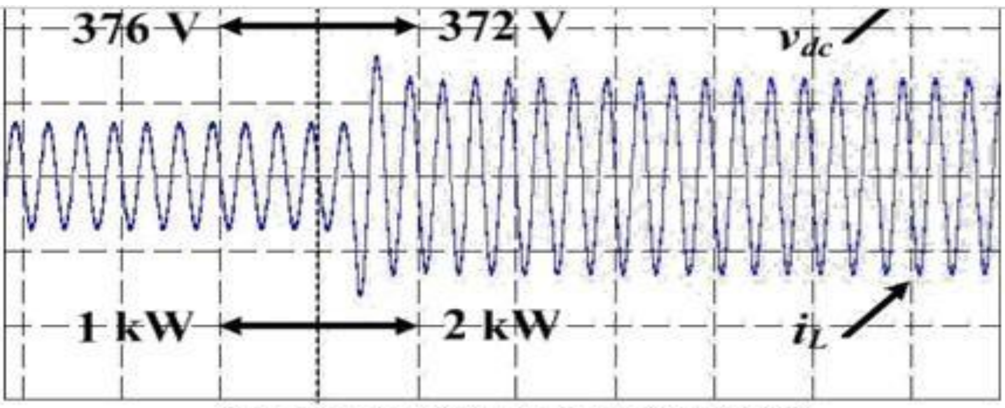
(v_{dc}: 10 V/div, i_L: 10 A/div, 0.5s/div)

g. 8. Simulated waveforms of dc-link voltage and inductor current with load variation in rectification mode.



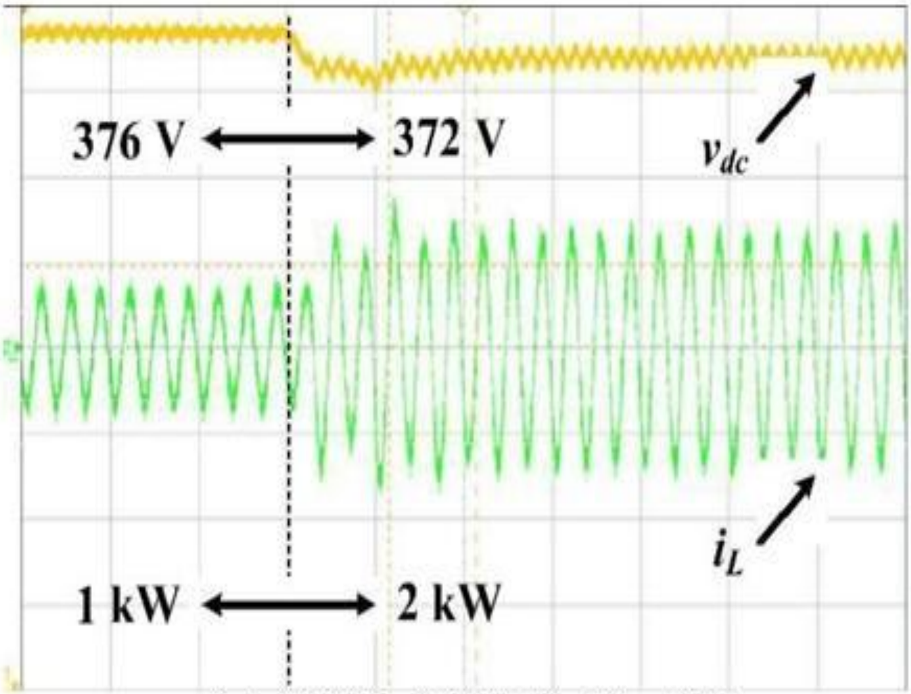
(v_{dc}: 20 V/div, i_L: 10 A/div, 2 s/div)

ig. 9. Measured waveforms of dc-link voltage and inductor current with load variation in rectification mode.



