

An interconnected single-star bridge-cell topology for grid support

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ARTICLE INFO

Keywords:

Cascade multilevel converter
DSTATCOM
Power quality
Single star bridge cells

ABSTRACT

This paper presents a novel transformerless interconnected cascade multilevel topology to improve the support of low- and medium-voltage distribution grids under unbalanced nonlinear loads. The proposed Interconnected Single-Star Bridge-Cells (iSSBC) is derived from the Single-Star Bridge-Cells (SSBC) and features the inclusion of three star-connected inductors, allowing the exchange of active power between the clusters. Therefore, the proposed topology can supply negative-sequence components to mitigate load disturbances at the grid-end current, enhancing the regulation capability in comparison to the SSBC. The power flux of the proposed topology is presented along with the control system. Experimental results validate the proposed topology combined to the proposed control system for grid current and dc voltage regulation under unbalanced nonlinear loads.

1. Introduction

The increase of power demand is growing steady worldwide. One way to postpone massive investments on power generation is to improve the transmission and distribution efficiency. A more efficient transmission/distribution grid has reduced losses, high power quality and power balance among the phases.

Existent solutions are based on distributed static synchronous compensator (DSTATCOM) with shunt connection to the grid [1–5]. The DSTATCOM is capable of absorb the reactive power as well as the harmonic distortions from the grid and/or the loads [6–8]. The aforementioned features guarantee the high power factor and contribute to the decrease of the losses. The power balance in the grid-end terminals is achieved by transferring active power between the phases, from the less to the more loaded phases.

The DSTATCOM can be implemented using wide range of converters. For medium-voltage high power converters, traditional two-level face technological limitations due to the high blocking voltage of the semiconductors and non-modular multilevel converters, i. e. diode- and capacitor-clamped multilevel, are impractical due to the massive number of clamping components [9]. To reduce the voltage stress, step-up transformers are employed [10–12].

Multilevel topologies are developed to use arrangements of consolidated and wide reachable semiconductors. Among the multilevel topologies, the topologies derived from string-connected clusters of low-voltage converters, named as cascaded multilevel converters, have caught the attention of researchers in the past years. The cascaded multilevel converters are classified in [13] according to the arrangement

of clusters. Among the topologies described, Double Star Chopper Cells (DSCC) and Single Delta Bridge Cells (SDBC) can transfer active power between the clusters, while the Single Star Bridge Cells (SSBC) lacks current paths between the clusters.

To address the power quality in medium-voltage grids and avoiding the usage of bulky line frequency transformers, solutions are based on DSCC [6,14,20]. However, DSCC is composed of a higher number of cells and the semiconductors must withstand higher dc voltage for the same number of output levels in comparison to SSBC [13]. On the other hand, the SDBC clusters withstand grid line voltage and are unable to compensate the zero-sequence components in the distribution grids. Therefore, SDBC has restricted applications [13].

The regulation of the dc voltages is one of the major concerns regarding the control of the cascaded multilevel topologies. The SSBC can only operates safely with a suitable control design which is commonly divided in three different voltage controls: total (overall), cluster and individual [2].

For balanced conditions, the cluster and individual voltage controls act on parameter deviations of the cells. On the other hand, unbalanced conditions, e.g. load unbalance, affect significantly the SSBC as sequence components flows through the grid. Therefore, special control systems are required.

Many papers address the control system for unbalanced conditions with the injection of zero-sequence voltage [4,15,21,25], negative-sequence current [16] and the combination of both [17,24]. The negative-sequence current injection capability of SSBC is investigated in [15], demonstrating there is a limit of negative-sequence current before losing the voltage regulation. In [23] is presented analysis of SSBC with

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zero-component injection and SDBC with negative-sequence component injection according to the degree of load imbalance and concludes the SDBC has greater compensation capability compared to SSBC for the same load imbalance.

To overcome the limitation of the SSBC and provide an alternative to the DSCC, this paper proposes a transformerless Interconnected Single-Star Bridge-Cells (iSSBC) converter for grid support in low- and medium-voltage distribution grids as DSTATCOM and active power filter. Three star-connected circulating inductors added to the conventional SSBC create current paths, which allows the proposed iSSBC to transfer active power between the clusters.

The power flux resultant of the iSSBC with the star-connected circulating inductors is derived in Section II. The proposed control system for the iSSBC is discussed in Section III. Section IV presents the down-scale 250 VA prototype and experimental results evaluate the proposed iSSBC for grid-end current and internal voltage cells regulation capability under unbalanced nonlinear loads, promoting balanced and sinusoidal current waveforms with high power factor.

2. Proposed iCHB

Active power transfer between clusters is only possible with current paths. As the iSSBC is a voltage source inverter, the current paths should be composed of inductive elements to provide a safe lossless coupling of the cells. The proposed iSSBC is presented in Fig. 1, composed of a conventional SSBC with the inclusion of three single-phase star-connected circulating inductors (L_{ca} , L_{cb} and L_{cc}) in the positive pole of the capacitors of the first cell of each cluster, denominated as upper cells. The remaining cells of the clusters are not connected with inductors and are denominated as lower cells. Existent SSBC converters can be upgraded to iSSBC easily but with a derating.

