Three Phase Cascaded 7 Level Current Source Inverter Fed Dc – Dc Converter In Uninterruptable Power Supplies

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Abstract - In this paper, a ZVS-PWM three-phase current fed push–pull dc–dc converter is proposed. When compared to single-phase topologies, the three-phase dc–dc conversion increases the power density, uses the magnetic core of the transformer more efficiently, reduces the stress on switches, and requires smaller filters since the frequency for its design is higher.

The proposed converter employs an active clamping technique by connecting the primary side of the transformer to a three-phase full bridge of switches and a clamping capacitor. This circuit allows the energy from the leakage inductances to be reused, increasing the efficiency of the converter. If appropriate parameters are chosen, soft-commutation of the switches (ZVS) can also be achieved. The soft-commutation improves the efficiency even further, allows higher switching frequencies to be used, and reduces the electromagnetic interference significantly. Applications such as fuel cell systems, transportation, and uninterruptable power supplies are some examples that can benefit from the advantages presented by this converter. The theoretical analysis, a design example, and the experimental results for a prototype implementing this topology are presented. The prototype was designed to process 4 kWat full load with an input voltage of 120 V, an output voltage of 400 V, and a switching frequency of 40 kHz.

Index Terms—Active clamping, dc–dc power conversion, multiphase, soft-commutation.

I. Introduction

The electric power generation, transmission, and distribution employ three-phase systems for economic reasons. The three-phase systems allow higher power density, the use of less material, and higher efficiency than equivalent single phase systems. In addition, the three-phase systems present constant average power over the time as a result of the phase angle differences. The same advantages encourage the use of three phase rectifiers and inverters.

Many industrial applications require high-power dc–dc conversion. These applications include distributed generation, uninterruptable power supplies, and transportation. The conventional isolated dc–dc converters use single-phase transformers, which are often big and heavy, and single-phase rectifiers.

Aiming at benefiting from three-phase systems advantages, some work have been done to use dc–dc converters that use a three-phase high-frequency transformer and a three-phase rectifier.

These changes contribute to lower volume, weight, and cost of the overall system.

Three-phase dc–dc converters have presented good performance when high-frequency isolation is desired, high components stresses are faced, and the reduction of the filters is required [1]. Some different topologies [2], [3] as well as soft commutation techniques [2], [4]–[6] were presented. In recent years, work has been done to apply three-phase dc– dc conversion to fuel cell energy processing [7]–[10] and batteries in automotive devices [11], which exemplify the potential of these converters in applications where the source voltage is low.

This paper proposes a three-phase current-fed dc–dc push– pull converter inspired by the conventional single-phase counterpart. In the proposed converter, the isolation between the power source and the load is provided by a high-frequency three-phase transformer, the losses are better distributed than in a single phase topology, and the chopping frequencies of the input current and output voltage are three times higher than the switching frequency, which reduces the size requirements for the filter. As in the converter of [12], the active switches are connected to the same reference, which simplifies the gate drive circuits, and presents boost characteristics for a unity transformer turns ratio, but only uses one input inductor.

Potentially, the proposed three-phase dc–dc converter is a good candidate to be widely used in fuel cell and photovoltaic applications.

Three-phase systems are well known by their use in electric power generation transmission and distribution. The cost saving that they provide by employing less material than single-phase systems assured success in these areas and led to three-phase rectifiers, inverters, and also dc–dc converters. Industrial environments have an increasing need for highefficiency dc–dc converters. Applications including distributed generation and uninterruptable power supplies generally count on single-phase dc–dc converters with big and heavy transformers.

The high volume associated with these converters makes them an expensive choice, and their use in the transportation area is sometimes impossible. The introduction of high-frequency three-phase transformers on dc–dc converters brought the possibility of increasing power density, using the magnetic cores more efficiently and reducing the current stress on power switches. In addition, the increase in the high-frequency component seen by the filters allowed the use of much smaller inductors and capacitors [1].

After this, other three-phase dc–dc converter topologies were developed and compared [2], and techniques to increase the efficiency even more using soft-commutation [3]–[5] and reducing the number of semiconductors in the output rectifier bridge [6] were studied. Most studies conclude that the three-phase structures perform better than their single-phase counterparts [7]–[9].