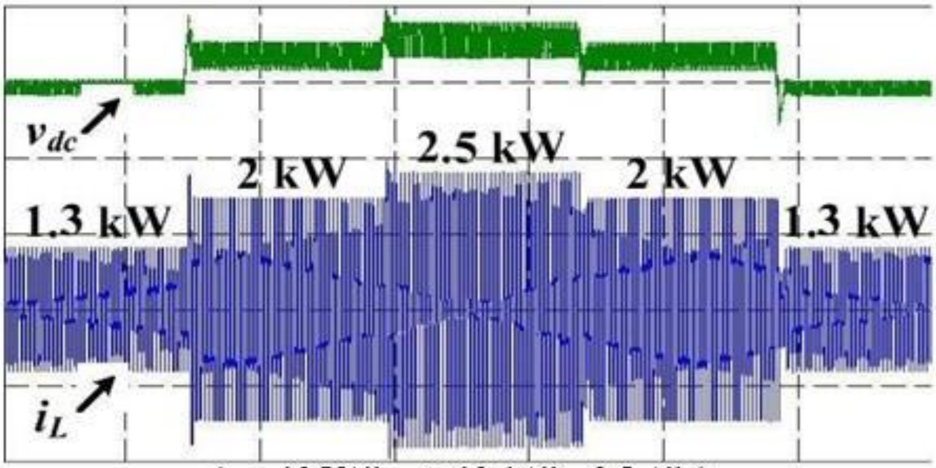
(v_{dc}: 10 V/div, i_L: 10 A/div, 50 ms/div)

Fig. 10. Simulated waveforms of dc-link voltage and inductor current when load condition varying from 1 kW to 2 kW in rectification mode.



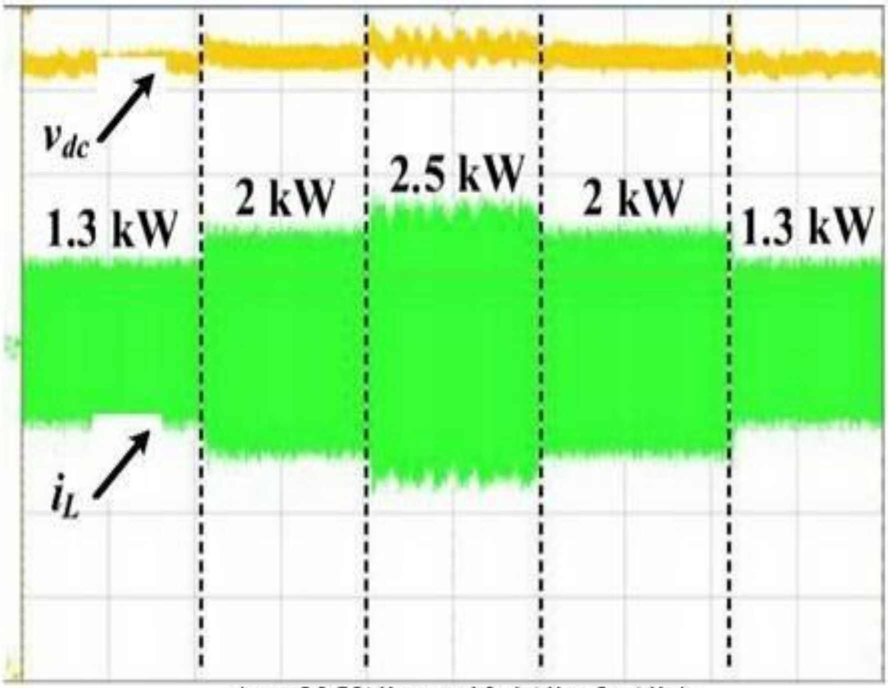
(v_{dc}: 20 V/div, i_L: 10 A/div, 50 ms/div)

Fig. 11. Measured waveforms of dc-link voltage and inductor current when load condition varying from 1 kW to 2 kW in rectification mode.



