Sensorless Neutral Point Voltage Stabilization in Three-Phase Four-Wire Converters

Citation for published version (APA):

Xu, X., Tibola, G., & Duarte, J. L. (2020). Sensorless Neutral Point Voltage Stabilization in Three-Phase Four-Wire Converters. In *22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe)* [9215759] Institute of Electrical and Electronics Engineers.
<https://doi.org/10.23919/EPE20ECCEEurope43536.2020.9215759>

DOI:

[10.23919/EPE20ECCEEurope43536.2020.9215759](https://doi.org/10.23919/EPE20ECCEEurope43536.2020.9215759)

Document status and date:

Published: 01/09/2020

Document Version:

Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Sensorless Neutral Point Voltage Stabilization in Three-Phase Four-Wire Converters

Xinwei Xu, Gabriel Tibola, Jorge L. Duarte
Eindhoven University of Technology
Eindhoven, The Netherlands
x.xu@tue.nl

Acknowledgements

This work has been conducted within HiPERFORM project, which has received funding from the ECSEL Joint Undertaking (JU) under Grant Agreement No. 783174. The JU receives support from the European Union's Horizon 2020 research and innovation program and Austria, Spain, Belgium, Germany, Slovakia, Italy, Netherlands, Slovenia.

Keywords

«Sensorless control», «Converter circuit», «Interleaved converters», «Three-phase system», «Midpoint voltage balancer»

Abstract

This paper presents a midpoint voltage balancer (MVB) which provides neutral point voltage stabilization to three-phase four-wire converters. The MVB consists of dual switching legs, two neutral inductors, and two split capacitors. A sensorless approach with open-loop control is adopted. It removes current/voltage sensors and alleviates computational demand. It is a cost effective and robust alternative to the closed-loop MVB. Due to the zero-crossing of the neutral inductor current, all switches of the MVB operates in zero-voltage switching mode when neutral current is smaller than the nominal phase current of the three-phase four-wire converter. Interleaving operation of the MVB minimizes the high-frequency current circulation in the split capacitors. In addition, the two neutral inductors are magnetically coupled to decrease the inductor current ripple. As a result, the size of passive components of the MVB is reduced. The proposed sensorless approach is verified by a 20 kVA prototype.

Introduction

Three-phase four-wire (3P4W) converters, being standalone or grid-connected, provide a path for neutral current. While the standalone can support various single-phase loads in an isolated micro-grid [1], most of the grid-connected inject energy from distributed resources to utility grid. A 3P4W grid-connected converter can offer zero-sequential voltage imbalance compensation to the point of common connection (PCC) in a low-voltage distribution network [2]. Nowadays, the adoption of single-phase rooftop photovoltaic system and electric car are increasing. These may lead to degradation of voltage balance in utility grid. Therefore, research and development of 3P4W grid-connected converters that offers voltage imbalance compensation is necessary.

Popular configurations of 3P4W converters are the split dc bus (2-C) [3], the four-leg converter (4-Leg) [4], the actively control split dc bus (ACSB) [5], and the midpoint voltage balancer (MVB) [6]. The 2-C configuration is easy to implement. However, it suffers from bulky size of electrolytic capacitors and incapability to process neutral current with dc component. The 4-Leg configuration adopts an extra switching leg to form a neutral point for the 3P4W GCC. Since the control of the fourth switching leg and the control of the three-phase inverter are not decoupled, it requires more development effort. The ACSB configuration combines the idea of 2-C and the 4-Leg, and it is easy to control. In addition, the split dc bus of an ACSB can be implemented using small capacitors.

The MVB configuration proposed in [6] doubles the neutral current handling capability of the 3P4W GCC by adopting dual switching legs, as shown in Fig. 1. Dual-loop control is implemented, and the neutral point voltage ripple is less than 1.5% under severe neutral current transient. It offers zero-voltage switching (ZVS) operation to the dual switching legs under a wide range of neutral current injection.

Fig. 1: Circuit diagram of the MVB in a three-phase four-wire grid-connected converter

The ZVS operation is achieved by adopting small neutral inductance so that inductor current cross zero at any switching cycle. Interleaved control is implemented to prevent high-frequency current from circulating into the split capacitor branch. Because of dual-loop control, usage of multiple sensors and high computational demand is inevitable.