With suitable switching of the semiconductors, obtained through the proposed control, it is possible to control the average dc voltages of the cells, transferring active power according to the stored energy in each cluster of the iSSBC.

Ref. [22] presents a new DSCC converter replacing lower star-connected string by passive filters. This topology has many similarities to iSSBC, in which the current path is made on the ac side of the string

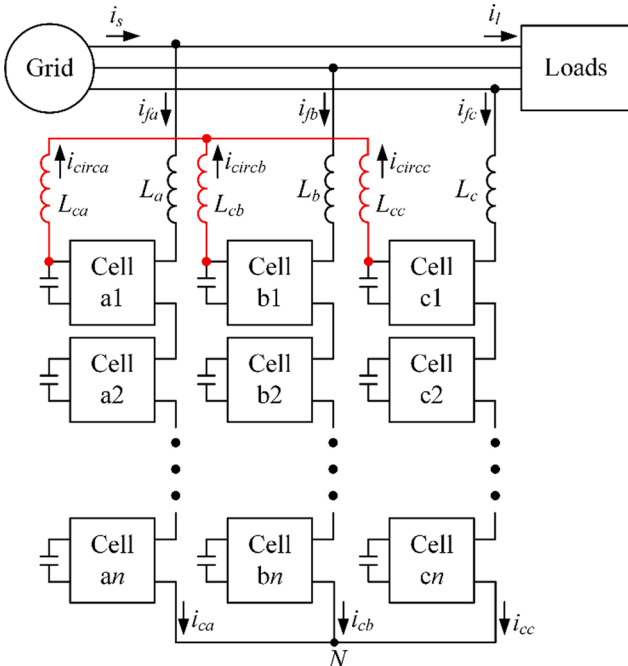


Fig. 1. Proposed Interconnected SSBC (iSSBC) with the inductive coupling of the clusters.

cells instead of the dc side of the first cells.

2.1. Global power flux of iSSBC

The global power flux sets the required active and reactive power of iSSBC to support the grid, guaranteeing three balanced sinusoidal current waveforms and high power factor at grid-end under any load pattern. The iSSBC output power can be derived analyzing Fig. 2 (a), where each cluster is considered to be able to provide and absorb unrestricted amount of power. The iSSBC must process:

$$S_x = P_x + jQ_x = P_{lx} - P_s + P_{loss} - jQ_{lx} \quad (1)$$

to support the grid, where P_{loss} is the cluster losses, P_{lx} and Q_{lx} are the load active and reactive power of phase x , respectively, and P_s is the average load active power defined as:

$$P_s = \frac{P_{la} + P_{lb} + P_{lc}}{3} \quad (2)$$

2.2. Internal power flux of iSSBC

The internal power flux of the iSSBC is depicted in Fig. 2 (b). The upper cells (Cell x1) have four power components, while the lower cells (Cell x2 to Cell xj) have three power components. The suffix j represents the cell number from the respective phase and the analysis is valid for

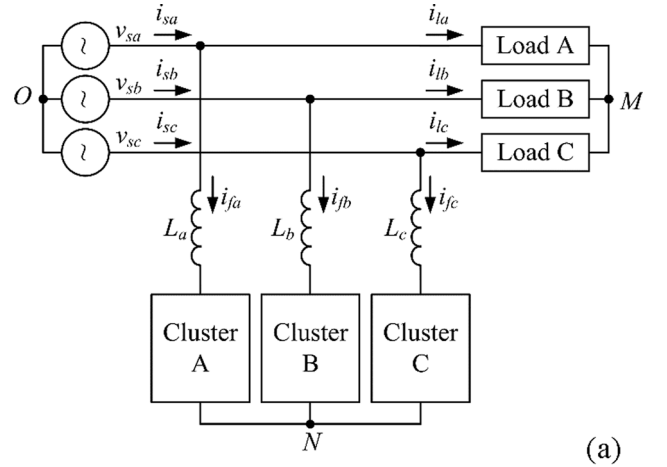


Fig. 2. Simplified diagram of iSSBC for (a) global and (b) internal power flux analysis.

unrestricted number n of cells.

The first component is the active power drawn from PCC (P_x), determined by the global power flux, which is equally distributed among the n cluster cells resulting in P_x/n . The losses are considered equal for all cells, represented by P_{loss}/n . The difference between P_x/n and P_{loss}/n is defined as P_{ixj} and must be exchanged within the cluster to keep the voltage of the lower cells regulated. The fourth component is the active power transferred between clusters (P_{circx}), which regulates the voltage of the upper cells.