However, depending on the topology, the voltage across the witches is not naturally clamped, requiring passive voltage clampers that dissipate energy stored in the leakage inductances [10]–[13] to prevent overvoltage. This energy loss reduces the efficiency of the converter. In order to avoid this problem, active clamping techniques have already been presented for single-phase converters and have successfully reused the energy that would be dissipated both in nonisolated [14] and isolated topologies [15]. To sum up, soft-commutation (ZVS) was also achieved with a correct parametric combination.

This paper proposes a three-phase current-fed push–pull dc–dc converter where the active clamping is performed, improving the topology presented in [12] and bringing the advantages
of this technique to the three-phase dc–dc conversion. In this topology, a full three-phase bridge and a clamping capacitor on the primary side of the transformer are responsible for the active clamping without the need for an extra switch [16]. The switching losses can be significantly reduced, and electromagnetic interference is minimized as long as soft-commutation (ZVS) is achieved using appropriate parameters. As usual in three-phase topologies, the filters are designed for a frequency that is three times higher than the switching frequency, allowing size reduction.

In the future, the proposed converter could be applied as a high-efficiency alternative to many applications such as the energy processing of photovoltaic arrays and fuel cell systems [17]–[20] or automotive devices [21] and fuel cell powered vehicles 22], where the three-phase dc–dc conversion is already showing its benefits.

II. LITERATURE SURVEY

The electric power generation, transmission, and distribution employ three-phase systems for economic reasons. The three-phase systems allow higher power density, the use of less material, and higher efficiency than equivalent single phase systems. In addition, the three-phase systems present constant average power over the time as a result of the phase angle differences. The same advantages encourage the use of three phase rectifiers and inverters.

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III. PROPOSED METHOD

The circuit of the proposed ZVS-PWM three-phase currentfed push–pull dc–dc converter is shown in Fig. 1. Switches S`1,S`2, and S`3 and the capacitor *Cg* were added to the converter presented in [12] in order to achieve active clamping. Inductances

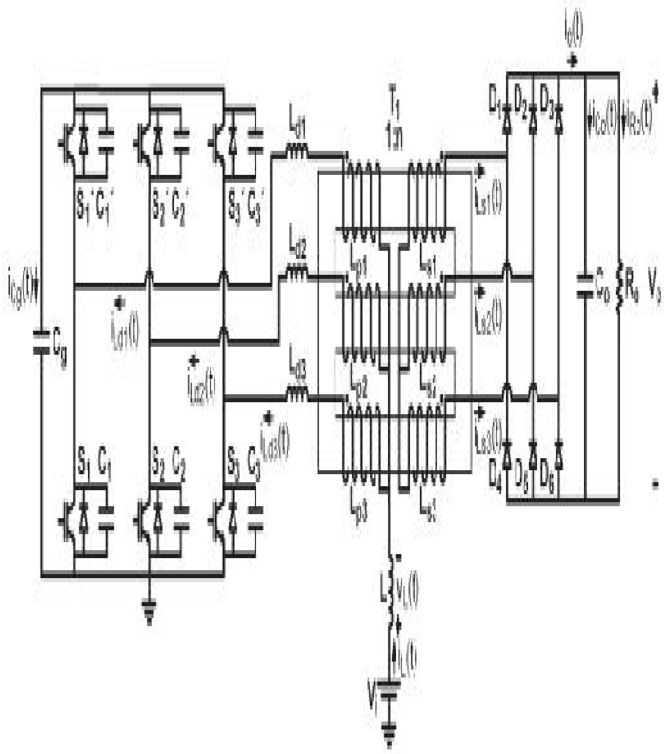


Fig. 1. Circuit of the proposed ZVS-PWM three-phase current-fed push–pull dc–dc converter