In this paper, the control strategy of the MVB is redesigned to allow sensorless neutral point voltage stabilization in the 3P4W converter. This approach is considered as a cost-effective alternative to the MVB proposed in [6]. It provides majority of the advantages existed in its predecessor, while it requires no information on neutral inductor currents, split dc bus voltages, nor neutral current. The MVB operates in open loop with a fixed duty cycle and fixed switching frequency. The neutral inductance is half compared to that in [6]. Nevertheless, same inductor current ripple is maintained due to coupling. In addition, capacitance of the split dc bus is also reduced. Moreover, the neutral point voltage is tolerant to capacitance mismatch, which might happen due to parameter deviation and component degradation.

Description of MVB

The MVB is connected to a 3P4W grid-connected converter, as shown in Fig. 1. It consists of dual IGBT switching legs with S_1, S_2, S_3, S_4 , two neutral inductors L_{N1}, L_{N2} , and two split capacitors C_{N1}, C_{N2} . Being connected to the common end of the neutral inductors, the midpoint of the split dc bus forms the neutral point N. Table 1 presents the specifications of the 20 kVA 3P4W converter, which adopts the MVB to stabilize the neutral point. This work focus on the MVB, while the design of the three-phase inverter and how it is controlled to offer voltage imbalance compensation is not covered. The MVB operates in open loop mode, requiring no current and voltage measurements. The PWM signals for each switching legs are 180° phase shifted so that the current ripple of the two neutral inductors are interleaved. As a result, the inductor output current i_{LN} is, theoretically, ripple free [7].

A three-phase voltage signal can be decomposed into positive-sequence components, negative-sequence components, and zero-sequence components. An unbalanced three-phase voltage measured at a PCC may contain negative-sequence components. During voltage imbalance compensation, the 3P4W converter injects unbalanced currents to the PCC. The injected currents contain suitable amount of zero sequential currents with reversed polarity to that of the voltage sequential components. The zero sequential currents, i.e. the neutral current directly flows into the midpoint of the dc bus. This current may contain components of fundamental frequency and certain harmonic frequencies based on the power quality compensation mode of the 3P4W converter.

Grid standard, EN 50160-2010, limits voltage total harmonic distortion (THD) at PCC up to 8%. To meet harmonic requirements of grid regulations, the adoption of 3P4W grid-connected converter is a good approach at mitigating harmonics, and compensating voltage imbalance. Since low-order voltage harmonics are dominant in utility grid, the 3P4W converter mentioned in this paper concerns harmonic order up to 13^{th} . This means that the neutral current could contain harmonic components from 3^{rd} up to 13^{th} order with various amplitude.

Table 1: Specifications of the 20 kVA 3P4W converter with the midpoint voltage balancer

Parameter	Symbol	Value	Unit
Apparent power of the 3P4W grid-connected converter	P_a	20	kVA
Input dc voltage	V_{dc}	760	V
Phase-to neutral grid fundamental voltage	V_g	230	V_{rms}
Grid fundamental frequency	f_g	50	Hz
Nominal phase current	$I_{a,b,c}$	29	A_{rms}
Maximum neutral current at 50 Hz	I_{N_m}	58	A_{rms}
Desired maximum neutral-point voltage ripple	ΔV_{CN}	20	V
Harmonic orders under compensation	h	3,5...13	-
Inductance of the neutral inductors	L_{N1}, L_{N2}	110	μH
Capacitance of the split dc capacitors	C_{N1}, C_{N2}	10	μF
Duty cycle of the IGBTs in the MVB	D	50	%
Switching frequency	f_{sw}	20	kHz

With the proposed MVB, this harmonic-abundant neutral current is redirected to the neutral inductor path, keeping the split capacitor free from the neutral current. Therefore, the voltage of the neutral point is stabilized.

Operation principle

The MVB either operates in closed loop [6, 8] or open loop. In closed loop, current and voltage signals are fed back to the loop, which modifies duty cycle to alter the neutral point voltage to a desired condition. Fig. 2 (a) shows the control implementation of the MVB, where dual loop is implemented [8]. The voltages of the upper and bottom split capacitor v_{CN1} , v_{CN2} , currents of the neutral inductors i_{LN1} , i_{LN2} , and the neutral current i_N are measured. Due to the existence of LC resonance in the MVB circuit, active damping is typically adopted. Two control commands u_{k_LN1} and u_{k_LN2} are compared with the 180° phase shifted carrier signals, from which the gate signals G_1 , G_2 , G_3 , and G_4 are derived.

