Duty Ratio Calculation for Digitally Feed Forward Controlled Parallel Connected Buck-Boost PFC

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Abstract—Power supply modules can be connected in parallel to build up a complex power system. Connecting many converters is more beneficial as compared to a single larger power unit because of components stress, modular implementation, flexible power requirements, and design variations. All of the above benefits can be achieved as long as the load current is distributed between the converters in a controllable manner. Digital feed-forward control method is derived and proposed in this article for parallel connected buck-boost converters operating in Discontinuous Conduction Mode, for maintaining the output voltage and to control the load current distribution amongst them. Proposed feed-forward control method is paralleled with two well-known current control schemes i.e. the Average Inductor Current Mode Control (AICMC) and the Hysteresis Current Control Method. MATLAB results shows that our proposed scheme demonstrates superior results in term of the harmonics reduction and power factor as linked to the other two methods.

Keywords—Power Factor Correction, Parallel Connected Buck-Boost Converter, Feed-Forward Control Algorithm, Average Inductor Current Mode Control, Hysteresis Current Control.

I. INTRODUCTION

Power electronic devices are enhanced for converting the AC supply voltage to the DC voltage according to the demand of the devices at consumer end. This transformed DC voltage comprises a high scale ripple which is adverse. To manage this ripple, a high value capacitor is placed at the output of switching power electronic circuitry. Due to this capacitor the waveform of the input current will be distorted which results in a high THD and low power factor. For dealing with such circumstances, the power factor correction systems are used. Parallel connection of the power factor correctors are advantageous in power sharing, output voltage ripple minimization and stress shrinking.

The control of converter modules connected in parallel for power factor correction are separated into two categories [1] i.e. the current sharing control and droop control. Current sharing control for parallel connected converters module are focused in [2] for both centralized and decentralized control method. Centralized control method has decent performance in terms of current sharing but it have some weaknesses in terms of dependability and also it needs some additional cables for connections between the converters for communication. As linked to the centralized control system, Decentralized control system executes droop control method to deal individually with each converter to attain modularity of the system. The distributed control system is also used for converter control which holds both the centralized and decentralized techniques. Distributed control system has moral performance in consistency, modularity and current sharing between the converters as it has the external linkage for communication between each controller [3].

Power Supplies used in telecommunication uses the method of parallel connecting converters to offer the service uninterruptedly. The currents and voltages are detected and their responses are taken into account for sustaining output voltage and current sharing between the converters. Connecting the switching converters in parallel design have many advantages in terms of the maintenance, stress, reliability, productivity and supervision [4]–[6].

For power factor correction, different types of techniques were used in switching converter devices. First of all the controllers were offered in analog form that implements enhanced results at small cost. Reference [7] has analog hysterisis control for Boost converter presenting its stability. Power factor correction with impedance matching using hysteresis control method is achieved in [8], [9]. The cons of analog control was their performance and high cost, for a complex system. So this analog control was switched initially in [10] with a smaller low cost chip with external multiplier. These external multipliers are then substituted by nonlinear control and single cycle control in [11]. Digital controllers are used as one of the most common controllers because of their computational skills and their versatility for dealing with even complex systems.

Digital control technique brings advancement in control for parallel connected power modules as it can process complex algorithm to accomplish power factor correction. It can execute more advance control techniques implementation. Digital control techniques are predominantly used in switching power converter modules. Digital control have several downsides when converters are used with high switching frequencies which contains a high cost and high switching frequencies limitations [12], [13].