To maintain the voltage regulation across the clusters cells the sum of the active power components must be zero. Hence, for the upper cells yields:

$$\frac{P_x}{n} = P_{circx} + \frac{P_{loss}}{n} + P_{ix1} \quad (3)$$

and for the lower cells:

$$\frac{P_x}{n} = \frac{P_{loss}}{n} + P_{ij} \quad (4)$$

From (3) and (4) it can be seen P_{bj} plays an important role in the power balance of the iSSBC cells, exchanging a significant amount of power, unlike the conventional SSBC. The lower cells exchange P_{bj} with the upper cells, holding:

$$P_{ix1} = - \sum_{j=2}^n P_{ixj} \quad (5)$$

2.3. Circulating current analysis

The circulating current is a function of the voltage applied to each star-connected inductor referred to N , v_{Lcirc} , as depicted in Fig. 3 (a). Due to the position of the circulating inductors, the upper and lower cells contribute with distinct voltages. The upper cell contribution can be

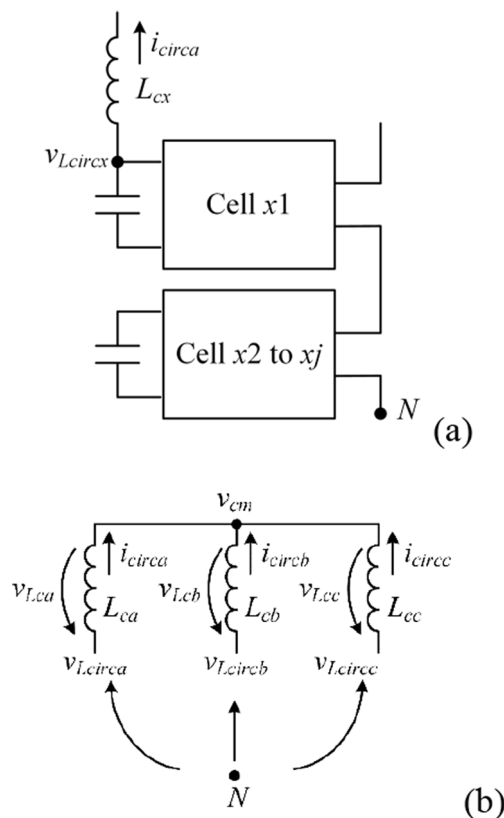


Fig. 3. Simplified diagram of iSSBC for the analysis of the (a) voltage and (b) current of the circulating inductors.

expressed as function of the nominal voltage of the cell V_{cc} and current control output v_{ox} as follows:

$$v_{Lcircx}^u = \frac{V_{cc}}{2} + \frac{V_{cc}}{2} \cdot v_{ox} \quad (6)$$

and the lower cells as:

$$v_{Lcircx}^l = V_{cc} \cdot v_{ox} \quad (7)$$

The combination of each contribution for n cells leads to:

$$v_{Lcix} = v_{Lcix}^u + (n-1) \cdot v_{Lcix}^l = \frac{V_{cc}}{2} + \frac{2n-1}{2} \cdot V_{cc} \cdot v_{ox} \quad (8)$$

Neglecting the common mode voltage v_{cm} and referring to Fig. 3 (b), the circulating current is calculated as:

$$i_{circx} = I_{dcx} + \frac{2n-1}{2} \cdot \frac{V_{cc}}{\omega L_{cx}} \cdot i_{ox} \quad (9)$$

where I_{dc} is the dc value of i_{circ} and i_{ox} lags v_{ox} by 90 degrees. The circulating active power, which is the product of the circulating current and the voltage applied to the circulating inductors, can be written as:

$$P_{circx} = \frac{1}{T} \int_0^T v_{Lcircx} \cdot i_{circx} dt \quad (10)$$

Replacing (8) and (9) in (10) and expanding the variables:

$$P_{circx} = \frac{1}{T} \int_0^T \left[\frac{V_{cc} \cdot I_{dxx}}{2} + \frac{2n-1}{4} \cdot \frac{V_{cc}^2}{\omega L_{cx}} \cdot i_{ox} + \frac{2n-1}{2} \cdot V_{cc} \cdot v_{ox} \cdot I_{dxx} + \left(\frac{2n-1}{2} \right)^2 \cdot \frac{V_{cc}^2}{\omega L_{cx}} \cdot v_{ox} \cdot i_{ox} \right] \cdot dt \quad (11)$$

the circulating power is shown to be composed of 4 terms. The second and third terms of (11) are waveforms at fundamental frequency and do not produce active power over one grid cycle. The fourth term is a waveform at double fundamental frequency and, due the displacement between i_{ox} and v_{ox} , also produces no active power. Therefore, the circulating power is given by:

$$P_{circx} = \frac{V_{cc} \cdot I_{dcx}}{\eta} \quad (12)$$

3. Control system of the proposed iSSBC

The control strategy for the iSSBC aims to synthesize three balanced current waveforms at the grid-end with low THD and high power factor, while it keeps the voltage across the capacitors of each cell regulated. To accomplish the requirements, the control strategy is composed of a current loop and two voltage loops, as depicted in Fig. 4.