The objective here is to keep the neutral point voltage as stable as possible. Since the neutral point voltage should be half of the total dc bus voltage, the duty cycle D of the switches is kept at 50%. Therefore, in open loop, control commands u_{k_LN1} and u_{k_LN2} are fixed values, which equal half of the carrier amplitude. As shown in Fig. 2 (b), same to the closed loop, the control commands are compared with the carrier signals, from which gate signals are derived.

According to Fig. 2 (b), at the midpoint N

$$i_{LN} + C_{N1} \frac{d}{dt}(V_{dc} - v_{CN2}) = C_{N2} \frac{d}{dt} v_{CN2} + i_N. \quad (1)$$

Assuming that the dc bus voltage is constant, so $dV_{dc}/dt=0$, (1) becomes

$$i_{LN} - i_N \triangleq C_N \frac{d}{dt} v_{CN}, \quad (2)$$

where $C_N = C_{N1} + C_{N2}$ and $v_{CN} = v_{CN2}$. Therefore, the MVB can be simplified into a buck converter with dual switching legs, as shown in Fig. 3 (a) [9]. This buck converter is connected to a capacitor C_N and a current source I_N .

As mentioned before, the duty cycle is 50% with switching pattern interleaved by 180° phase shift. Neglecting dead time effect, there are only two switching states. In state 1, S_1 and S_4 are switched on, S_2 and S_3 are switched off; in state 2, the switches work in the opposite. Both states last half switching period T_s . Fig. 3 (b) shows some key waveforms of the MVB under different switching states. Note that the dotted lines in Fig. 3 (b) are meant for inductor currents of the MVB with coupled neutral inductor, which is covered in the next section.

In state 1, the inductor voltages are represented as

$$v_{LN1} = V_{dc} - V_{CN}, \quad (3)$$

$$v_{LN2} = V_{dc} - V_{CN}. \quad (4)$$

Fig. 2: Control implementation of the MVB with (a) dual loop with active damping and with (b) sensorless approach

Fig. 3: (a) Simplified circuit of the MVB. (b) Key waveforms of the MVB under different switching states

The current through L_{N1} increases, while the current through L_{N2} decreases. Assume that the inductance of both inductors is equal, $L_{N1}=L_{N2}=L_N$. Since the duty cycle is 50%, $V_{CN}=V_{dc}/2$. The inductor current change during each switching cycle are expressed as

$$|\Delta i_{LN1}^+| = |\Delta i_{LN2}^-| = \frac{V_{CN}}{2L_N} T_s. \quad (5)$$

Similarly, in state 2, the inductor current change during each switching cycle are denoted as

$$|\Delta i_{LN1}^-| = |\Delta i_{LN2}^+| = \frac{V_{CN}}{2L_N} T_s. \quad (6)$$

Based on (5) and (6), the increment and decrement of neutral inductor current in each switching cycle are equal. Therefore, the current ripple on the two neutral inductor counteracts each other. Ideally, the total inductor current i_{LN} is a straight line and ripple-free, as shown in Fig. 3 (b)

Passive component design

Because of sensorless approach, design of the neutral inductors and dc split capacitors are particularly crucial. According to (2), if i_{LN} counteracts i_N , no current flows into C_N , which stabilizes the neutral voltage v_{CN} . This requires the impedance of the neutral inductor branch to be much smaller than that of the split capacitor branch at selected frequencies, which range from grid fundamental and its harmonic up to 13th order as indicated in Table 1. In closed loop, impedance reduction of the neutral inductor branch is achieved by paralleling a virtual impedance to the existing inductor [9, 10]. However, this requires multiple sensors and multiloop control implementation. The sensorless approach proposed in this paper removes the need for control loops and keeps the neutral point voltage stable by selecting appropriate neutral inductors and split capacitors.

