A Field Programmable and Dynamic Configurable Power Electronic Converter Concept

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Abstract

This paper proposes the concept of a field programmable and configurable power electronic converter together with a new synthesis method. By considering the converter as a pack of resources, the converter topology and configuration of inputs and outputs can be programmed in the field through, utilising the available device resources.

Introduction

Power electronic converters have been widely adopted for most areas requiring efficient control of power, including renewable energy, electric transport, industrial drives, and numerous household appliances and power supplies. So far, these power converters have mainly been designed as a fixed topology where only the firmware or control software can be upgraded. There has been a trend to create more application specific converters, for instance can converters can be integrated inside the electrical machine housing [1], but it is also possible to go in the opposite direction and make the converter more universal.

In many cases, several converters are wired together in the same system for form a complete solution, where electric transport is a good example. For an electric ship, numerous converters are used to handle loads like propulsion, charging, hydraulic pumps and on-board power supply. Not all converters are used simultaneously, such as propulsion and charging. It is an obvious possibility to allow the same power electronic devices to serve multiple purposes. Although a converter could be built to have several predefined configurations, such customised solution could limit the application if the requirements are changing.

An upgrade of the solution, in this example the ship, could result in replacing the converter to include new functionality. If a power electronic converter could be seen as a generic field programmable and configurable pack of resources, new functionality can be programmed within the limitations of available resources. By making it dynamic configurable, the utilisation of those resources can be increased.

For a converter to be field programmable and dynamic configurable, one can imagine a power converter along the same idea as the field programmable gate array (FPGA). An FPGA uses an synthesis procedure to realise programmable digital electronics. While an FPGA is less efficient than an application-specific integrated circuit (ASIC), its programmability and off-the-shelf versatility makes it the preferred choice in an increasing number of applications.

Methods for synthesis of converter in the literature are used as design tools, mainly to explore different topologies before a final topology is selected for the physical implementation. It needs to be evaluated if existing methods can be expanded in to a programming tool, where the structure in the synthesis process can be realised in hardware. Input requirements to the synthesis process is also important, as it will decide what type of converter structures that can be synthesised.

In [2], Erickson describes the synthesis process based on the DC conversion ratio, absence of pulsating input or output currents, the number of reactive elements, and the number of switching elements used. The method is based on a general state-space description of RLC networks, where there is a finite number of configuration options once the number of reactive elements are known. The advantage of Erickson's method in [2] is that all possible topologies is considered, but the method is based on manually inspecting all feasible configurations, where the value of the reactive elements and ripple current requirements are not taken into account. A state-space approach is also used in [3] to realise arbitrary converter configurations and [4] expands with a synthesis method, but relies in intuition to select the right topology among the feasible alternatives.

Synthesis through combination of basic converter blocks are explored in [5], although design objectives are limited to voltage and current conversion ratio and single input single output configurations. The concept of using basic converter cells is also applied to three-port DC-DC converters in [6], where an iterative computer program reduces the time spent on manual examination. Flux balance equations are used to synthesise converter topologies in [7, 8] based on a chosen voltage conversion equation. Instead of examining a pool of topologies, [9] proposes a method based on the voltage conversion equation that is decomposed before circuits are synthesised.

Common for the synthesis methods reported in literature, is the ambition to use the synthesis process to realise new converter topologies that is unlikely to be discovered by manual circuit manipulation and combination of known basic converter types.

Power converter with configurable structures have been presented to increase voltage range of a series resonant DC-DC converter in [10], where a DC-DC converter has four predefined configurable operation states to increase its allowed voltage range. The voltage range for a LLC resonant converter is increased with a configurable structure in [11], while a non-isolated configurable bidirectional DC-DC converter is used to increase voltage range for interfacing retired batteries from electric vehicles in [12]. Common for [10, 11, 12] is that a configurable structure is used to increasing the voltage range, not fundamentally change the converter topology.