The current loop is responsible for the synthesis of the iSSBC output currents to support the grid with balanced, sinusoidal waveforms with high power factor. The total voltage loop replenishes the power losses. The individual voltage loop regulates the dc voltage in each cell,

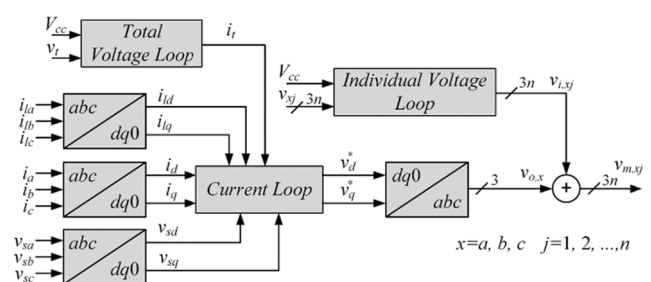


Fig. 4. Complete control diagram of the iSSBC.

exchanging active power within and among the clusters.

The design procedure of the control system is presented in [18] and the methodology will not be present in this paper.

3.1. Current loop

The current control is responsible for synthesize the iSSBC output current to provide proper reactive power compensation and harmonic mitigation to the grid-end currents.

The current references are generated using the instantaneous power theory in the dq frame as presented in [3,6]. The current references (i_d^* and i_q^*) are composed of the load currents (i_{ld} and i_{lq}) and the total voltage control output (i_t), as depicted in Fig. 5.

The commanding references v_d^* and v_q^* are given by [18] using proportional-integral controllers.

$$\begin{aligned} v_d^* &= v_{sd} + \omega L_f i_q - k_i (i_d^* - i_d) - \frac{k_i}{T_i} \int (i_d^* - i_d) \\ v_q^* &= v_{sq} - \omega L_f i_d - k_i (i_q^* - i_q) - \frac{k_i}{T_i} \int (i_q^* - i_q) \end{aligned} \quad (13)$$

The block diagram of the current control loop is presented in Fig. 6.

3.2. Total and individual voltage loop

The total voltage loop aims the regulation of the sum of the dc voltage of the cells. By adding a dc component to the d axis of the current reference, the active power drawn from the grid is equal to the iSSBC losses [2], as seen in Fig. 7. The error between the nominal voltage and the measured average voltage of the cells v_t feeds a proportional-integral controller, which sets the suitable control output i_t .

The individual voltage loop is described in [18] with the objective to keep the dc voltage of each cell regulated at the cluster average voltage. On the other hand, the individual voltage loop of the proposed iSSBC regulates the dc voltages of each cell at the nominal voltage V_{cc} . The individual voltage control output generates a voltage component at the ac side of the cells that produces active power ($P_{i,xj}$) by interacting to the reactive component of the inner currents i_{cx} . The inner current is the subtraction of i_{fx} and i_{circx} according to Fig. 1. The control of the dc voltages of the upper cells at the nominal voltage indirectly regulates the dc component of the circulating current.

Each dc voltage is compared to the nominal voltage and a proportional controller sets the amplitude of a sinusoidal signal displaced by 90 degrees regarding the output voltage, defined as $v_{i,xj}$ in Fig. 8.

The commanding signal of each cell, defined as $v_{m,xj}$, is the composition of the current ($v_{o,x}$) and individual ($v_{i,xj}$) control output. Phase-shift modulation was chosen to equally distribute the losses among the cells of the iSSBC.

4. Experimental results of the proposed iSSBC

To verify the performance of the iSSBC under unbalanced nonlinear loads, a downscale prototype is built, as shown in Fig. 9. Experimental results are carried out with the parameters presented in Table 1.

Table 2 summarizes the unbalanced linear loads. To c-phase is included a single-phase capacitive-filter rectifier. The controllers were designed using the methodology presented by [18] and the control gains

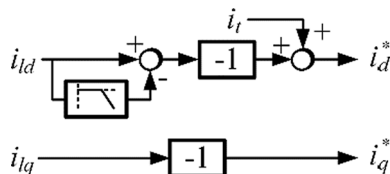


Fig. 5. Block diagram of the current reference generator.

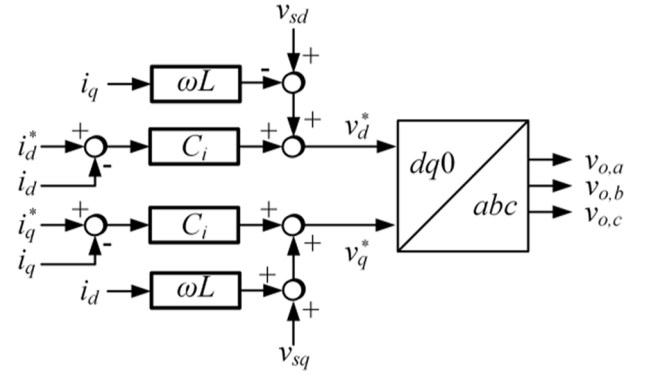


Fig. 6. Block diagram of the current control loop.

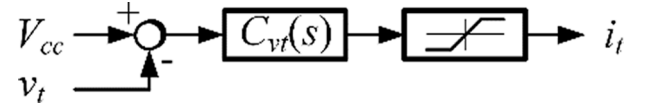


Fig. 7. Block diagram of the total voltage control loop.

