Abstract—This paper introduces an input impedance and current (IIC) feedforward control with leading-lagging phase admittance cancellation (LLPAC) for ac-dc boost converter applications requiring higher efficiency and higher power quality. Whereas the conventional voltage feedforward method guarantees its ideal input admittance by generating average switch voltage effectively under well-regulated current compensator, the proposed IIC method contains an extra compensation term reducing the effects of external input parameters as well as an average switch voltage, resulting in improving input power quality in low switching frequency and high line frequency applications. Consequently, the proposed method allows obtaining more constant input admittance in both regions of leading and lagging phase. In order to compare three different control approaches, the small-signal input admittances of the ac/dc boost converters are modeled and analyzed. A MATLAB/Simulink model and a 1.2kW dual boost PFC prototype board controlled by a digital signal processor are implemented to demonstrate the effectiveness of the proposed IIC feedforward control.

I. INTRODUCTION

Recently, power factor correction (PFC) of single-phase ac-dc boost converters is attracting widespread interest for mitigating grid harmonic pollution and operating power systems economically. This technology has been applied to many industrial and commercial products, as popular as diode rectifiers, for ac-dc power conversion in order to feed loads at different power ranging up to several hundred kilowatts power. Nevertheless, PFC technology may be considered a mature discipline in terms of high efficiency and high power quality achieved through advanced circuit topologies and control algorithms by dedicated efforts through an immense amount of research [1]-[3]. Hence, the demands for higher efficiency and higher quality power are major concerns for manufacturers. A dual boost PFC converter, also called bridgeless PFC converter, is one of outstanding innovations, developed to meet the demand of higher efficiency by reducing conduction loss of power devices [4]-[9].

Many compensation methods for improving input power quality have been presented in [10]-[14]. In general, there are tradeoffs between high efficiency and high power quality in terms of switching frequency when converters are designed. Reducing the switching loss while using high switching frequency is fairly restricted by the electrical characteristics of semiconductors unless a new paradigm of the power device, such as silicon carbide (SiC) and gallium arsenide (GaAs) devices, is considered [15]-[16]. Therefore, using switching frequency as low as possible provides more feasible manners to increase the efficiency of the converter. In addition, it can be a desirable approach for the growing trend toward employing digital control for sophisticated functions.

Several advanced control algorithms have been presented to enhance THD of input current through the feedforward controller approaches [17]-[23]. A simple control method through DNLC that allows operation in continuous conduction mode (CCM) without input voltage sensor has been described in [17]-[18]. DNLC uses only an instantaneous input current and a proportional gain for controlling the dc link voltage constantly. However, these methods excluded the current-loop compensator, and might not guarantee a stable operation in transient state or protect devices and circuits from overcurrent in unexpected fault conditions.

LPAC techniques have been presented in [19]-[20] to improve the current-shaping control structure and to eliminate the leading-phase of line current through a properly designed admittance compensator without increasing the bandwidth of the current-loop compensator. Nevertheless, these methods considered only leading phase admittance and the complexity of designing an admittance compensator makes it less attractive in digital applications.

The attempts to eliminate zero-crossing distortion of input current through voltage feedforward control methods have reported in [21]-[23]. A feedforward duty ratio signal relating to input voltage waveform is adopted to effectively produce an average switch voltage over a switching cycle, hence reducing the control proportions of a regular current-loop compensator.
These techniques, however, take only the leading-phase admittance region into account. Thus, these methods might not accomplish a unit power factor due to lagging-phase admittance if the methods are applied in a low switching and sampling frequency for high line frequency applications, such as airborne power system, in order to attain higher efficiency and lower electromagnetic interference (EMI). In other words, all compensation methods reported in the literature focus on the compensation methods to leading-phase effects in ac-dc boost converters in spite of the advent of lagging phase admittances in some conditions.

The purpose of this study is to describe and evaluate an input impedance and current (IIC) feedforward controller with simple modification of the conventional voltage feedforward control for the dual boost PFC converter feeding DC loads such as motor drives or battery chargers, as shown in Fig. 1. DC link voltage along with root mean square (RMS) values of input voltage/current as the input impedance compensation term and instantaneous input current are used, which result in a new feedforward signal to cancel undesirable leading and lagging-phase admittances as well as to yield the average switch voltage. Moreover, it can be found that the performance of the proposed IIC feedforward method is less sensitive to variations of the boost inductor values often caused by imperfections of core materials and variations of temperature and the current level. Hence, this feature leads to ideas for a cost-effective ac-dc converter without redesigning the input filter and control parameters for operating a wide input frequency range.