This paper proposes the idea of a field programmable and dynamic configurable converter (FPCC) as an universal power control device by combining synthesis with a configurable converter design, allowing the converter to be seen as a programmable pack of active and passive resources.

A new synthesis method is proposed for the FPCC together with a configurable structure, where the objective is to realise a converter based on a known physical structure and performance requirements. The ambition is not to synthesise new converter topologies, but to realise a specified functionality by mapping circuit configurations into known predefined structures.

Concept of Configurable Converter

The FPCC is considered to be a pack or collection of active switches and passive components, such as a selection of transistors, diodes, inductors and capacitors. A set of power IO's (inputs and outputs) will interface the converter with electrical sources and loads, while control IO's will be the interface to controlling the switches for whatever topology that is realised. The converter topology and internal connections can be realised based on a synthesis process, where configuration switches are used to realise the desired topology through a set of configuration inputs. Power switches can also be used as part of the configuration in addition to the switching action to increase the flexibility in configurations. An overview of how such converter can be arranged is shown in Fig. 1.

The internal construction of the converter and the way different active and passive elements are connected will act as constraints in the synthesis process, together with the user requirements. To design such

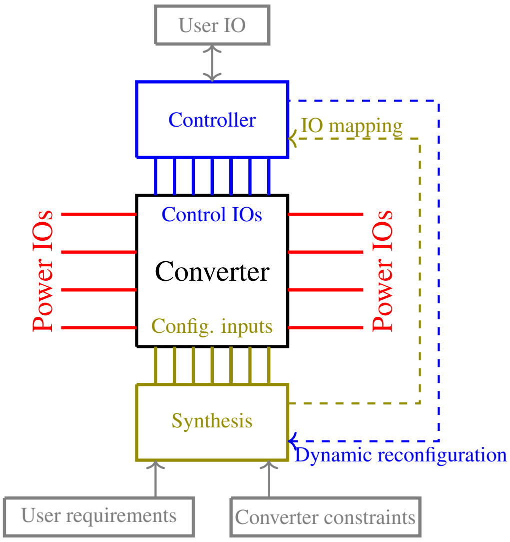


Fig. 1: Configurable converter

converter structure and include the right number of active and passive elements, their parameter values, and interconnection possibilities is an optimisation and synthesis process in its own. There is also the question if each sub-component in the converter can be configured individually, or if there should be basic cells with predefined groups of components. This internal structure is critical for the converter to achieve the versatility, where the greatest (or required) number of topologies can be realised given the available resources. As with FPGAs, one can imagine the converters to come in different standard sizes with a given number of internal resources and power levels.

Applications

While an example of configurable converter has been presented in [10] to increase voltage range, the concept can be taken further. This section presents two examples where such converter could be applied.