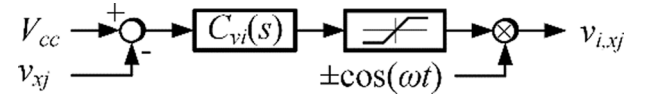


Fig. 8. Block diagram of the individual voltage control loop.

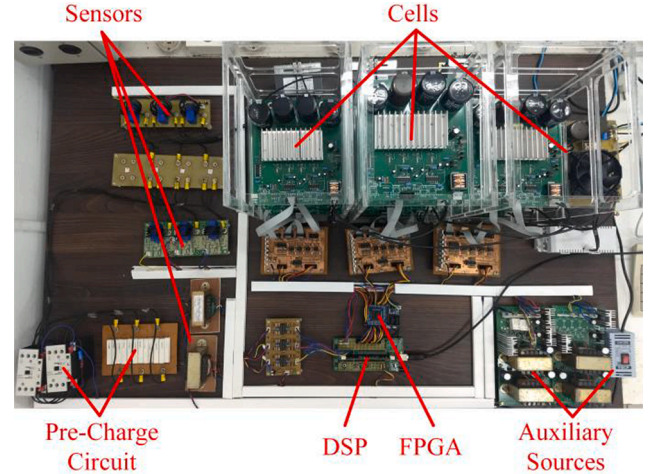


Fig. 9. iSSBC experimental setup.

Table 1
iSSBC parameters.

Nominal power	S_n	250 VA
Grid voltage	V_s	60 V
Grid frequency	f_s	60 Hz
Switching frequency	f_{sw}	5 kHz
Number of cells per cluster	n	3
Nominal cell voltage	V_{cc}	50 V
Capacitance of cell	C_c	2,300 μ F
Output inductance	L_f	10 mH
Circulating inductance	L_c	111 mH
Grid resistance	R_s	0.75 Ω
Grid inductance	L_s	16.5 mH

Table 2

Experimental load parameters.

Phase	Linear	Nonlinear
A	122 Ω (38.4 Ω)	16 mH
B	61 Ω	32 mH
C	122 Ω	16 mH
		3mF, 244 Ω

Table 3

Experimental control gains.

		Proportional	Integral
Current loop	C_i	8	0.005
Total voltage loop	C_{vt}	0.05	0.1
Individual voltage loop	C_{vi}	0.1	–

are presented in Table 3.

4.1. Circulating inductor design

The ac component magnitude of the circulating current depends on the grid voltage and the circulating inductance, as presented in (9). Rearranging (9) and neglecting the dc component I_{dcx} , the circulating inductance is written as:

$$L_{cx} = \frac{2n-1}{2} \cdot \frac{V_{cc}}{\omega i_{circx}} \cdot i_{ox} \quad (14)$$

The modulation index i_{ox} can be expressed as function of the grid voltage V_{sx} and total dc voltage of the cluster nV_{cc} :

$$i_{ox} = \frac{V_s}{nV_{cc}} \quad (15)$$

Replacing (18) in (17) yields:

$$L_{cx} = \frac{2n-1}{2n} \cdot \frac{V_s}{\omega i_{circx}} \quad (16)$$

Considering the ac component of the circulating current i_{circx} as the same magnitude as the output current i_{fx} , the circulating inductance is determined using (19):

$$L_{cx} = 95.49 \text{ mH} \quad (17)$$

Due to availability, L_{cx} is specified as 111 mH. As one can see in (20), the circulating inductor have significant value in comparison to the output inductance L_f in this example. Keeping the proportion, an increase of i_{fx} decreases linearly the L_{cx} according to (19) considering the same grid voltage. Therefore, for higher power iSSBCs the inductance of L_{cx} can be reduced to values around the output inductance L_f and the size of L_{cx} can be reduced.

4.2. Performance of iSSBC under unbalanced nonlinear loads

The iSSBC output current is presented in Fig. 10 (a), containing significant harmonic distortions in response to the load Current Unbalance Factor (CUF equal to 17.5%) and Total Harmonic Distortion (THD equal to 7.41%, 7.61% e 14.4%, respectively), as shown in Fig. 10 (b). As result of the iSSBC, the grid-end currents are balanced (CUF equal to 3.9%), have low THD (3.3%) and high power factor (0.999) as depicted in Fig. 10 (c). The CUF is the current equivalent of the Voltage Unbalance Factor (VUF), defined in [19].

Fig. 11 shows the voltage of the cells regulated at the nominal voltage. With the same loss to each cell, the lower cells in the clusters have the same waveform. On the other hand, the upper cells have significant ripple in the fundamental frequency as result of the circulating current. It is verified a minor steady state error (less than 4%) due to proportional controller of the individual voltage loop.