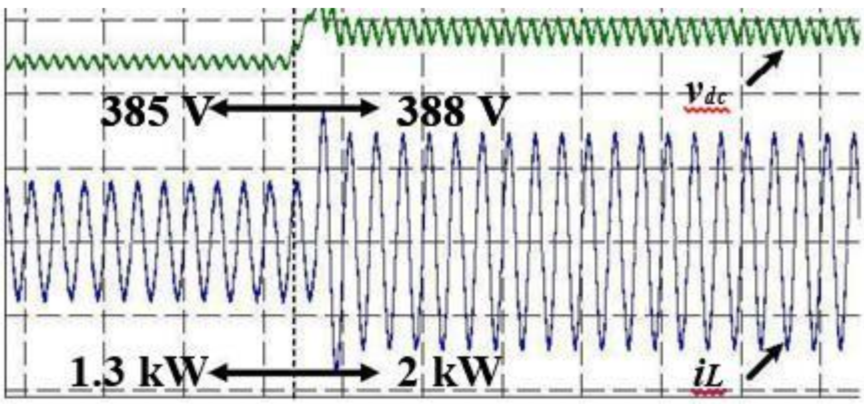
(v_{dc}: 10 V/div, i_L: 10 A/div, 0.5s/div)

Fig. 12. Simulated waveforms of dc-link voltage and inductor current with load variation in grid-connection mode.



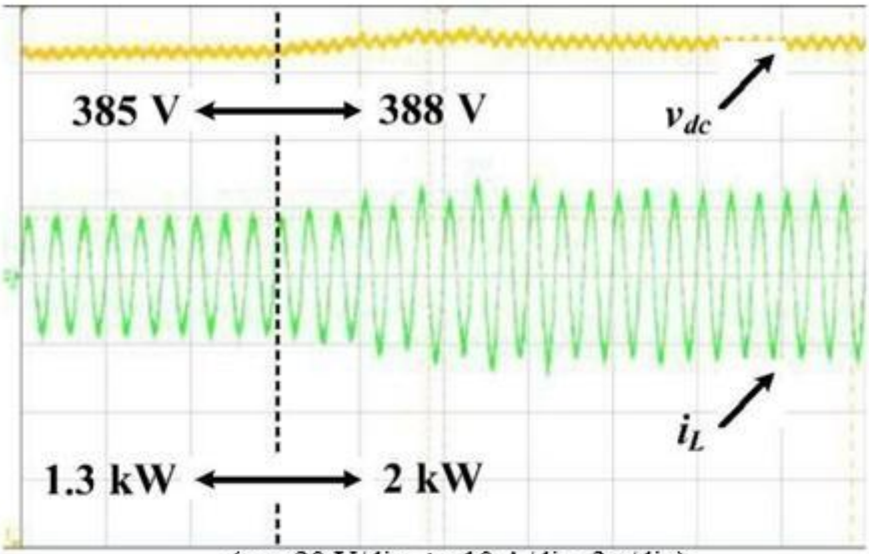
(v_{dc}: 20 V/div, i_L: 10 A/div, 2 s/div)

Fig. 13. Measured waveforms of dc-link voltage and inductor current with load variation in grid-connection mode.



(v_{dc}: 10 V/div, i_L: 10 A/div, 50 ms/div)