II. VOLTAGE FEEDFORWARD CONTROL

A. Derivation of the conventional voltage feedforward control

From Fig. 2 depicting a simple circuit diagram of the power stage of general ac-dc boost converters with an input inductor \( L \) and its parasitic resistor \( R \), the closed circuit equation consisting of the source voltage \( v_s \), the switch voltage \( v_d \) and the input line current \( i_s \) can be expressed as

\[
\begin{align*}
v_s &= Ri_s + L \frac{di_s}{dt} + v_d \\
\end{align*}
\]

It should be noted in (1) that the switch voltage would usually be a major factor determining the waveforms of input current. In other words, for producing a pure sinusoidal input current, waveform as the average switch voltage. As a result, the input current tracking is improved and the frequency range for which input admittance acts as a resistor can be extended to higher frequencies owing to this feedforward duty. The average switch voltage over a switching cycle in CCM, can be expressed as

\[
v_d = (1-d)v_o
\]

(2) is the average on-time duty ratio of switches and \( v_o \) is the output voltage in dc-link. Using (1) and (2), and rearranging in terms of \( d \), a duty ratio equation can be obtained as

\[
d = \frac{1}{v_o} \left( Ri_s + L \frac{di_s}{dt} \right) + \left(1 - \frac{v_i}{v_o} \right)
\]

(3) and (5) describe that \( d_c \) contributes to generate the exact phase difference between the source voltage and the average switch voltage and \( d_n \) produces inversed source voltage waveform as the average switch voltage. As a result, the input current tracking is improved and the frequency range for which input admittance acts as a resistor can be extended to higher frequencies owing to this feedforward duty. Usually, \( d_c \) can be obtained through the proportional-integral (PI) compensator because the direct calculation method for (4) has a computationally demanding task to solve the differential equation of inductor current, which may be very sensitive to the noise of feedback signals from sensors under hard-switching conditions of high voltage devices. Therefore, employing the PI controller would be a more proper way to obtain the feedback duty than computing an exact duty. As the most general way, the feedback duty as output from PI current-loop compensator can be expressed as

\[
d_c = K_{pc} (i'_s - i_s) + K_{ic} \int (i'_s - i_s) dt
\]

(6) describes that \( d_c \) and \( d_n \) are the feedback duty ratio and the feedforward duty ratio, respectively. Theoretically, the duty ratio in (3) should be generated for the ideal switch voltage as accurately as possible through the adequate converter control algorithms to yield pure sinusoidal input current. Under the assumption that the phase difference by the input impedance is relatively small, the two voltage waveforms would be almost identical [21]. As will be discussed later, however, this assumption may lead to the lagging-phase shift problems of input current in the case using large inductance and low bandwidth of current-loop compensator in high line frequency. In order to classify duty ratio \( d \) of system in (3), the feedback duty ratio \( d_c \) and the feedforward duty ratio \( d_n \) can be defined as

\[
d_c = \frac{1}{v_o} \left( Ri_s + L \frac{di_s}{dt} \right)
\]

(4) and (5) describe that \( d_c \) and \( d_n \) are the feedback duty ratio and the feedforward duty ratio, respectively.
where $K_{pc}$ and $K_{ic}$ are the proportional gain and integral gain of the current-loop compensator, respectively, and $i_s^*$ is the input current reference.

B. Problems in low switching and high-line frequency applications

The conventional voltage feedforward control shows an acceptable performance by producing average switch voltage effectively in general design conditions. In some applications with limited switching/sampling frequency operations under high line frequency, however, the phase difference between $v_s$ and $v_L$ is not small and the regular current compensator may compensate this phase difference incompletely. As a result, it may have significant lagging-phase shift problems, because this condition causes a violation of the previously defined assumption for deriving the control rules of the conventional feedforward method. Therefore, the uncompensated input admittance advents in the frequency ranges of interest, resulting in yielding undesired current distortion and displacement. Most papers [19]-[23] did not take into account this lagging-phase region caused by effects of the boost inductor and the unsatisfied current-loop compensator, but only focuses on compensating distortions of input admittances in the leading-phase region caused by dynamics of the current loop. To explain the needs of the alternative approach for canceling effects of the input impedance, (3) can be rewritten in Laplace domain as

$$d(s) = \frac{i_s(s)}{v_o(s)}(sL + R) + \left(1 - \frac{v_L(s)}{v_o(s)}\right)$$  \hspace{1cm} (7)

It can be noted in (7) that there are no compensator terms to reduce lagging-phase effects from an inductance in the conventional feedforward duty, thus it depends on only the performance of current-loop compensator to eliminate lagging-phase effects. As a result, if the current-loop compensator has been unsatisfied and the operating line frequency is within the lagging phase region, the converter has a problem with the non-unity fundamental displacement power factor under this inferior condition.