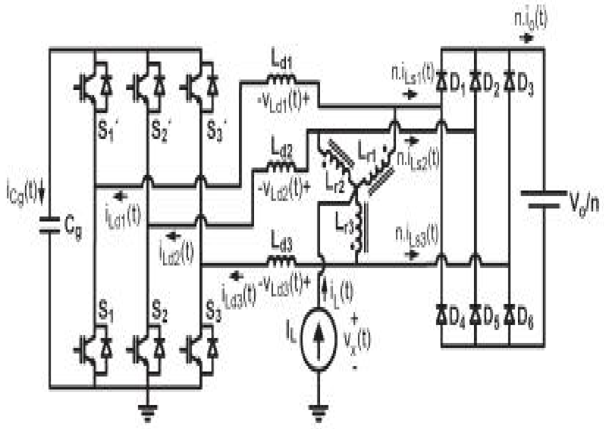


Fig. 2. Simplified nonisolated version of the active-clamped three-phase current-fed push–pull dc–dc converter

*Ld*1, *Ld*2, and *L*d3 are responsible for maintaining the current during the commutation intervals. They represent the sum of the leakage inductance of the transformer and an external inductance, which is added to each phase if needed. The addition of capacitors *C*1, *C*` 1, *C*2, *C*` 2, *C*3, and *C*`
3 and appropriate dead time between main and complementary gate signals provide the possibility to operate with soft-commutation.

B. Simplified Circuit

Despite the complete circuit being the one shown in Fig. 1, the analysis can be simplified, maintaining the same waveforms using the circuit of Fig. 2. This circuit, which will be used to describe the operation stages, represents the nonisolated equivalent version of the proposed converter with current source input and voltage source output. The transformer was substituted by a coupled three-phase reactor. Voltages and currents originally from the secondary side are referred to the primary side in this circuit. The time intervals related to the commutations will not be considered during the description of the operation stages due to being very short and interfering very little in the voltage gain. The commutation will be discussed separately in a later section.

C. Modulation

The gate signals are generated by the comparison of the modulating signal *VM* and three saw tooth carriers 120◦ out of phase from each other. Fig. 3 shows the resulting gate signals. *VG*1, *VG*2, and *VG*3 are the gate signals of S1, S2, and S3, respectively, and *V* `*G*1, *V* `*G*2, and *V*`*G*3 are the gate signals of switches S`1, S`2, and S`3, respectively.

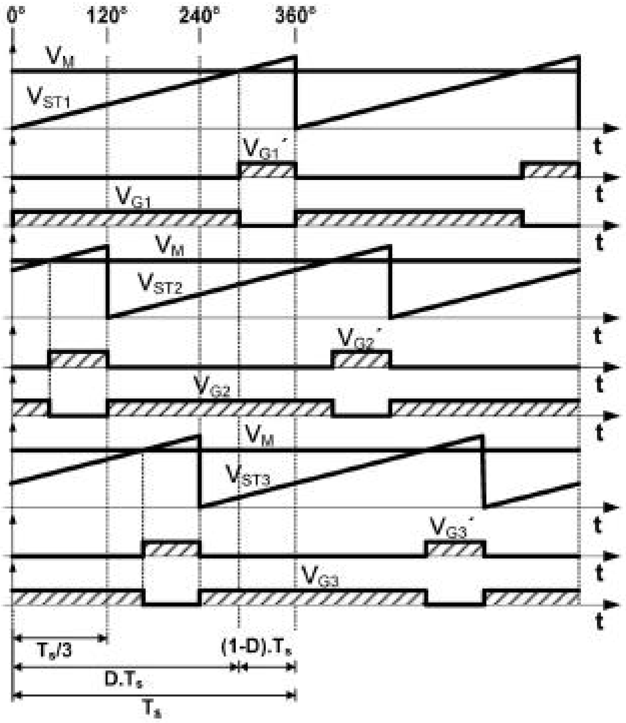


Fig. 3. Signals generated by the modulator.

The proposed converter presents three different operation regions depending on the duty cycle *D* according to Table I. The topology studied in this paper is capable of operating in the

Region	Duty cycle	Switches simultaneously on
R1	0 < D < 1/3	None
R2	1/3 ≤ D ≤ 2/3	Up to two
R3	2/3 < D < 1	Up to three

Table I operation regions

three regions defined by Table I differently from the converter presented in [12] which could not operate in region R1 due to the absence of a demagnetizing path for the inductor. The converter proposed in this paper can transfer energy stored in the input inductor to the clamping capacitor if operation in region R1 is desired.