Fig. 4: MVB impedance model for (a) state 1 and (b) state 2

Fig. 5: Equivalent circuit of the MVB with coupled neutral inductors

Split capacitor

As mentioned before, the MVB only has two switching states. At any given time, one of the neutral inductors is connected to the positive potential of the dc bus, while the other is connected to the negative. The circuit diagram of an impedance model of the MVB is shown in Fig. 4, where the neutral inductors L_{N1} , L_{N2} , and the split capacitors C_{N1} , C_{N2} are represented by Z_{LN1} , Z_{LN2} , Z_{CN1} , Z_{CN2} , respectively. Based on the assumption that L_{N1} equals L_{N2} , thus $Z_{LN1}=Z_{LN2}=Z_{LN}$. Therefore, the voltage of the neutral point N is expressed as

$$V_N = \left[\frac{Z_{CN1}}{Z_{CN2}} \left(\frac{Z_{LN} + Z_{CN2}}{Z_{LN} + Z_{CN1}} \right) + 1 \right]^{-1} V_{dc}. \quad (7)$$

Given the premise that

$$\begin{cases} Z_{LN} \ll Z_{CN1} \\ Z_{LN} \ll Z_{CN2} \end{cases} \quad (8)$$

at frequencies of interest, equation (7) becomes

$$V_N = \frac{V_{dc}}{2}. \quad (9)$$

Therefore, as long as (8) is satisfied, the neutral point voltage V_N equals half of the dc bus voltage, even if the split capacitors does not match in capacitance.

In [6], the neutral inductance is designed to be $L_N=220 \mu\text{H}$, such that the IGBTs of the MVB operate in ZVS mode under a wide neutral current injection range ($I_N \leq 29 \text{ A}_{\text{rms}}$). Under this circumstance, the neutral inductor currents i_{LN1} , i_{LN2} cross zero at any given switching cycle when the neutral current i_N is less than the nominal phase current I_{abc} . Re-arrangement of (8) yields

$$(C_{N1}, C_{N2}) \ll 1/\omega^2 L_N, \quad \omega \in \{50 \cdot 2\pi, 150 \cdot 2\pi, \dots 650 \cdot 2\pi\}. \quad (10)$$

where $\omega = 2\pi f_N$ and f_N is the frequency of the neutral current, ranging from 50 Hz to 650 Hz.

Therefore, two split capacitors of $10 \mu\text{F}$ are selected to meet the requirement of (10). Note that C_{N1} and C_{N2} can be different without deteriorating the neutral point voltage stabilization of the 3P4W converter. In addition, the tolerance of the neutral point voltage stability to split capacitance mismatch is verified through experiments.

Neutral inductor

Interleaved control of two switching legs significantly reduces the output current ripple of i_{LN} . However, the inductor current ripple remains unchanged. On the one hand, inductor current ripple is deliberately increased to facilitate ZVS of the MVB. On the other hand, less inductor current ripple is desired to reduce copper loss. In this paper, neutral inductor coupling is employed to address the trade-off between current ripple and power loss.

By coupling the neutral inductors, as shown in Fig. 5, in a way that the derived ideal transformer is connected out of phase with the polarity dots on opposite ends, one obtains the MVB with coupled neutral inductors. The coupled inductor is represented as an ideal 1:1 transformer, two leakage inductors L_{lk1} , L_{lk2} , and a magnetizing inductor L_m [11]. Same to the MVB with independent inductors, there are only 2 operational states of the MVB with the coupled inductors.

In state 1, the inductor voltages are represented as (3) and (4). As elaborated in [11], the current changes through neutral inductors in this state are

$$\Delta i_{LN1}^+ = \frac{V_{CN}}{L_{lk}} \left(\frac{1-D-kD}{(1+k)D} \right) DT_s, \quad (11)$$

$$\Delta i_{LN2}^- = \frac{V_{CN}}{L_{lk}} \left(\frac{k-D-kD}{(1+k)D} \right) DT_s, \quad (12)$$

where k is the coupling coefficient of the coupled inductor, L_s is the self-inductance, and $k = L_m/L_s$, $L_s = L_{lk} + L_m$. Since the duty cycle D is always 50%, the inductor current changes are denoted

$$|\Delta i_{LN1}^+| = |\Delta i_{LN2}^-| = \frac{V_{CN}}{2L_s} \left(\frac{1}{1+k} \right) T_s. \quad (13)$$

Similarly, in state 2, the current changes are expressed as

$$|\Delta i_{LN1}^-| = |\Delta i_{LN2}^+| = \frac{V_{CN}}{2L_s} \left(\frac{1}{1+k} \right) T_s. \quad (14)$$