III. INPUT IMPEDANCE AND CURRENT FEEDFORWARD CONTROL

A. Derivation of the IIC feedforward control

The proposed IIC feedforward control signal based on the idea for including the input impedance can be derived as follows. In order to include compensation terms for canceling the effects of the input impedances, a new feedforward control signal related to the input current and input power under the steady state and ideal control, using a simple current control law and the conventional voltage feedforward control duty, can be expressed in the rectifying power stage under the assumption that the power factor value is unity [14], [17]-[18], [24].

$$d_a = 1 - \frac{v_o}{v_o} \left(1 - \frac{v_L^{rms}}{v_o} \right)$$  \hspace{1cm} (8)

$g_c (=i_/v_o)$ is the emulated input admittance, $v_L^{rms}$ is the RMS value of input voltage, and $P_{in}$ is the input power of the PFC rectifying stage. Furthermore, the input power into the converter can be expressed by RMS values of the input voltage and input current $i_s^{rms}$ as

$$P_{in} = v_o^{rms} \cdot i_s^{rms}$$  \hspace{1cm} (9)

By combining (8) and (9), the proposed IIC feedforward duty equation can be obtained as

$$d_a = 1 - \frac{v_o^{rms}}{i_s^{rms}} \left(1 - \frac{v_L^{rms}}{v_o} \right)$$  \hspace{1cm} (10)

Using (4) and (10), the total duty ratio for the proposed method can be rewritten in the Laplace domain as

$$d(s) = 1 - \left(\frac{v_o^{rms}(s)}{i_s^{rms}(s)} - (sL + R)\right) \frac{i_o(s)}{v_o(s)}$$  \hspace{1cm} (11)

It can be observed that the derived feedforward duty in (11) contributes to cancel the lagging effects of input inductances through emulated input impedance compared to (7). Hence it is clear intuitively that it alleviates the task of the current-loop compensator more than the conventional feedforward controller, resulting in improving PFC performance where the current-loop compensator does not have enough high bandwidth to achieve the required input current quality. Fig. 3 shows the control block diagram for the proposed IIC feedforward controller.
In (14)-(16), the linearized version of the feedback duty obtained as multiplied to the PWM modulator as regulator and the feedforward controller needs to be from steady state. The final duty output from the current operating point and hated small letters are small perturbations In (12), capitals are values of system variables at steady-state output duties to three control methods can be obtained as From Fig. 4, the small-signal transfer functions of the final feedforward duty and the proposed IIC one, respectively.

Equations of the feedback duty, the conventional voltage feedforward duty and with the proposed IIC one, the regular current-loop compensator, with the conventional voltage feedforward controller, and Gm(s) with the proposed IIC one. Furthermore, if a delay influence of the PWM modulator is uring only the regular current-loop compensator without the feedforward controller, Gf(s) with the conventional voltage feedforward controller, and Gm(s) with the proposed IIC one. Under the assumption that the output of the voltage compensator is constant and the delay from transducers is small when calculating the input impedance in the high-frequency region. In (20)-(22), Gm(s) is the transfer function of the small-signal input admittance of the converter considering only the regular current-loop compensator without the feedforward controller, Gf(s) with the conventional voltage feedforward controller, and Gm(s) with the proposed IIC one. Furthermore, if a delay influence of the PWM modulator is negligible over frequency ranges of interest and static gain is unity, GPWM(s) can be modeled as a constant unity gain under average current control. Hence, the small-signal input admittances can be approximated by

\[ G_{vc}(s) = \frac{1 + G_c T(s)}{sL + R + T(s)} \]  
\[ G_{ff}(s) = \frac{G_c T(s)}{sL + R + T(s)} \]  
\[ G_{m}(s) = \frac{G_c \left( T(s) + \frac{1}{G_c} \right)}{sL + R + \left( T(s) + \frac{1}{G_c} \right)} \]

where, \( T(s) = V_o G_c(s) G_{PWM}(s) \), \( G_c = \frac{I_{OREF}}{V_M} \).