In this paper, this converter will be analyzed for operation in region R3. Operating in region R3 proves the principle of the active clamping in this topology for the worst case as, the higher the duty cycle is, the higher is the voltage across the switches. A good design for the other regions could achieve an even better result.

. Operation in Region R3

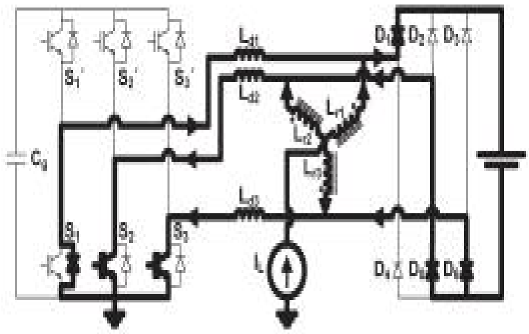
Operating in region R3, the proposed converter has nine topological stages per switching period that can be described as follows.

Before the first stage, S` 1, S2, and S3 are already conducting.

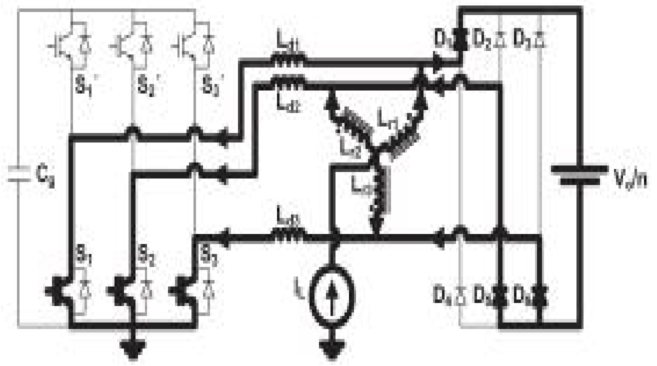
1) First stage (*t*0, *t*1)—Starts when switch S1 is turned on before this stage, S` 1 was conducting, and capacitor *Cg* was delivering energy. Current *i*Ld1(*t*), initially negative and equal to −*IL*/3, increases linearly through the intrinsic diode of S1, as shown in Fig. 4(a), becoming positive and increasing its value though S1 until reaching *IL*/3, as shown in Fig. 4(b). Currents *i*Ld2(*t*) and *i*Ld3(*t*) decrease linearly from 2*IL*/3 to *IL*/3 through switches S2 and S3, respectively. The load receives energy from the commutation inductances through diodes D1, D5, and D6. The source does not transfer energy to the load during this stage.

2) Second stage (*t*1, *t*2)—Starts when currents *i*Ld1(*t*), *i*Ld2(*t*), and *i*Ld3(*t*) are equal to *IL*/3. Currents *i*Ld1(*t*), *i*Ld2(*t*), and *i*Ld3(*t*) remain at *IL*/3, and the diodes of the rectifier bridge remain off. This stage can be seen in Fig. 4(c). The source does not transfer energy to the load during this stage.

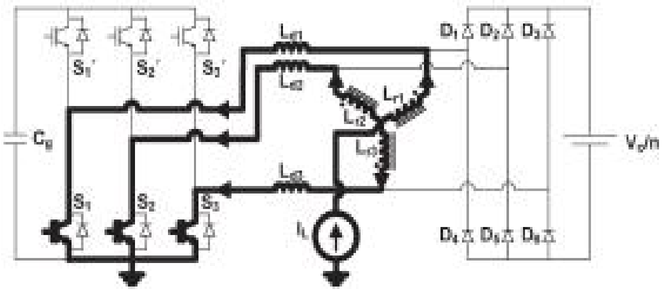
3) Third stage (*t*2, *t*3)—Starts when switch S2 is turned off. Current *i*Ld2(*t*) decreases linearly from *IL*/3 through the intrinsic diode of S` 2, as shown in Fig. 4(d), and then, it is equal to zero and starts to increase negatively, as shown in Fig. 4(e), until it reaches −*IL*/3. In Fig. 4(d), the clamping capacitor *Cg* receives energy from the commutation inductance, and in Fig. 4(e), the capacitor *Cg* returns this energy. Currents *i*Ld1(*t*) and *i*Ld3(*t*) increase linearly from *IL*/3 to 2*IL*/3 through switches S1 and S3, respectively. The load receives energy from the source through diodes D2, D4, and D6.