Electric Vessels

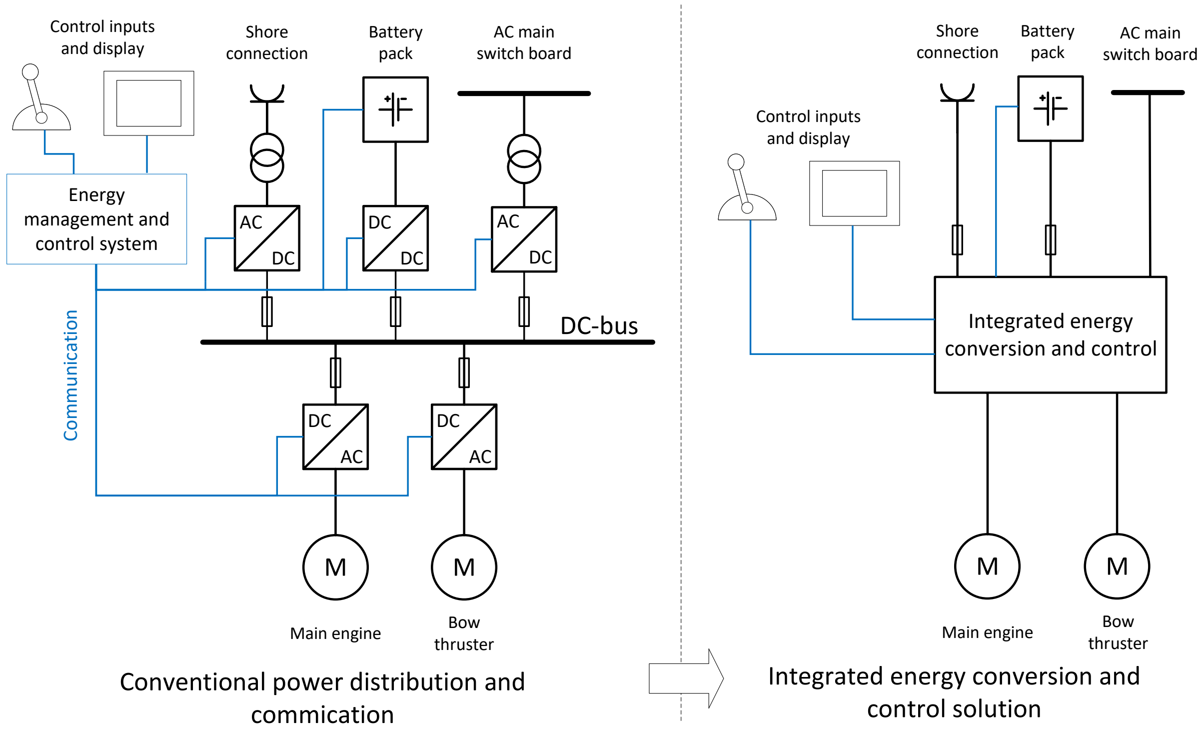
Electric vessels uses numerous power converters for propulsion, charging, internal power distribution and other vessel specific loads. Not all converters are used simultaneously, where several functions could be combined into one configurable converter as shown in Fig. 2. This is especially relevant for smaller vessels, where space is limited. The concept has been applied to electric vehicles by combining charging with the electric drive in [13], but reconfiguration was made outside the converter.

If spare resources are available in the converter, redundancy for component failure could also be implemented on small single motor vessels by temporary reconfigure to another optimal or a sub-optimal topology until repairs can be made.

For retrofit application converting from diesel to batteries or fuel cells, it would be an advantage if the converter was one integrated box, where all sources and loads were connected and functionality of the power electronics could be programmed during commissioning. This will not only reduce the number of individual components, but also reduce the wiring on the vessel, reduce the need for a complex communication network between converters and the integration of those in energy management systems.

Mobile Fuel Cell based Electricity Supply

If hydrogen is used as energy carrier on an off-grid construction site, it might not be known if the machines would require AC or DC, and at what voltage level. Such mobile generation units would be moved from site to site and would benefit from a versatile design in terms of electricity output. In that case, a configurable converter can change its topology according to the required voltage, current and frequency, making a versatile electricity source for the site. One could also imagine supplying different



Conventional power distribution and commication

Integrated energy conversion and control solution

Fig. 2: Integrated power conversion in electric vessels

types of electricity supply simultaneous if required, or switches could be paralleled to increase current in high demand periods.

Work towards realisation

To realise this field programmable and dynamically re-configurable converter, several advanced in research is required.

Some key challenges are considered to be:

1. Optimal internal design of the converter and configuration options
2. Optimal choice of parameters for the internal components
3. Synthesis method taking constraints regarding available components and configuration options into account
4. Practical realisation of the configurable converter
5. Develop control algorithms to support dynamic configurable converters

While the realisation of the proposed converter would initially be by wire or printed circuit board tracks, one could imagine a future of integration on a semiconductor level inspired by the potential in additive manufacture process [14]. At this stage, it is not known if the realisation and the advantage of field programmable converter will make a this cost competitive solution, although the author's opinion is that the concept is worth exploring. Each of these five key challenges require a significant research effort and it is out of the scope of this paper to address all these in detail. To illustrate the feasibility of the concept, a simplified configurable structure and new synthesis methods is proposed in the following two subsections.