For worthy use of the digital control, the feed-forward control technique is introduced in [14] in which duty cycles are calculated on the basis of the sensed output voltage and inductor current. It also considers the former duty cycle value for calculating next value so if there is problem in the previous duty cycle value then it may affect the new generating value. For the tenacity of better performance in terms of high switching frequency with low cost and less calculations, feed-forward control is the ultimate solution. Digital feed-forward control with the dead beat technique is presented in [15]. In this, duty cycle calculation is not
executed for every cycle because of the slow speed DSP. Dead beat method causes harmonics in the line current. The digital feed-forward control method is offered in this paper which holds feed-forward control for two buck-boost converters that are attached in parallel to achieve high switching frequency with low cost DSP for obtaining unity power factor duty cycles. For assessment purpose, our feed-forward control is linked with two other well recognized current control methods i.e. average inductor current mode control and hysteresis current control method. All the results are validated in SIMULINK. The rest of the paper is arranged as section II is about the average inductor current mode control. Section III offers an overview of the hysteresis current control method. In section IV, the digital feed-forward control is obtained for single buck-boost converter operating in discontinuous conduction mode. All the calculations are done for the duty cycle calculation process in detail and this feed-forward control is prolonged for parallel connected two buck-boost converters. Section V contains Simulations and results that reflects the comparison between proposed and other two control techniques. On the basis of results, conclusion is made in section VI of the paper.

II. AVERAGE INDUCTOR CURRENT MODE CONTROL AICMC

Stating to the reduction in THD of current and improving the power factor of the system containing two buck-boost converters connected in parallel, AICMC is used, as shown in the fig. 1. Buck-boost converter is a capable DC-DC converter that has MOSFET as a switch. Subject to the pulse width modulation of the switch, buck-boost converter works in two basic modes i.e. Continuous Conduction Mode CCM or Discontinuous Conduction Mode DCM. This paper proposed buck-boost converter with Discontinuous Conduction Mode DCM. AICMC is a feedback control method that sense the output voltage and inductor current and guides there values to the controller. Controller contains two basic PI controller to minimize the error to obtain system stability. AICMC chiefly encompasses of two loops [16].

![Fig. 1. AICMC for Parallel Connected Buck-Boost Converter.](image)

a. Current Control Loop/Inner Loop

This loop is used for shaping the current waveform according to the input voltage waveform. In this loop, average current flowing into the inductor is sensed and compared with the reference current. Reference current is coming from outer voltage loop. The difference between average inductor current and reference current is then processed by current PI controller. The outgoing signal from this PI current controller is compared with certain saw tooth wave for producing PWM signals for the switch. This inner loop is a fast loop because it can manage the abrupt change in current. The second loop is:

b. Voltage Control Loop/Outer Loop

This loop maintains the output voltage at certain reference value. Capacitors and resistors are used to sense and trap the output voltage harmonics. This output voltage is compared with some predefined reference voltage in order to generate error and then this error is feed in to the voltage PI controller to minimize the error and provide the reference current voltage for inner loop. For Digital AICMC, all set-ups are performed through software. A fast digital controller is mandatory for execution of all the duty cycle calculations for every switching cycle. So a high speed DSP is necessary for AICMC to accomplish its operation.

III. HYSTERESIS CURRENT CONTROL METHOD

It is also a current control method in which the output/line current tends to track the reference current. It is one of the simplest way for current control in terms of execution. Inductor current is ramped up and down to follow the reference current by adjusting the switch of the converter. Equating with extraction error signal, the lower and upper tolerance boundaries are defined in hysteresis control method. The hysteresis bandwidth is double of error which is obtained by taking the difference between upper and lower borders [17]. As far as, the error signal is within the boundaries, the converter switch will hold its position. But when the error signal extends out the upper border then switching pulse will produced to turn off the switch and if the signal leaves the lower border then switching pulse will turn on the switch. Deducting the reference current from maximum error will give the upper limit of hysteresis band while deducting the reference current from minimum error will define the lower limit of hysteresis band. if there is a case in which both the maximum and minimum error have similar values then bandwidth of hysteresis will be twice of the error. The downside of hysteresis current control method is no switching frequency limitations. Hysteresis control method with functional block diagram is shown in fig. 2.

IV. FEED-FORWARD ALGORITHM FOR BUCK-BOOST CONVERTER

The feed-forward controller for the buck-boost PFC converter is discussed under the assumption that the converter operates in Discontinuous Conduction Mode DCM. Furthermore input voltage $V_{in}$ can be well approximated by holding the sampled voltage during each sample period as the sampling frequency is larger than line frequency.