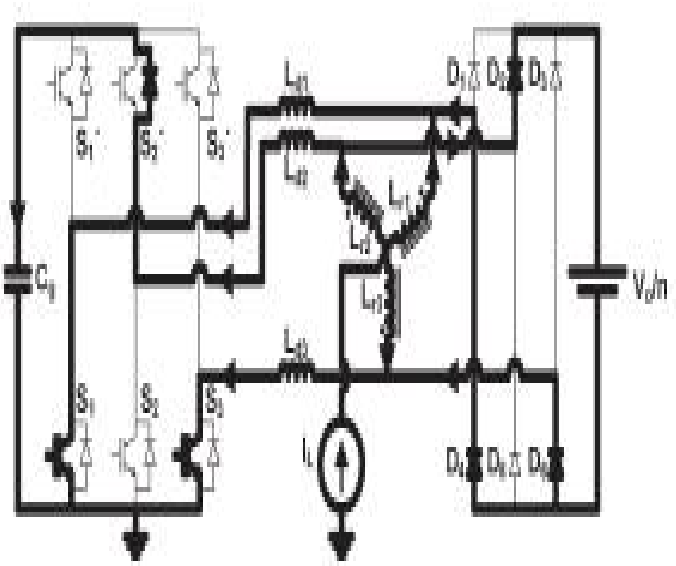
(a)



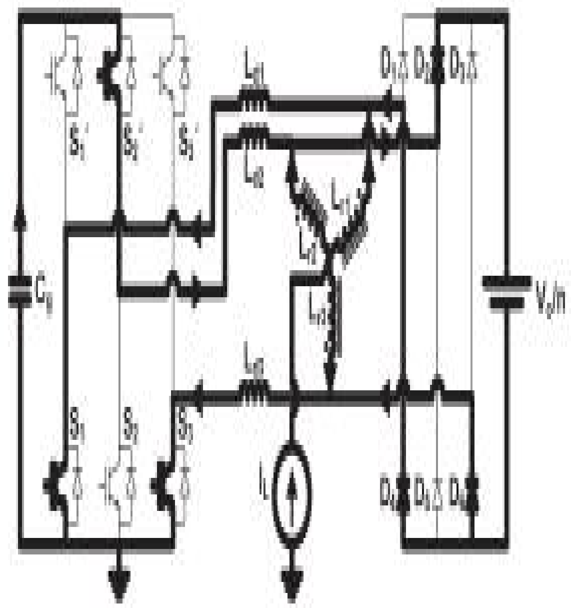
(b)



(c)



(d)



(e)

Fig. 4. Topological stages. (a) First stage—part 1. (b) First stage—part 2. (c) Second stage. (d) Third stage—part 1. (e) Third stage—part 2.

The fourth and seventh topological stages are similar to the first stage, the fifth and eighth topological stages are similar to the second stage, and the sixth and ninth stages are similar to the third stage. The only difference is that other switches are on. After the ninth stage, the switching period is complete, and a new period starts with the first stage.

The main voltages of the circuit during the described stages are shown in Table II. The main theoretical waveforms for region R3 are shown in Fig. 5, whose time intervals are described by equations as presented in Table III. The waveforms shown in Fig. 5 and the voltages presented in Table II correspond to the symbols presented previously in Figs. 1 and 2.