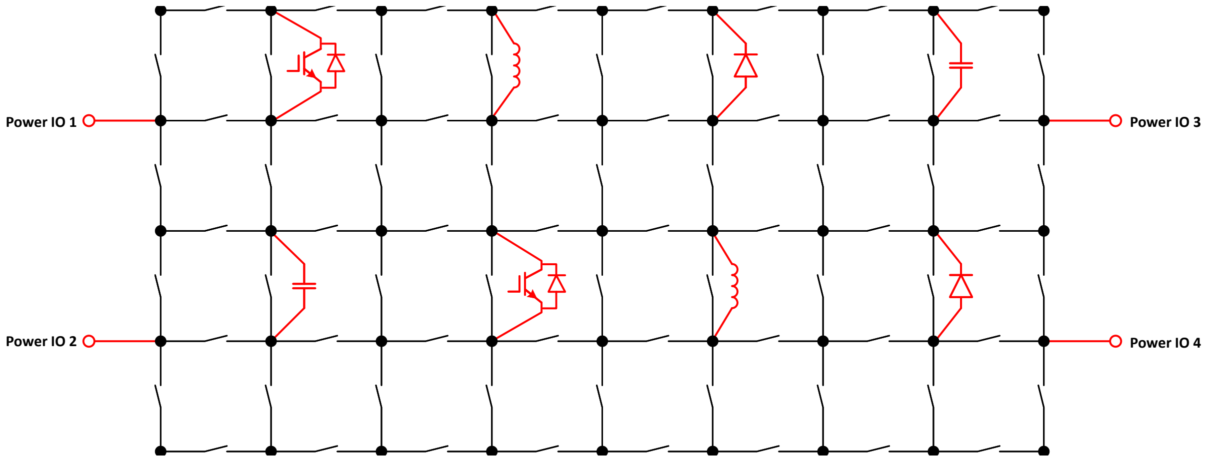


Fig. 3: Configurable structure with power electronic components

Configurable structure

A configurable structure will consist of a given number of active switching elements and passive components, connected by a grid of configuration switches. Nodes in this grid is used as connection points for active and passive elements and power IO's. Note that the structure may contain components of different sizes for increased flexibility.

To demonstrate the concept, a small 2 dimensional structure with a few selected components are shown in Fig. 3, although a three dimensional structure is also possible. How to optimally arrange this structure, the number of configuration switches, and where to connect active and passive element is an area where more research is required and out of the scope in this paper.

Synthesis

The proposed synthesis procedure consist of five steps. If the intended application has different operating modes, each mode can be synthesised such that the structure can alternate between then as required.

Step 1 - Set requirements

The requirements for the converter has to be defined with the functionality and performance parameters relevant for the solution. As a minimum one should specify which inputs and outputs sources and loads are connected to, including the properties of those. That will include if there is a voltage or current source, conversion ratio, voltage or current limits, and how many quadrants the converter should work within. The structure can include several independent converter functions.

In addition, parameters like voltage and current ripple, efficiency and harmonic distortion can be added to later choose between several feasible topologies.

Step 2 - Identify all feasible configurations

By cycle through all configurations options, those that does not connect to the assigned power IO's, provide no path from input to output, or violate basic electric constraints such a short circuit is ruled out in this step.

Step 3 - Mapping of known structures

The synthesis process has a predefined list of known converter topologies, or basic cells that is identified and mapped to all the feasible configurations in Step 2. Each of those predefined topologies have a known set of parameters like voltage conversion range, ripple current and voltages, and efficiency, taking into account known parameters for the individual components. Depending on the requirements and available resources, several converters can be mapped within the configurable structure as indicated in Fig. 4.