For a transformer with perfect coupling, the leakage inductance L_{lk} is zero, and the coupling coefficient k is then equal to 1. Compared to (5) and (6), it is beneficial to build a coupled inductor with $k \approx 1$. Therefore, the current ripple through the coupled neutral inductor Δi_{Lc} is half of that through the independent neutral inductors Δi_{Li} , as shown in Fig. 3 (b) and expressed as

$$\lim_{k \rightarrow 1} \Delta i_{Lc} = \frac{\lim_{k \rightarrow 1} \Delta i_{Li}}{2}. \quad (15)$$

However, as mentioned before, the neutral inductor current ripple is deliberately brought up to maintain ZVS operation under a wide neutral current injection range. To preserve the same amount of inductor current ripple, a 50% neutral inductance reduction becomes a good alternative, hence $L_{N1}=L_{N2}=110 \mu\text{H}$.

Experimental verification

In order to verify the effective of the proposed MVB, A 20 kVA 3P4W grid-connected converter prototype is built. Main components of the converter are shown in Fig. 6. Key specifications of the converter has already been presented in Table 1. The converter provides harmonic mitigation and voltage unbalance compensation to the PCC. Two three-phase IGBT modules are adopted in the prototype. A dSPACE MicroLabBox is employed to handle current and voltage signal acquisition and PWM signal generation.

Key waveforms of one switching leg during switching operation are shown in Fig. 7. These waveforms include gate signal of S_2 , neutral inductor current i_{LN1} , current through S_2 , and voltage across S_2 . The conventions of these signals are referred in Fig. 5. The inductor current has a high current ripple, and it crosses zero at every switching cycle. During switching period T_1 , gate signal G_2 is positive, however, $i_{S2} \leq 0$, diode D_2 conducts until the current reverses its polarity. During switching period T_2 , G_2 is still positive, $i_{S2} > 0$, S_2 conducts until the G_2 goes to negative. After that, in T_3 , D_1 conducts and in T_4 , S_1 conducts. S_2 operates in hard turn-off at the transition between T_2 and T_3 , as shown in Fig. 7. However,

Fig. 6: Main components the 20-kVA 3P4W grid-connected converter with proposed MVB

Fig. 7: Voltage and current waveforms of leg S_1 , S_2 during switching operation

since the anti-parallel diode D_2 conducts before S_2 , there is only a diode forward voltage across the emitter and the collector during the turn-on of S_2 . As a result, the turn-on loss of S_2 is almost zero. This operational principle also applies to S_1 , S_3 and S_4 . Therefore, the ZVS turn-on is great advantage of the MVB, since turn-on loss of IGBT is normally higher than turn-off losses due to diode reverse recovery.

The 3P4W converter injects unbalanced current i_a , i_b , i_c to the PCC, such that a certain amount of i_N is injected to the neutral point. Due to component availability, coupled inductor whose self-inductance is $85 \mu\text{H}$ is chosen instead of $110 \mu\text{H}$. To verify the response of the proposed MVB, experimental tests under four different cases were performed, as described in the following.

- Case 1: Open loop based on independent inductors with $C_{N1}=C_{N2}=10 \mu\text{F}$, $L_{N1}=L_{N2}=220 \mu\text{H}$.
- Case 2: Closed loop based on independent inductors with $C_{N1}=C_{N2}=100 \mu\text{F}$, $L_{N1}=L_{N2}=220 \mu\text{H}$.
- Case 3: Open loop based on coupled inductor with $C_{N1}=C_{N2}=10 \mu\text{F}$, $L_{N1}=L_{N2}=85 \mu\text{H}$.
- Case 4: Open loop based on coupled inductor with $C_{N1}=5 \mu\text{F}$, $C_{N2}=10 \mu\text{F}$, and $L_{N1}=L_{N2}=85 \mu\text{H}$.

The test results of case 1 are shown in Fig. 8, which includes PCC voltage v_{an} , v_{bn} , v_{cn} , converter output currents i_a , i_b , i_c , neutral current i_N , neutral voltage v_{CN} , and inductor currents i_{LN1} , i_{LN2} , i_{LN} . A sudden output current change happens at 3.13 s, which results in a neutral current transient of $32 \text{ A}_{\text{peak}}$. The neutral current flows into the midpoint of the dc bus and it is re-directed to the inductor branch. Even with open-loop approach, the MVB reacts to the transient within half a grid cycle, maintaining the voltage ripple of the neutral point around 20 V. Due to interleaving operation, the current ripple across two inductors counteracts each other. As a result, the output current i_{LN} is almost ripple free, keeping the split capacitors from high-frequency current circulation.