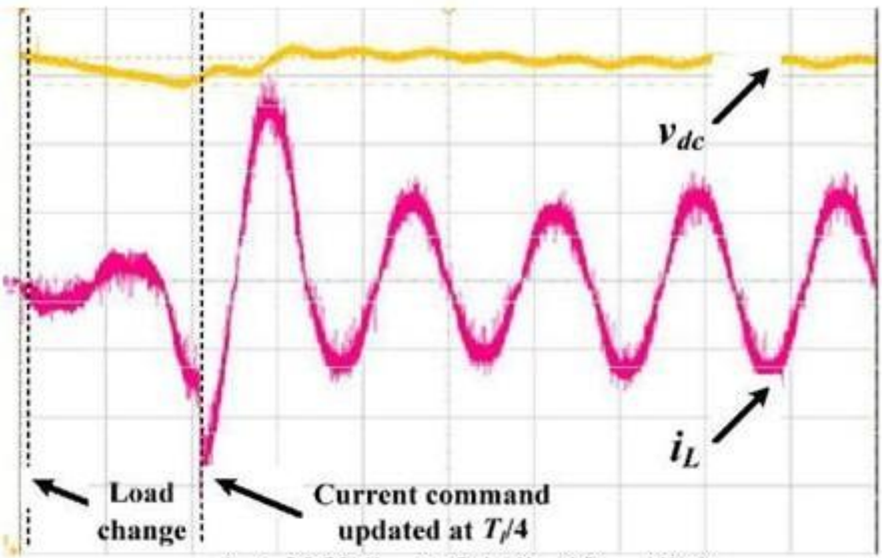
Fig. 14. Simulated waveforms of dc-link voltage and inductor current when load condition varying from 1.3 kW to 2 kW in grid-connection mode.



(v_{dc}: 20 V/div, i_L: 10 A/div, 2 s/div)

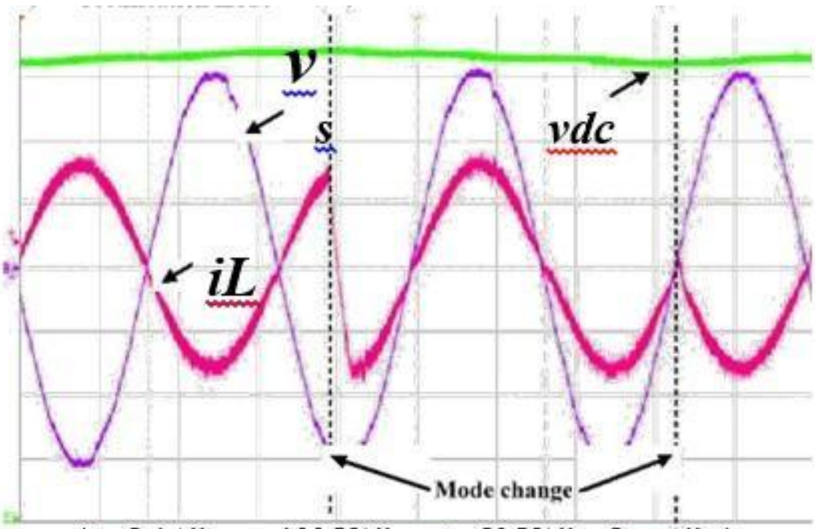
Fig. 15. Measured waveforms of dc-link voltage and inductor current when load condition varying from 1.3 kW to 2 kW in grid-connection mode.

With the proposed regulation mechanism, it takes only one line cycle to adjust the dc-bus voltage to a new set point and balance the power. However, if there is a heavy step load change during one line cycle, it will result in high dc-bus voltage variation, as shown in Fig. 16, and the inductor current command will be updated every *Tl*/4. Moreover, the control may change mode operation within a line cycle, as shown in Fig. 17. However, this will cause high current distortion.



(v_{dc}: 20 V/div, i_L: 5 A/div, 10 ms/div)