A simple example of synthesis of a step-down converter based on the structure in Fig. 3 is shown in Fig. 5 and Fig. 6.

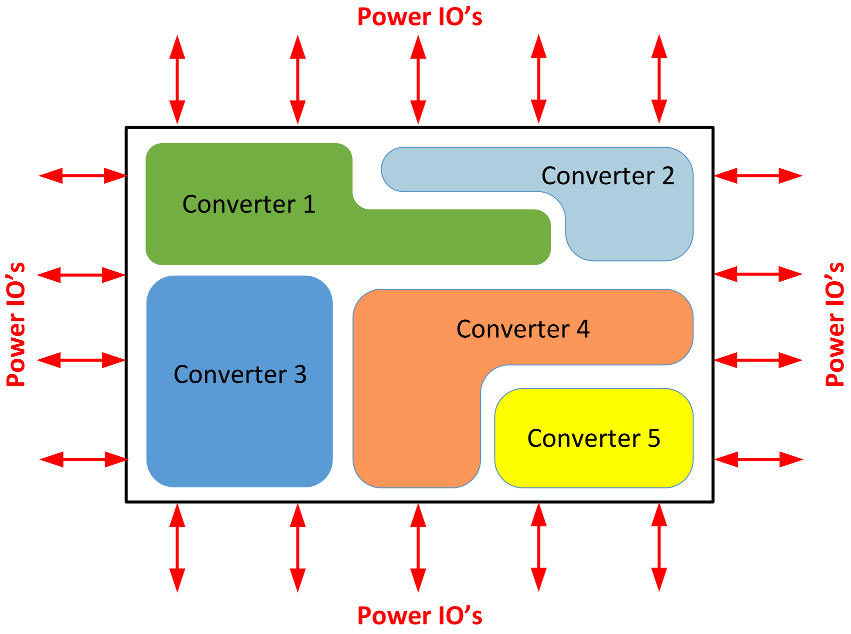


Fig. 4: Multiple converters mapped in one FPCC structure

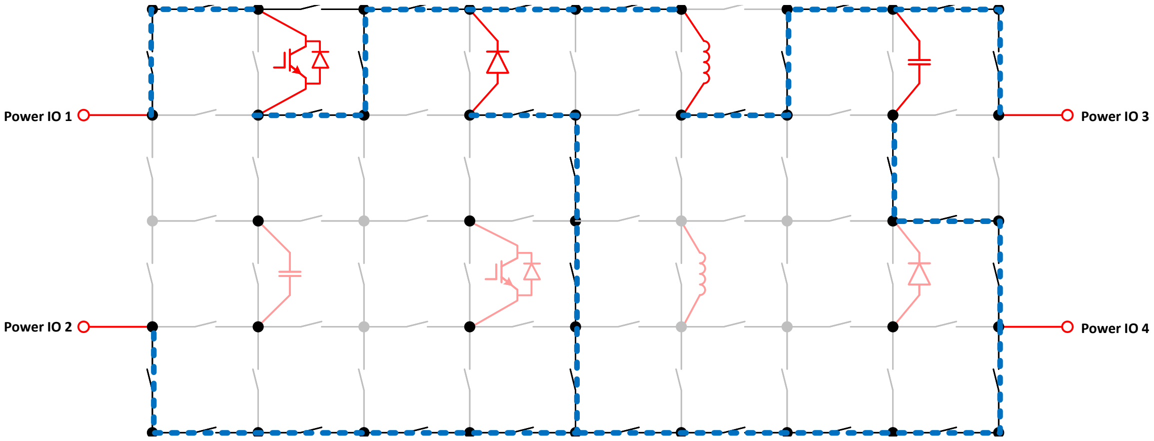


Fig. 5: Structure configured as an asynchronous Buck converter

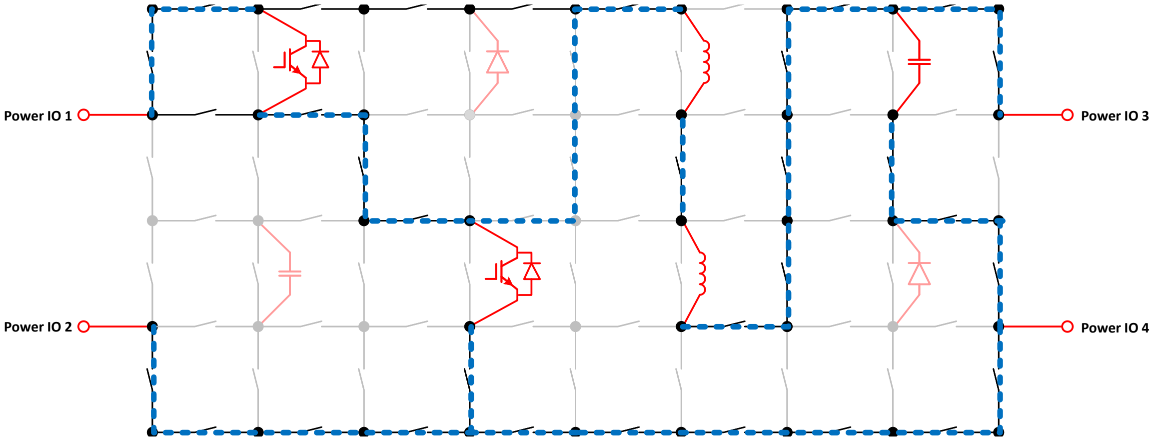


Fig. 6: Structure mapped and configured as s synchronous Buck converter

From all configurations that connects the four Power IO's, two of them was mapped as asynchronous in Fig. 5 and synchronous Buck converter in Fig. 6, the latter one with both inductors in series. Both will perform as a step-down converter, but will have different performance in terms of efficiency and ripple. Note that this example is simplified for illustrative purposes and multiple converter structures are expected to be mapped within the same configuration, together with more Power IO's.

Step 4 - Performance evaluation

In this step, all mapped converter structures from the previous step is evaluated and compared to the requirements set in step 1. Based on this, the best configuration that achieves the desired converter functions can be selected. That might include several simultaneous converters in the same configuration, and several configuration options if the application is specified to have several operation modes.

Step 5 - Implementation

The final step is to implement the chosen configuration from step 5 by programming the configurable structure. This includes mapping the control algorithm to the active switches in use from step 5.

Practical limitations