Fig. 9 shows the test results of the MVB under case 2. It contains i_N , v_{CN} , i_{LN1} , i_{LN2} , and i_{LN} . Similarly, a neutral current transient of $60 \text{ A}_{\text{peak}}$ is created at 2.44 s to verify the dynamic response of the MVB. It takes the MVB around two grid cycles to fully react to the neutral current transient, and to maintain the

Fig. 8: Experimental results of case 1: (a) voltages v_{an} , v_{bn} , v_{cn} . (b) currents i_a , i_b , i_c . (c) i_N (d) voltage v_{CN} . (e) currents i_{LN1} , i_{LN2} , and i_{LN} . (f) currents i_{LN1} , i_{LN2} , and i_{LN} in high-frequency detail

Fig. 9: Experimental results of case 2: (a) voltage v_{CN} . (b) currents i_{LN1} , i_{LN2} , and i_{LN}

Fig. 10: Experimental results of case 3: (a) voltages v_{an} , v_{bn} , v_{cn} . (b) currents i_a , i_b , i_c . (c) i_N (d) voltage v_{CN} . (e) currents i_{LN1} , i_{LN2} , and i_{LN} . (f) currents i_{LN1} , i_{LN2} , and i_{LN} in high-frequency detail

neutral point voltage ripple around 20 V. Same to the test in case 1, the interleaving operation alleviates

Fig. 11: Experimental results of case 4: (a) i_N . (b) v_{CN}

Table 2: Comparison of the open-loop MVB described in this paper and closed-loop MVB in [6]

Comparison	Parameter/Condition	Open-loop MVB	Close-loop MVB
Quantity of sensors	Voltage sensor	0	2
	Current sensor	0	2-3 ¹
Control loop	Loop implementation	Open loop	Dual loop
Passive components	Neutral inductance	110 μH^2	220 μH
	Split capacitance	10 μF	100 μF
Tolerance to	Split capacitance mismatch	High	Medium
	Neutral inductance mismatch	Medium	High
Steady-state performance	Max. neutral current at 50 Hz ³	40 A_{peak}	60 A_{peak}
Dynamic performance	Neutral current transient	Fast	Relatively fast

1. Since the neutral current signal can be constructed by adding three-phase current measurements together, so the sensor necessary for the close-loop MVB ranges from 2 to 3.
2. In correspondence to the theoretical analysis, the neutral inductance should be 110 μH . However, due to component availability, a coupled inductor with self-inductance of 85 μH is used in the experiments.
3. The neutral current handling performance of the MVB is evaluated under a desired maximum neutral point voltage ripple.

the high-frequency current circulation in the split capacitors. This means that capacitors with low RMS rating are sufficient for the proposed MVB.

Test on case 3 is performed to verify the effectiveness of the coupled neutral inductor, with results shown in Fig. 10. These results include v_{an} , v_{bn} , v_{cn} , i_a , i_b , i_c , i_N , v_{CN} , i_{LN1} , i_{LN2} , and i_{LN} . Neutral current transient is introduced at 2.44 s. The MVB reacts to the transient within half a grid cycle and keeps the neutral point voltage ripple around 15 V. Even though, the self-inductance of the coupled inductor is 39% of that in case 1, the average current ripple across the coupled inductor is just 47% more than that in case 1. Due to some piratical issues, the coupling coefficient of the inductor is never 1, and the leakage inductance L_{k1} and L_{k2} are not the same. As it shown in Fig. 10 (f), currents i_{LN1} and i_{LN2} does not cancel each other fully, which results a 9.4 A_{peak} current ripple in i_{LN} . Nevertheless, the coupled implementation of the neutral inductors is a way to reduce core and copper use of the proposed MVB.

In order to show voltage stability tolerance to split capacitance mismatch, C_{N1} is chosen to be 100% more than that of C_{N2} . The test results of case 4 is shown in Fig. 11, which includes waveforms of i_N and v_{CN} . The MVB regulates the neutral point voltage to half of the dc bus voltage with ripple around 15 V rapidly. It can be concluded that the dynamic performance of the MVB is not compromised under split capacitance mismatch.