The circulating current is depicted in Fig. 12. Along with the dc

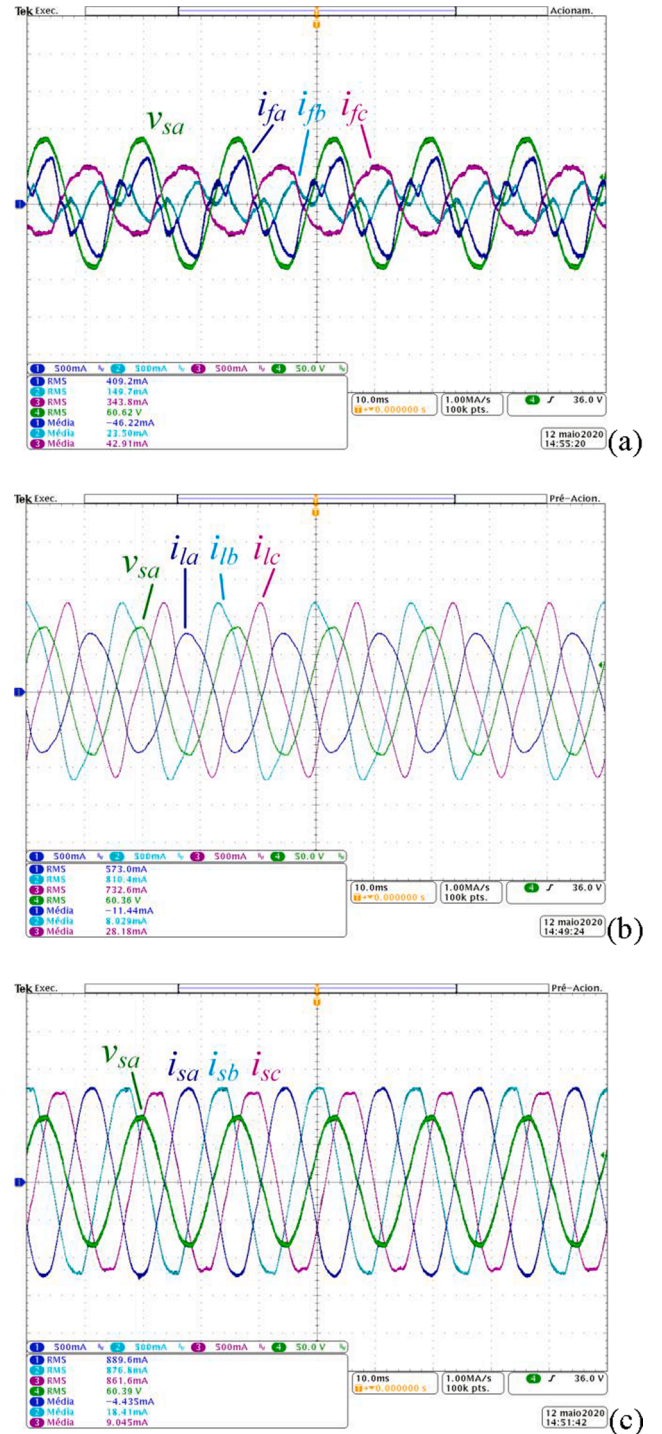


Fig. 10. Current waveforms of (a) iSSBC output, (b) load and (c) grid-end (0.5A/div, 10 ms/div).

component to promote the circulating active power, the circulating current waveform contains ac component proportional to the grid voltage. The ac component can be mitigated with the increase of the circulating inductance. The dc component of the circulating current is 82 mA, 2 mA and -64 mA, respectively and the ac component is 1.22 A, 1.17 A and 1.19 A, respectively. Fig. 13 presents voltage waveforms across the circulating inductors.

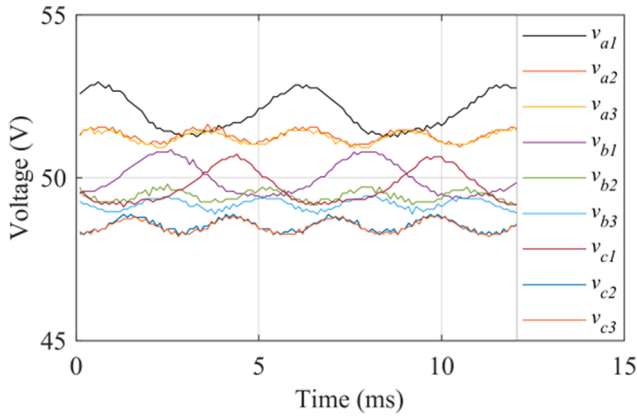


Fig. 11. Voltage of the cells (10 V/div, 4 ms/div).

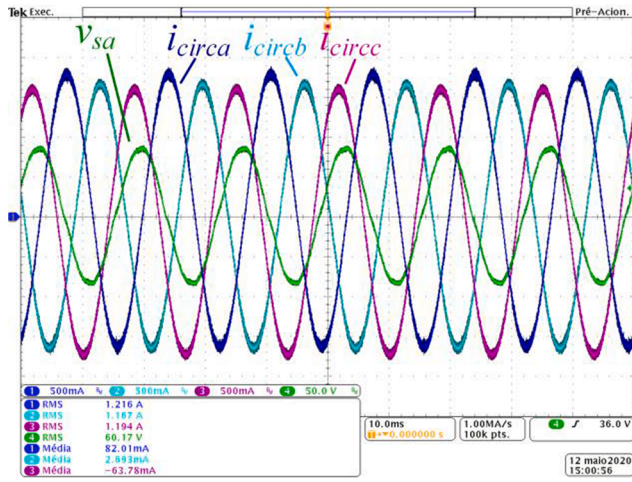


Fig. 12. Waveforms of circulating current (0.5A/div, 10 ms/div) (Mean value of 82 mA, 2 mA and -64 mA, RMS value of 1.22 A, 1.17 A and 1.19 A, respectively).