With an ideal setup as shown in Fig. 3, a full matrix of ideal switches can configure the converter in any feasible configuration. In a practical realisation of the concept, those configuration switches will result in losses, depending on the type of switch. Semiconductor switches will introduce a power loss due to their on-state resistance, in addition to an additional constraint if they are not bidirectional devices. Both losses on the configurable structure itself and limitations in the configuration switches should be part of the synthesis process, making it more complex than the ideal case. The use of transistors as configuration switches will also require isolated power supplies to drive the gate-source voltage for MOSFET's or gate-emitter for IGBT's, complicates the control circuitry for the converter.

If reconfiguration is expected to occur seldom with low timing requirements in the reconfiguration event, one could realise a structure using mechanical relays. The on-state resistance will be lower, but there will be some power loss in the relay coils used to activate the switch. Efficiency can be improved if bi-stable relays is used, which does not require the coil to be kept energised for the relay to stay closed. Depending on the power level, mechanical relays can result in a large unit with complex wiring, unless it can be integrated on a circuit board together with the power electronic components. On the other hand, relay coils are galvanic isolated from the relay switch, removing the need for isolated power supplies in the control circuitry.

In any practical realisation, there will be advantageous to reduce the number of configuration switches as much as possible while maintaining necessary configurability of the structure. This is highlighted in the key challenge number 1 in the beginning of this section and something that as to be addressed for this to be a commercial viable solution.