Voltage	1st Stage	2nd Stage	3rd Stage
$v_{Lr1}(t)$	$\frac{2}{3}\cdot\left(\frac{V_o}{n}\right)$	0	$-\frac{1}{3}\cdot\left(\frac{V_o}{n}\right)$
$v_{Lr2}(t)$	$-\frac{1}{3}\cdot\left(\frac{V_o}{n}\right)$	0	$\frac{2}{3}\cdot\left(\frac{V_o}{n}\right)$
$v_{Lr3}(t)$	$-\frac{1}{3}\cdot\left(\frac{V_o}{n}\right)$	0	$-\frac{1}{3}\cdot\left(\frac{V_o}{n}\right)$
$v_{Ld1}(t)$	$\frac{2}{3}\cdot\left(\frac{V_o}{n}\right)$	0	$\frac{1}{3}\cdot\left(V_{Cg}-\frac{V_o}{n}\right)$
$v_{Ld2}(t)$	$-\frac{1}{3}\cdot\left(\frac{V_o}{n}\right)$	0	$-\frac{2}{3}\cdot\left(V_{Cg}-\frac{V_o}{n}\right)$
$v_{Ld3}(t)$	$-\frac{1}{3}\cdot\left(\frac{V_o}{n}\right)$	0	$\frac{1}{3}\cdot\left(V_{Cg}-\frac{V_o}{n}\right)$
$v_s(t)$	0	0	$\frac{V_{Cg}}{3}$

Table II main voltages during each topological stage

B. Voltage Gain

Equation (1) is the average current through the clamping capacitor *Cg*

$$\frac{3}{T_s}\cdot\int_0^{(1-D)\cdot T_s}\left(\frac{I_L}{3}+\frac{V_{Ld2}}{L_d}\cdot t\right)\cdot dt=0. \quad (1)$$

Substituting *V*Ld2 during the third stage from Table II in (1) and solving the integral yield

$$V_{Cg}-\frac{V_o}{n}=\frac{L_d\cdot f_s\cdot I_L}{1-D}. \quad (2)$$

Considering the analysis that there are no losses in the converter, the following is valid

Vi ・ IL = Vo ・ Io . (3)

Substituting *IL* from (3) in (2), the following is found

$$\frac{V_{Cg}}{V_o}=\frac{\overline{I_o}}{1-D}+\frac{1}{n} \quad (4)$$

where *Io* is given by

$$\overline{I_o}=\frac{L_d\cdot f_s\cdot I_o}{V_i}. \quad (5)$$

As the average voltage across the inductors is zero, the average voltage across the switches S1, S2, and S3 is the input voltage *Vi*, and the following can be written

Vi = (1 − *D*) ・ *V*Cg. (6)

Equation (6) leads to the input–clamping capacitor voltage gain shown in

$$\frac{V_{Cg}}{V_i}=\frac{1}{1-D}. \quad (7)$$

CONCLUSION

In this paper, a ZVS-PWM three-phase current-fed push–pull dc–dc converter has been proposed. The operation stages were described, and the main waveforms were plotted. The equations of voltage gain and the equations involving the commutation parameters were derived to help the design process. A prototype was built for a rated power of 4 kW based on the parameters calculated in the design example. This prototype was able to operate with active clamping and soft-commutation (ZVS) of the MOSFETs. The waveforms acquired validate the theoretical analysis, and the measured efficiency for full load was 93.2%, remaining above 94% for most of the load range.

As an isolated topology, this converter presents competitive efficiency and can be applied with good performance as an energy processing stage for many renewable sources. The most suitable applications include distributed generation, uninterruptable power supplies, and transportation.

REFERENCES

[1] A. R. Prazad, P. D. Ziogas, and S.Manias, "Analysis and design of a three phase off-line dc–dc converter with high frequency isolation," in *Proc. IAS*, 1988, pp. 813–820.

[2] L. D. Salazar and P. D. Ziogas, "Design oriented analysis of two types of three-phase high frequency forward SMR topologies," in *Proc. 5th Annu. APEC*, Mar. 11–16, 1990, pp. 312–320.

[3] R. W. A. A. De Doncker, D. M. Divan, and M. H. Kheraluwala, "A three-phase soft-switched high-power-density dc/dc converter for highpower applications," *IEEE Trans. Ind. Appl.*, vol. 27, no. 1, pp. 63–73, Jan./Feb. 1991.