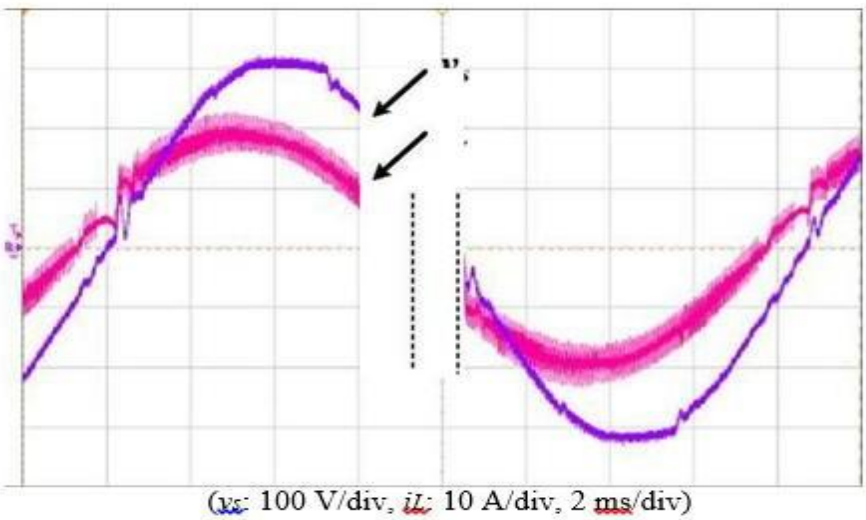
Fig. 16. Measured waveforms of i_L and v_{dc} illustrating fast load change and fast dc-bus voltage regulation mechanism.



(i_L: 5 A/div, v_s: 100 V/div, v_{dc}: 50 V/div, 5 ms/div)

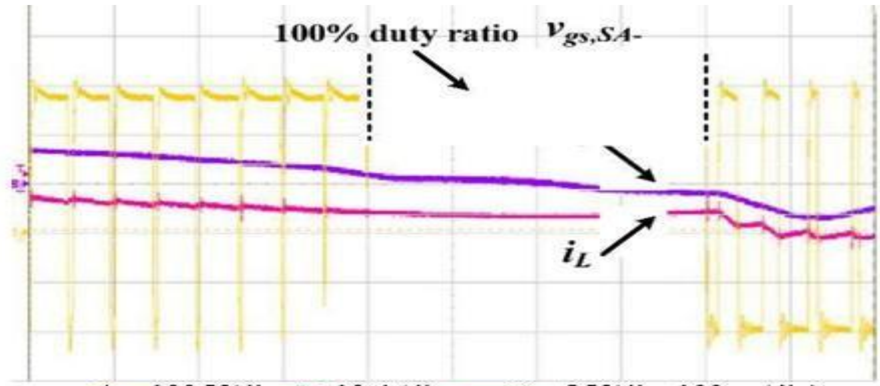
Fig. 17. Measured waveforms of i_L, v_{dc} and v_s illustrating that mode changes to fast regulate the dc-bus voltage.

For power compensation, if the electric equipment is an inductive load, the inverter shifts its inductor current leading line voltage, as shown in Fig. 18, in which current distortion can be observed explicitly. In the marked region, the inverter changes operational mode from grid connection to rectification at the PHC, and inductor *Ls* is magnetized with line voltage *vs* only. Since the magnetizing line voltage is not high enough, a current distortion occurs near the zero crossing. From Fig. 19, it can be seen that even with the duty ratio of 100 %, the inductor current still cannot track the current command precisely. Therefore, to increase the magnetizing voltage and improve the inductor current distortion, switch *SB+* should be turned on to increase magnetizing voltage to *vL vdc vs* at the PHC, which is just like a grid-connection mode operation, until the inductor current reaches the reference level. On the other hand, if the load at ac grid is capacitive, a lagging power factor is generated, as shown in Fig. 20.