Conclusion

The concept of a field programmable and dynamic configurable converter (FPCC) has been suggested, together with two application examples and a new synthesis method to realise the potential. Such converters could never compete with a single application specific converter, but fundamentally change how power electronics is implemented in a system perspective that normally would require multiple power converters. Its programmability can also provide component redundancy and versatility with changing requirements.

There is fundamental research that remains to realise such converter and this paper does not attempt to solve all of these, but merely introduce the concept to inspire future research.

References

[1] T. M. Jahns and B. Sarlioglu, “The incredible shrinking motor drive: Accelerating the transition to integrated motor drives,” *IEEE Power Electronics Magazine*, vol. 7, no. 3, pp. 18–27, 2020.

[2] R. W. Erickson, “Synthesis of switched-mode converters,” in *1983 IEEE Power Electronics Specialists Conference*, 1983, pp. 9–22.

[3] J. Burdio and A. Martinez, “A unified discrete-time state-space model for switching converters,” *IEEE Transactions on Power Electronics*, vol. 10, no. 6, pp. 694–707, 1995.

[4] J. Burdio, A. Martinez, and J. Garcia, “A synthesis method for generating switched electronic converters,” *IEEE Transactions on Power Electronics*, vol. 13, no. 6, pp. 1056–1068, 1998.

[5] A. Purwadi, K. A. Nugroho, A. Rizqiawan, and P. A. Dahono, “A new approach to synthesis of static power converters,” in *2009 International Conference on Electrical Engineering and Informatics*, vol. 02, 2009, pp. 627–633.

[6] G. Chen, Z. Jin, Y. Liu, Y. Hu, J. Zhang, and X. Qing, “Programmable topology derivation and analysis of integrated three-port dc–dc converters with reduced switches for low-cost applications,” *IEEE Transactions on Industrial Electronics*, vol. 66, no. 9, pp. 6649–6660, 2019.

[7] S. S. Nag, R. Panigrahi, S. K. Mishra, A. Joshi, K. D. T. Ngo, and S. Mandal, “A theory to synthesize nonisolated dc–dc converters using flux balance principle,” *IEEE Transactions on Power Electronics*, vol. 34, no. 11, pp. 10 910–10 924, 2019.

[8] R. Panigrahi, S. K. Mishra, and A. Joshi, “Synthesizing a family of converters for a specified conversion ratio using flux balance principle,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 3854–3864, 2021.

[9] T. S. Ambagahawaththa, D. Nayanasiri, and A. Pasqual, “A four-step method to synthesize a dc–dc converter for multi-inductor realizable arbitrary voltage conversion ratio,” *IEEE Transactions on Industrial Electronics*, vol. 69, no. 6, pp. 5594–5603, 2022.

[10] Y. Shen, H. Wang, A. Al-Durra, Z. Qin, and F. Blaabjerg, “A structure-reconfigurable series resonant dc–dc converter with wide-input and configurable-output voltages,” *IEEE Transactions on Industry Applications*, vol. 55, no. 2, pp. 1752–1764, 2019.

[11] Y. Zuo, X. Pan, J. Zhu, J. Ye, and Y. Wang, “A bidirectional isolated llc resonant converter with configurable structure for wide output voltage range applications,” in *2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia)*, 2020, pp. 1716–1721.

[12] J. Teng, P. Shen, B. Liu, and S. Chen, “Circuit configurable bidirectional dc-dc converter for retired batteries,” *IEEE Access*, vol. 9, pp. 156 187–156 199, 2021.

[13] I. Subotic, N. Bodo, and E. Levi, “An ev drive-train with integrated fast charging capability,” *IEEE Transactions on Power Electronics*, vol. 31, no. 2, pp. 1461–1471, 2016.

[14] L. Lopera, R. Rodriguez, M. Yakout, M. Elbestawi, and A. Emadi, “Current and potential applications of additive manufacturing for power electronics,” *IEEE Open Journal of Power Electronics*, vol. 2, pp. 33–42, 2021.