[4] J. Jacobs, A. Averberg, and R. De Doncker, "A novel three-phase dc/dc converter for high-power applications," in *Proc. Power Electron. Spec. Conf.*, Aachen, Germany, vol. 3, pp. 1861–1867.

[5] D. S. Oliveira, Jr. and I. Barbi, "A three-phase ZVS PWM dc/dc converter with asymmetrical duty cycle for high power applications," *IEEE Trans. Power Electron.*, vol. 20, no. 2, pp. 370–377, Mar. 2005.

[6] D. S. Oliveira, Jr. and I. Barbi, "A three-phase ZVS PWM converter with asymmetrical duty cycle associated with a three-phase version of the hybridge rectifier," *IEEE Trans. Power Electron.*, vol. 20, no. 2, pp. 354– 360, Mar. 2005.

[7] D. Segaran, D. G. Holmes, and B. P. McGrath, "Comparative analysis of single and three-phase dual active bridge bidirectional dc–dc converters," in *Proc. AUPEC*, Sydney, NSW, Australia, Dec. 2008, pp. 1–6.

[8] J. Aguillon-Garcia and G. W. Moon, "A high efficiency three-phase ZVS PWM converter utilizing a positive double-star active rectifier stage for server power supply," *IEEE Trans. Ind. Electron.*, vol. 58, no. 8, pp. 3317– 3329, Aug. 2011.

[9] D. Vinnikov and I. Roasto, "Quasi-Z-source-based isolated dc/dc converters for distributed power generation," *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 192–201, Jan. 2011.

[10] S. V. G. Oliveira and I. Barbi, "A three-phase step-up dc–dc converter with a three-phase high frequency transformer," in *Proc. IEEE ISIE*, Dubrovnik, Croatia, Jun. 2005, vol. 2, pp. 571–576.

[11] S. V. G. Oliveira and I. Barbi, "A three-phase step-up dc–dc converter with a three-phase high-frequency transformer for dc renewable power sources applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 8, pp. 3567–3580, Aug. 2011.

[12] R. L. Andersen and I. Barbi, "A three-phase current-fed push–pull dc–dc converter," *IEEE Trans. Power Electron.*, vol. 24, no. 2, pp. 358–368, Feb. 2009.

[13] H. R. E. Larico and I. Barbi, "Three-phase Weinberg isolated dc–dc converter: Analysis, design and experimentation," *IEEE Trans. Ind. Electron.*, vol. 59, no. 2, pp. 888–896, Feb. 2012.

[14] C. M. C. Duarte and I. Barbi, "An improved family of ZVS-PWM active clamping dc-to-dc converters," *IEEE Trans. Power Electron.*, vol. 17, no. 1, pp. 1–7, Jan. 2002.

[15] F. J. Nome and I. Barbi, "A ZVS clamping mode-current-fed push–pull dc–dc converter," in *Proc. IEEE ISIE*, Pretoria, South Africa, Jul. 7–10, 1998, vol. 2, pp. 617–621.

[16] H. Cha, J. Choi, and P. N. Enjeti, "A three-phase current-fed dc/dc converter with active clamp for low-dc renewable energy sources," *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp. 2784–2793, Nov. 2008.

[17] D. Liu and H. Li, "A three-port three-phase dc–dc converter for hybrid low voltage fuel cell and ultracapacitor," in *Proc. 32nd Annu. Conf. IEEE IECON*, Paris, France, Nov. 2006, pp. 2558–2563.

[18] S. R. Moon and J. S. Lai, "Multiphase isolated dc–dc converters for lowvoltage high-power fuel cell applications," in *Proc. 22nd Annu. IEEE APEC*, Anaheim, CA, Feb./Mar. 2007, pp. 1010–1016.

[19] H. Cha and P. Enjeti, "A novel three-phase high power current-fed dc/dc converter with active clamp for fuel cells," in *Proc. Power Electron. Spec. Conf.*, Orlando, FL, Jun. 2007, pp. 2485–2489.

[20] H. Cha, J. Choi, and B. Han, "A new three-phase interleaved isolated boost converter with active clamp for fuel cells," in *Proc. Power Electron. Spec. Conf.*, Rhodes, Greece, Jun. 2008, pp. 1271–1276.