The comparison between the open loop regulated MVB with sensorless approach and the closed loop controlled MVB is summarized in Table 2. The open loop regulated MVB is inferior in terms of neutral current handling capacity and tolerance to neutral inductance asymmetry. However, considering the fast-dynamic performance, absence of control loops and sensor, as well as small passive components, the proposed MVB is a cost-effective and robust alternative to the closed loop controlled MVB.

Conclusion

A voltage stable neutral point is essential to normal operation of 3P4W converters, especially those in voltage imbalance compensation applications. An unstable neutral point could lead to undesired output current distortion, which degrades the compensation performance of the converter at PCC. This paper proposes a cost-effective and robust MVB for neutral point voltage stabilization in 3P4W converters.

The MVB requires no current nor voltage measurements, and it operates in open loop mode. The passive components (110 μ H and 10 μ F respectively) are carefully selected so that most of the neutral current is re-directed into the inductor branch, keeping the neutral voltage stable. Coupled implementation of neutral inductor is adopted, which cuts the required inductance to half. In order to achieve the best result, high coupling coefficient and symmetrical inductor construction are desired. Due to interleaving operation, high-frequency current circulation inside the split capacitor branch is alleviated. All IGBT switches of the MVB operates under ZVS when the neutral current is less than the nominal phase current of the 3P4W converter.

Compared to the closed loop counterpart, the sensorless approach does reduce the neutral current handling capability of the MVB by about 33%. However, it stabilizes the neutral point voltage much faster by around 300%. In addition, the performance of the proposed MVB is not compromised even under a 100% split capacitance mismatch.

References

- [1] M. Dai, M. N. Marwali, J.-W. Jung, and A. Keyhani, "A three-phase four-wire inverter control technique for a single distributed generation unit in island mode," *IEEE Transactions on power electronics*, vol. 23, pp. 322-331, 2008.
- [2] R. S. R. Chilipi, N. A. Sayari, K. H. A. Hosani, and A. R. Beig, "Adaptive Notch Filter-Based Multipurpose Control Scheme for Grid-Interfaced Three-Phase Four-Wire DG Inverter," *IEEE Transactions on Industry Applications*, vol. 53, pp. 4015-4027, 2017.
- [3] M. Aredes, J. Hafner, and K. Heumann, "Three-phase four-wire shunt active filter control strategies," *IEEE Transactions on Power Electronics*, vol. 12, pp. 311-318, 1997.
- [4] R. Zhang, V. H. Prasad, D. Boroyevich, and F. C. Lee, "Three-dimensional space vector modulation for four-leg voltage-source converters," *IEEE Transactions on power electronics*, vol. 17, pp. 314-326, 2002.
- [5] M. K. Mishra, A. Joshi, and A. Ghosh, "Control schemes for equalization of capacitor voltages in neutral clamped shunt compensator," *IEEE Transactions on Power Delivery*, vol. 18, pp. 538-544, 2003.
- [6] X. Xu, G. Tibola, J. Duarte, and F. Wang, "Fast Voltage Stabilization Control of Split DC Bus Midpoint in 3P4W Shunt APFs," presented at the 21st European Conference on Power Electronics and Applications, Genova, 2019.
- [7] W. Li and X. He, "Review of nonisolated high-step-up DC/DC converters in photovoltaic grid-connected applications," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 1239-1250, 2011.
- [8] X. Xu, "Midpoint voltage stabilization of split DC bus in three-phase four-wire shunt active power filters: prototyping of a midpoint voltage balancer for the ECSEL JU funded project CONNECT," PDEng Thesis, Eindhoven University of Technology, Eindhoven, 2019.
- [9] W. Zhao, X. Ruan, D. Yang, X. Chen, and L. Jia, "Neutral Point Voltage Ripple Suppression for a Three-Phase Four-Wire Inverter With an Independently Controlled Neutral Module," *IEEE Transactions on Industrial Electronics*, vol. 64, pp. 2608-2619, 2017.
- [10] K. K. Patricio Cortes Estay, Armin Schmiegell, "Method for DC-Link Voltage Balancing for a Grid-Connected Inverter in Case of Asymmetric Operation," in *19th European Conference on Power Electronics and Applications*, Warsaw, Poland, 2017.
- [11] J.-P. Lee, H. Cha, D. Shin, K.-J. Lee, D.-W. Yoo, and J.-Y. Yoo, "Analysis and design of coupled inductors for two-phase interleaved DC-DC converters," *Journal of power electronics*, vol. 13, pp. 339-348, 2013.