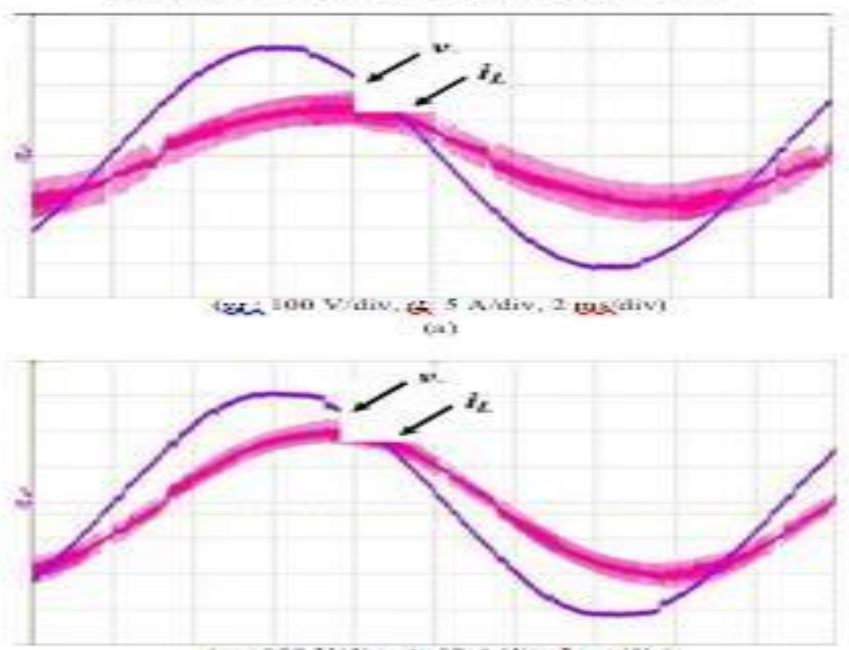
(v_s: 100 V/div, i_L: 10 A/div, 2 ms/div)

Fig. 18. Measured waveforms of inductor current and line voltage with a leading power factor under 3 kW power level.



(v_s: 100 V/div, i_L: 10 A/div, $v_{gs,SA-}$: 5 V/div, 100 us/div)

Fig. 19. Measured waveforms of inductor current, line voltage and gate signal with the duty ratio of 100 % under 3 kW power level.



(v_s: 100 V/div, i_L: 5 A/div, 2 ms/div)
(a)

(v_s: 100 V/div, i_L: 10 A/div, 2 ms/div)
(b)

Fig. 20. Measured waveforms of inductor current and line voltage with a lagging power factor under load conditions of (a) 1 kW and (b) 3 kW.

Figs. 21 and 22 show the measured waveforms of inductor current and line voltage in grid-connection mode and rectification mode with unity power factor and under the load conditions of 1 kW and 5 kW. It can be seen explicitly that the inductor waveforms are sinusoidal and in phase with the line voltage. Fig. 23 shows a photograph of the prototype of the proposed bi-directional inverter. For islanding protection, the system controller varies the power factor between leading and lagging periodically and detect the change of line period at voltage zero crossing. If a change has been detected, the controller will keep decreasing the power factor to further exaggerate the change, which can doubly confirm the detection and identify an islanding operation.

IV. FIGURES AND TABLES

Fig. 23. Photograph for the prototype of the designed bi-directional inverter.

Table 1. Specifications and components of the proposed inverter.

Specification	**Value**
DC Voltage	380 ± 20 V
AC Voltage	220 Vrms / 60 Hz
Switching Frequency	20 kHz
Output Power (max)	5 kW
Grid-connection mode	400 ≧ Vdc ≧ 381 V
Rectification mode	379 ≧ Vdc ≧ 360 V
Component	**Value**
Inductor Ls	3 mH~650 uH
AC Capacitor	4.7 μF
DC Capacitor	560 μF × 10
Microcontroller	TMS320LF2406A
IGBT	40N60A4
Diode	RURG5060

V. CONCLUSION

In this paper, a single -phase bi-directional inverter with dc-bus voltage regulation and power compensation has been analyzed and implemented. The inverter controls the power flow between dc bus and ac grid, and regulates the dc bus to a certain range of voltages. An on-line regulation mechanism according to the inductor current levels have been proposed to balance power flow and enhance the dynamic performance. Additionally, for power compensation and islanding protection, the bi-directional inverter can shift its current commands according to the specified power factor at ac grid side. Simulated and experimental results obtained from a 5 kW single-phase bi-directional inverter have verified the analysis and discussion.

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