Fig. 3 shows a buck-boost converter topology. Buck-boost converter is categorized in to either ON-State or OFF-State (shown in fig. 4) subject to the switch.
The inductor voltage for ON state is given by:
\[
\frac{V_{\text{out}}}{L} \delta \leq t \leq t_k \Rightarrow d \frac{dV_{\text{out}}}{dt} = \delta
\]
For OFF state, inductor voltage is
\[
\frac{V_{\text{out}}}{L} \delta \leq t \leq t_{k+1} \Rightarrow d \frac{dV_{\text{out}}}{dt} = 0
\]
Where
\[
\delta = -\frac{V_{\text{out}} d_k}{V_{\text{out}}}
\]

Considering the assumptions i.e. DCM mode of buck-boost converter as shown in fig. 5 and the input voltage of the converter to be constant, so the above two equations can be rewritten as:

**Fig. 2.** Hysteresis Control. (a) Hysteresis Control Practical diagram and (b) Hysteresis Band and PWM Waveform.

**Fig. 3.** Buck-Boost Converter Topology.

**Fig. 4.** Buck–Boost Converter topology when switch is ON and OFF.

For ON state, inductor voltage is
\[
\frac{V_{\text{out}}}{L} \delta \leq t \leq t_k \Rightarrow d \frac{dV_{\text{out}}}{dt} = \delta
\]
For OFF state, inductor voltage is
\[
\frac{V_{\text{out}}}{L} \delta \leq t \leq t_{k+1} \Rightarrow d \frac{dV_{\text{out}}}{dt} = 0
\]
Where
\[
\delta = -\frac{V_{\text{out}} d_k}{V_{\text{out}}}
\]

Here \(i_L(t_k)\) and \(i_L(t_{k+1})\) represents the inductor current at \(k^{th}\) and \((k+1)^{th}\) switching cycle. For \((t_k+d_kT_s)^{th}\) switching cycle, inductor current can be derived from above two equations i.e. For ON state,
\[
i_L(t_k) = d \frac{dV_{\text{out}}}{dt} = \frac{V_{\text{out}} d_k}{L}
\]
And for OFF state,
\[
i_L(t_{k+1}) = d \frac{dV_{\text{out}}}{dt} = \frac{V_{\text{out}} d_k}{L}
\]

Putting the value of \(i_L(t_{k+1})\) from (5) in (6) for obtaining the inductor current for \((k+1)^{th}\) switch cycle:
\[
i_L(t_{k+1}) = i_L(t_k) + \frac{V_{\text{out}} d_k}{L}
\]

As output voltage is initially compared with the reference voltage and then fed in to a PI voltage regulator to follow the reference voltage \(V_{\text{ref}}\), while inductor current is inclined to follow the reference current \(i_{\text{ref}}\) attained from voltage PI regulator and is proportional to the rectified input voltage as shown in fig. 6. So the following subsequent substitutions in (7) can be done;

\[
V_{\text{out}} = V_{\text{ref}} = \frac{V_{\text{out}} d_k}{L}
\]
\[
i_L(t_k) = i_{\text{ref}}(t_k) = \frac{V_{\text{out}} d_k}{L}
\]
\[
t_k = \frac{k}{n}
\]

Putting all the substitutions in (7) and solved for duty cycle we get,
\[
d_k = \frac{(i_L(t_k) + i_{\text{ref}}(t_k))}{2V_{\text{ref}}} = \frac{(\frac{V_{\text{out}} d_k}{L} + \frac{V_{\text{out}} d_k}{L})}{2V_{\text{out}}}
\]

Equation 11 can be used for obtaining the duty cycle values for buck-boost PFC. \(V_{\text{in}}(k)\) is the peak input voltage. Instantaneous current \(i_L(t_k)\) and \(i_L(t_{k+1})\) will tail reference current \(i_{\text{ref}}\) as shown by fig. 7. Digital feed-forward control for buck-boost PFC contains the voltage control loop and the current control loop. Feedback signals in this feed-forward
Algorithm are $V_{out}$ and $V_{in}$. Reference current $i_{ref}$ is took from voltage loop, where output voltage is matched with the reference voltage and then supplied through a voltage PI regulator. For sinusoidal shape it is multiplied by $\sin(\omega_{line}t)$ from sine-wave lookup table and zero cross detection. The output from feed-forward control block is the gate signals to the switch which are liable for the unity power factor. Prolonging feed-forward control for parallel connected buck-boost converters (shown in fig. 7), Keeping the assumptions alike that both PFCs are operating in DCM and switching frequency is greater than line frequency, so input voltage during one cycle is taken constant. It will provide the duty cycle values responsible for unity power factor [18].