It can be observed in (23)-(25) that if it is assumed that the impedance of boost inductors is negligible over the low frequency ranges of interest, \( G_{vc}(s) \) approaches \( 1/T(s) + G_c(s) \) yielding the leading-phase effects caused by the dynamics of the current-loop compensator [14], while \( G_{ff}(s) \) and \( G_{m}(s) \) approach the constant \( G_c(s) \) acting as a pure resistor. For this reason, a higher quality of input current can be obtained through feedforward controllers, as presented in many papers.
IV. COMPARISON OF SMALL-SIGNAL INPUT ADMITTANCES

The benefits of employing the proposed IIC feedforward control are investigated in this section using the obtained transfer functions of input admittances in (23), (24) and (25). In order to compare behaviors of input admittances in the frequency domain, the distortion factors to input admittances for three control methods can be introduced as

\[ G_{cc}(s) = A_{cc}(s)G_e \]  
\[ G_{ff}(s) = A_{ff}(s)G_e \]  
\[ G_{iic}(s) = A_{iic}(s)G_e \]  

In (26)-(28), \( A_{cc}(s) \), \( A_{ff}(s) \), and \( A_{iic}(s) \) are the distortion factors of input admittances for \( G_{cc}(s) \), \( G_{ff}(s) \) and \( G_{iic}(s) \), respectively, and can be expressed as

\[ A_{cc}(s) = \frac{1/G_e + T(s)}{sL + R + T(s)} \]  
\[ A_{ff}(s) = \frac{T(s)}{sL + R + T(s)} \]  
\[ A_{iic}(s) = \frac{T(s) + 1/G_e}{sL + R + T(s) + 1/G_e} \]  

It can be observed that three distortion factors in (29)-(31) have almost the same values if the total input impedance \((1/G_e)\) of converters approaches zero, but this is not a practicable condition in real applications because input current should be a few hundred times of the input voltage for this condition. Similarly, if the inductance and parasitic resistance \((sL+R)\) of the boost inductor are ignored as assumptions in [21], the other two distortion factors for feedforward controllers would be unity indicating input admittances behave as pure resistors. However, the boost inductor impedance term, which overwhelms the influence of leading-phase in the denominator terms of distortion factors as grid line frequency increases, is not negligible in low switching frequency applications due to large inductance. Therefore, this lagging-phase effect should be eliminated by other effective terms because of unsatisfied performance of the regular current-loop compensator in high line frequency. Otherwise, it induces the significant degradation of the input power quality. Due to this problem, the conventional voltage feedforward control without considering the inductor impedance may not be a suitable approach under given operating conditions. Meanwhile, the proposed IIC feedforward method in (31) indicates that the added input impedance term in both the numerator and denominator reduces the effects of the lagging-phase as well as the leading-phase, resulting in LLPAC. As an example for above descriptions, Fig. 5 shows the magnitude and phase response of distortion factors when the input impedance increases where line frequency is 400 Hz and the bandwidth of the current-loop compensator is 1 kHz kept the same in all three cases as an inferior condition. For agreement with analysis results for (29)-(31), the proposed IIC method approaches an ideal magnitude and phase value closer than other control methods, and its performance is acceptable in normal operating power ranges. Also, it can be noticed that the conventional voltage feedforward control has some deviations to the ideal value due to unsatisfied current-loop compensator regardless of the input impedance.

As another factor for comparison, the contribution factors of feedforward controllers to the converter using only the regular current compensator can be introduced in (32) and (33) to figure out how the proposed IIC feedforward method can effectively reduce undesired distortion terms of input admittances.

\[ G_{ff}(s) = K_{ff}(s)G_{cc}(s) \]  
\[ G_{iic}(s) = K_{iic}(s)G_{cc}(s) \]  

From (23)-(25) and (32)-(33), the contribution factors for the feedforward controllers can be calculated as

\[ K_{ff}(s) = \frac{G_e T(s)}{1 + G_e T(s)} \]  
\[ K_{iic}(s) = \frac{sL + R + T(s)}{sL + R + T(s) + 1} \frac{1}{G_e} \]

Fig. 6 shows the Bode plots of contribution factors \( K_{ff}(s) \) and \( K_{iic}(s) \) to the input admittance \( G_{cc}(s) \). Both contribution factors start to compensate undesired leading-phase and distorted magnitude of input admittance when \( G_{cc}(s) \) is deviated from the ideal input admittance.
be noted that the amounts of contribution factors for two feedforward methods are different. As can be seen in Fig. 6, these controllers show a similar feature for compensating the undesired input admittance of $G_c(s)$ below 100 Hz, but $K_{ff}(s)$ cancels the distorted and displaced input admittance more correctly than $K_{ic}(s)$ in the higher frequency region. With regard to the result for input admittances with feedforward controllers shown in Fig. 7, the proposed IIC feedforward acts to compensate not only a capacitive behavior of input admittance, but also inductive behavior tending to be the dominant impedance due to the low bandwidth compensator and large inductance value as line frequency increases. Thus, the input admittance behaves as more pure resistor through the proposed method. The superiority of the proposed method will be significantly distinguished from the conventional one as the performance of the current-loop compensator become worse. Further, it can be seen in (34) and (35) that the contribution factor of the proposed IIC feedforward method includes inductor impedance in both the numerator and denominator, from which it can be inferred that $G_{ic}(s)$ has robust characteristics naturally under inductance variations. 