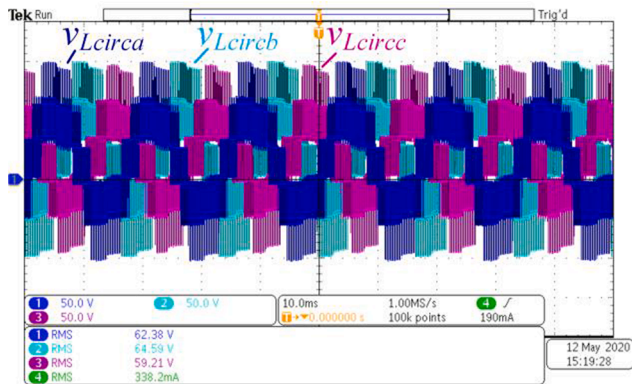


Fig. 13. Waveforms of circulating voltage (50 V/div, 10 ms/div).

4.3. Dynamic response of iSSBC under load step

The proposed iSSBC is evaluated under sudden load step. To perform the load step, a-phase load resistance is decreased to 38.4 Ω . The dynamic response of the a-phase voltage cells is presented in Fig. 14.

The transitory of the currents is depicted in Fig. 15. The grid-end currents remain regulated during the transient and the unbalance factor rises to 4.1%.

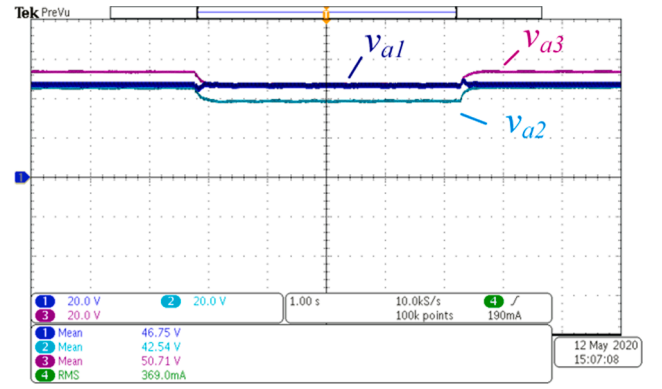


Fig. 14. Dynamic response of the voltage cells under load step (50 V/div, 1 s/div).

The circulating current under the transient is shown in Fig. 16, which can be seen that the ac component has no significant amplitude change. On the other hand, the dc component of the each circulating current stabilizes in new operation point (-227 mA, 21 mA e 225 mA, respectively).

4.4. iSSBC comparison to DSCC

Regarding the capability of supporting the grid, both iSSBC and DSCC have similar performance achieving high power quality at grid-end current. However, the proposed iSSBC is composed of half the number of cells, control loops and electrical quantities to be measured and the same number of inductors and switches for the same λ number of output levels.

Other aspects for comparison are cost, reliability, and efficiency. For a medium- and high-voltage grid, the solution requires a high number of cells to withstand the voltage stress. In this case, iSSBC becomes a more feasible solution than DSCC.

The iSSBC has more reliability compared to DSBC due to reduced number of capacitors, which may extend the converter life cycle, along with reduced number of measured quantities and cells, which reduce the transmission data required for measurements. On the other hand, the iSSBC has reduced efficiency as the inner currents i_{cx} are higher than in DSBC. Regarding the cost, the advantage of iSSBC is the fewer capacitors and cells, but the size of circulating inductor is greater and the current stress on the semiconductors are higher, which may make the iSSBC more expensive. The comparison is summarized in Table 4.

5. Conclusion

This paper presents an interconnected cascaded multilevel topology for distribution grid support able to transfer active power between the clusters, enhancing the support compared to the SSBC. The active power transfer allows the iSSBC to have equal performance and compensation capability of the DSCC with less cells, simpler control system and the same number of inductors.

The iSSBC power flux is analyzed in two different points of view. The global power flux sets the compensating active and reactive power to support the grid and. The internal power flux promotes the voltage regulation of the cells and demonstrates the key role of the individual voltage control, exchanging considerable amount of active power among and within the clusters. This feature is not seen in the standard modular multilevel converters. The analysis of the circulating current concludes that large inductors are required to mitigate the ac component, especially in medium-voltage systems. The magnitude of the circulating current is major drawback of the iSSBC and it will be addressed in future works.