Summing both the inductor current will results in the source current $I_s(k)$ i.e.

$$I_s(k) = i_L(k) + i_L(k+1)$$

Replacing $i_L(k)$ in (11) by $I_s(k)$ provides the feed-forward algorithm for parallel connected buck-boost converters shown in fig. 7.

This method helps in calculating duty cycle in particular switching instant and it will also eradicate errors from the system that happens in previous switching cycle.

V. SIMULATIONS AND RESULTS COMPARISON

MATLAB/SIMULINK is the software used for obtaining results. All the three types of schemes labelled above are simulated for tenacity of displaying each of their effectiveness and their capability to cope with the total harmonic distortion. Results are linked for presenting that our proposed control model has improved results in terms of the harmonics reduction and in power factor enhancement of the system. Two parallel buck-boost converters are used with inductors values, $L_1=5\,\text{mH}$ and $L_2=0.5\,\text{mH}$. Input voltage is 300V with switching frequency 10kHz and the line frequency at 50Hz. Reference output voltage is maintained at 400 volts for half of simulation and then 450 volts for other half of the simulation. Output voltage waveform is same for all schemes shown in fig. 8.

The simulations are performed for variant loads to verify our proposed scheme. Results clearly reflects that Harmonics in the current waveforms are reduced well by our proposed scheme as related to the other two schemes, which results in low THD value. Power Factor has been also improved. For Ideal supply voltage and current, there waveforms are shown for all three control schemes in the fig. 9. The steady state input ideal source voltage and currents are all in phase to each other. Our proposed scheme has far enhanced current waveform and less THD rate as compared to the AICMC and hysteretic control scheme which is shown in the fig. 10 and 11 respectively.

THD value for AICMC is 20.63% and for Hysteresis Control method, THD value is 19.85% while THD value for our proposed scheme is 5.45% which reflects strong difference in contrast with the other two schemes. With this THD value,
feed-forward control scheme have the superior power factor for parallel connected buck-boost converter system. Robustness of the inductor current with inductance of both inductors is shown in the fig. 12 and power factor with output power with different input voltage is shown in fig. 13.

Fig. 9. Input Voltage and current waveforms. (a). AICMC, (b). Hysteresis Control Scheme and (c). Proposed Feed-Forward Control Scheme.

Fig. 2. Total Harmonic Distortion THD Analysis. (a). AICMC, (b). Hysteresis Control Scheme and (c). Proposed Feed-Forward Control Scheme.

Fig. 1. Zoomed Input Current Waveforms. (a). AICMC, (b). Hysteresis Control Scheme and (c). Proposed Feed-Forward Control Scheme.

Fig. 3. Input Rectified Voltage and Current. (a). AICMC, (b). Hysteresis Control Scheme and (c). Proposed Feed-Forward Control Scheme.
VI. CONCLUSION

Two buck-boost converter system connected in parallel is studied for harmonic factor and power factor correction in this paper. Three different current control schemes are used for load current distribution between the converters. Two well-known schemes i.e. AICMC and hysteresis current control Scheme are used first on two parallel connected buck-boost converters and there results are obtained which performs healttier for Harmonic reduction and also there input voltage and currents are in phase to each other. Then our proposed scheme is presented, in which the calculations are obtained for feed-forward control for single buck-boost converter and then it is extended to two parallel connected buck-boost converter. On the basis of this scheme, results are obtained for THD and for power factor corrections which are compared with the former often used control scheme. The result comparison clearly shows that difference is made on the basis of comparison i.e. our proposed scheme displays superior outcomes as linked to the other two schemes. Feed-forward control scheme is simpler to implement and also it has no limitations on switching frequency.

REFERENCES