Fig. 8 shows input admittances of the feedforward methods under boost inductance ($L$) variations to compare sensitivities and uncertainties to both feedforward methods. As expected, the deviation of the input admittance in the conventional voltage feedforward is significant under inductance variations from 50% to 200%, as shown in Fig. 8(a). On the contrary, the proposed IIC feedforward control is less sensitive than the conventional one under the same conditions shown in Fig. 8(b). As a result, the proposed method can provide a more flexible design without the redesigning of input filters, which may reduce the total manufacturing cost by avoiding many different versions of input filters to meet harmonic regulations for both conditions of normal and high input frequency.
V. SIMULATION RESULTS

In order to investigate the effectiveness and the performance of the proposed IIC feedforward control, the dual boost PFC converter is implemented in MATLAB/Simulink® environment. For the evaluation of performances, the converter operation under three control strategies with 1 kHz bandwidth of current-loop compensator was simulated. Fig. 9 compares the steady state input current waveforms obtained in the condition of input voltage 110Vrms/400Hz. The distortion and displacement factors of the input current are significantly degraded as shown in Fig. 9 (a) and (b) due to inductance lagging effects, meanwhile the proposed IIC feedforward control maintains a better distortion factor and still the displacement factor is close to unity due to the compensation of the input impedance, as shown in Fig. 9(c).

VI. EXPERIMENTAL RESULTS

The single-phase dual boost converter based on low-cost digital implementation was used to verify the proposed IIC feedforward control.

Fig. 10 shows experimental results for comparing the performance of the conventional feedforward control and the proposed IIC feedforward control. It indicates in Fig. 10(a)-(b) that the measured input currents when employing feedforward controllers show exceptionally high performance with a low distortion factor and a low displacement factor at the normal line frequency (60 Hz), although the bandwidths of the current-loop compensator is not enough. However, the input current shown in Fig. 10(c) using the conventional feedforward controller is displaced significantly at high line frequency (400 Hz) because of the effect of

![Fig. 9. Simulation results; line frequency : 400Hz (a) without any feedforward control (PF: 0.89, THD:28.7%), (b) the conventional voltage feedforward (PF: 0.86, THD: 10.1%), and (c) the proposed IIC feedforward (PF: 0.99, THD:7.3%).](image)

![Fig. 10. Experimental results - 50V/div and 10A/div (a) conventional feedforward (line freq.: 60Hz, PF: 0.99, THD: 4%) (b) proposed feedforward (line freq.: 60Hz, PF: 0.99, THD: 3%) (c) conventional feedforward (line freq.: 400Hz, PF: 0.80, THD: 5.3%) (d) proposed feedforward (line freq.: 400Hz, PF: 0.97, THD: 5%).](image)
uncompensated lagging-phase admittance. Meanwhile, the input current shown in Fig. 10(d) using the proposed IIC feedforward control is less displaced and still has an acceptable PFC performance under an inferior condition indicating reduced a ratio of switching frequency to line frequency. Clearly, the proposed IIC feedforward control has further improved performance which is 17% better in terms of displacement factor and 0.3% better in the distortion factors in the case that the ac–dc boost converter has a large inductance value in 400Hz line frequency. In conclusion, the experimental results demonstrated that the proposed IIC feedforward controller can be a feasible solution in order to utilize low switching/sampling frequency technique for higher efficiency and digital implementations.

VII. CONCLUSION

This paper has presented the input impedance and current (IIC) feedforward control to solve the phase shift problems of the input current caused by leading-lagging-phase admittances in high line frequency applications employing low switching/sampling frequency. The added input impedance term in the proposed method reduces the undesired effects of input admittances over wide frequency ranges as a leading-lagging phase admittance cancellation (LLPAC). Simulation and experimental results show that input power quality improved through the proposed IIC feedforward control under given operating conditions while supporting the theoretical analysis. In addition, the proposed IIC feedforward method can be utilized easily with a simple modification of the existing voltage feedforward equation. Consequently, these features make the proposed IIC feedforward algorithm extremely suitable for digital implementation of the ac–dc boost converter with limited bandwidths.

REFERENCES