The grid-end current regulation capability of iSSBC was verified via

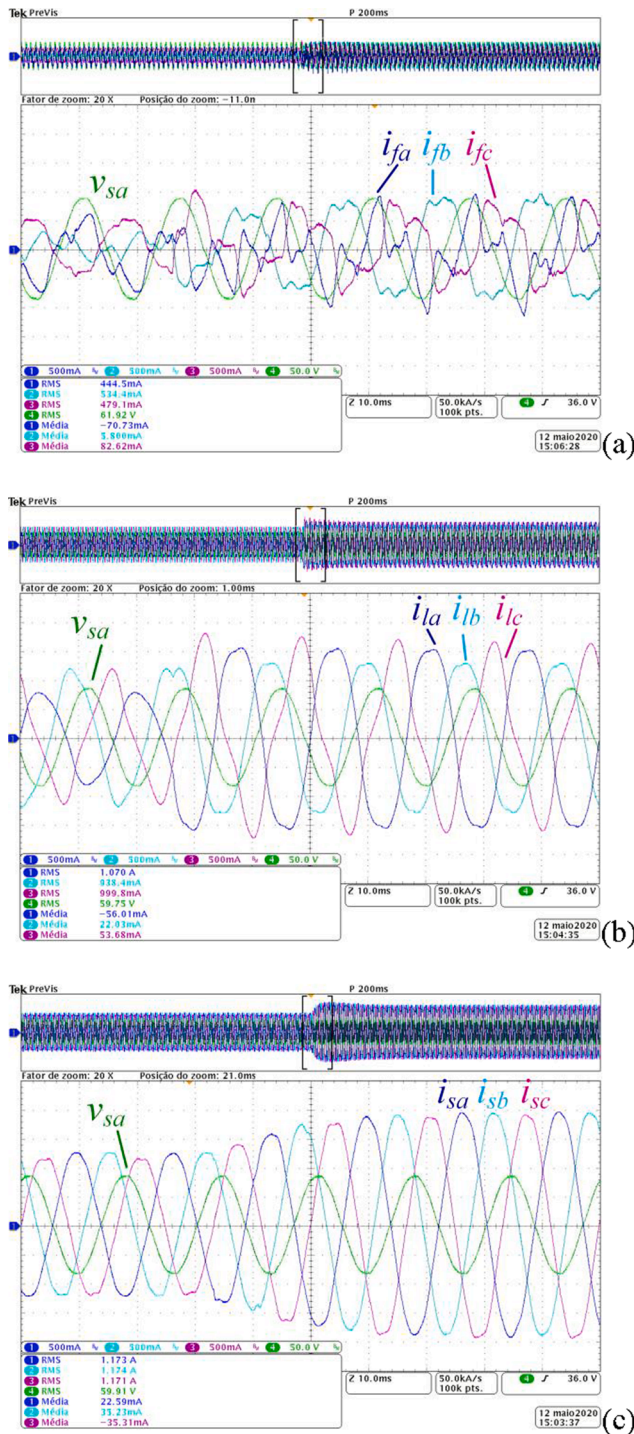


Fig. 15. Dynamic response of the (a) iSSBC output, (b) load and (c) grid-end currents under load step (0.5A/div, 200 ms/div).

experimental results, providing three balanced and sinusoidal waveforms with high power factor. The voltage cells remain regulated under load step demonstrating the effectiveness of the proposed control system.

CRediT authorship contribution statement

Rubens Tadeu Hock: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Project administration. **Alessandro Luiz**

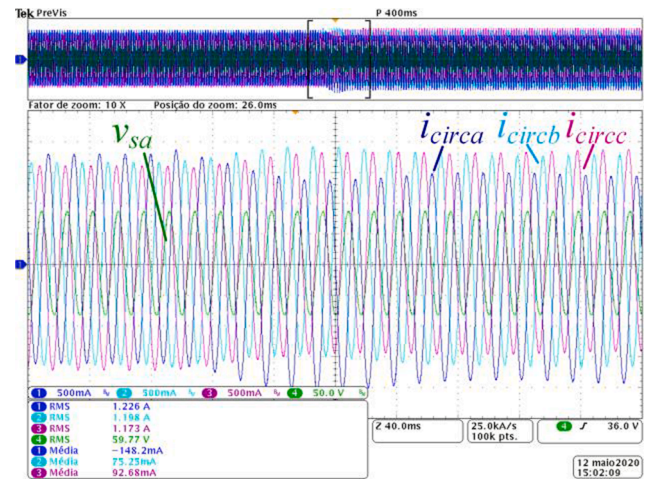


Fig. 16. Dynamic response of the circulating current waveform (0.5A/div, 100 ms/div).

Table 4

Comparison between DSCC and iSSBC.

Number of	DSCC	iSSBC
Cells and capacitors	$3(\lambda - 1)$	$\frac{3}{2}(\lambda - 1)$
Switches	$12(\lambda - 1)$	$12(\lambda - 1)$
Inductors	6 (1 each arm)	3 output
Control loops	Output current Total voltage Cluster voltage Arm voltage	Output current Total voltage - -
Measured electrical quantities	6 circulating currents $3(\lambda - 1)$ cell voltages	Individual voltage 3 output currents $\frac{3}{2}(\lambda - 1)$ cell voltages
Reliability	Higher	Smaller
Cost	Higher	Smaller
Efficiency	Smaller	Higher

Batschauer: Conceptualization, Resources, Writing – review & editing, Visualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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