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Short communication

Study of a PEFC power generator modular architecture based on a multi-stack association

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Abstract

This paper presents a study of a polymer electrolyte fuel cell (PEFC) power generator based on a multi-stack association dedicated to transportation applications. First, a dynamic model of the fuel cell for high frequencies, which can be used in association with the power converter is presented. In a second hand, an original power converter architecture has been studied which authorizes the electrical association of two fuel cell stacks. Such a configuration is well adapted for the testing of fuel cell in normal or degraded mode which corresponds to real operating conditions encountered on-board a vehicle. Finally, simulation results of the complete twin-stacks power system are presented and discussed.

Keywords: Dynamic fuel cell modelling; High-frequency transformer; Multi-stack; PEFC; Simulation

1. Introduction

Polymer electrolyte fuel cell (PEFC) seems to be the most promising technology for fuel cell dedicated to power applications. Automotive applications (typically, 50–80 kW) or stationary applications require a power increase thus forcing the manufacturers to multiply the number of cells and to use larger MEA areas. Moreover, the use of bulky stacks involves many thermal and gas management problems. It appears that the PEFC elementary modules (stacks) association is in better agreement with industrial and technological solutions. This power electrical multi-stack architecture should take into account different connection modes (serial or parallel) for the stacks and the choice of the power electronic converter is essential. The study of a PEFC modular architecture constitutes the aim of this paper. First, a definition of a simplified dynamic model for the stack versus high-frequency (HF) current solicitations is developed. The second point concerns the study of an original electrical structure for the power converter, which authorizes different connection modes of the elementary modules. Then, the stack model and the power converter model are used in order to simulate the two stack generator associations. The simulation will able a better comprehension of the electrical behavior of the twin-stack system.

2. Stack modelling

In order to compute the stack voltage, electrode potentials have been calculated assuming irreversible oxido-reduction reaction on both electrodes [1,2]. Then, the static response of stack can be computed by Eq. (1):

$$E_{\text{stack}}(i) = N(E_{\text{a}}(i) - E_{\text{c}}(i) - r_{\text{m}} \cdot i) \quad (1)$$

where r_{m} represents the membrane resistance of the cell, $E_{\text{a}}(i)$ the potential of the anode, $E_{\text{c}}(i)$ the potential of the cathode and N is the number of cells. Model parameters can be evaluated by impedance spectroscopy.

This first computation allows simulation of the static response of a 20-cell stack (Fig. 1). The detail of the calculation and the experimental identification and validation is described in Ref. [3].

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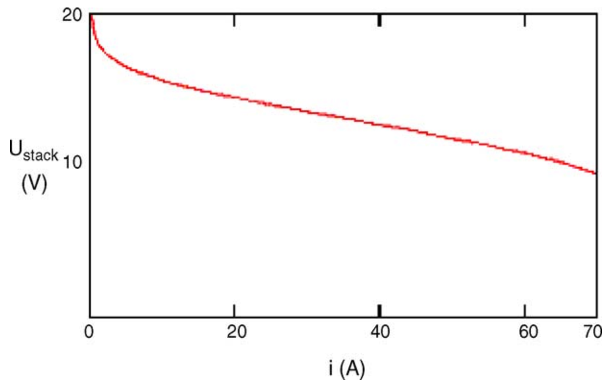

Fig. 1. Static response of a 20-cell stack.

In order to compute electrode impedance and dynamic behavior of the stack, potentials electrodes have been derivate with respect to the current i, with a limitation to the first order of the Taylor series [4].

Then, the final impedance of the both circuits gives an equivalent circuit representation of the fuel cell stack (Fig. 2).

R_{t_a} (respectively, R_{t_c}) is the transfer resistance of the anode (respectively, cathode) and W_δ is a diffusion–convection impedance. W_δ impedance is not linear but it can be decomposed in an infinite number of RC cells. In the implementation, it has been limited to 10 RC cells.

The use of this equivalent circuit representation allows an easier analysis of the fuel cell impedances and a simplified implementation in the simulation process of the vehicular power supply.

Fig. 3 shows measured impedance spectra of the fuel cell for different current solicitations from 5 to 50 A for a constant fluid flow and for a frequency excursion from 1 to 100 kHz. The spectra show two arcs; the right one corresponds to low frequencies, the left one corresponds to high frequencies. The

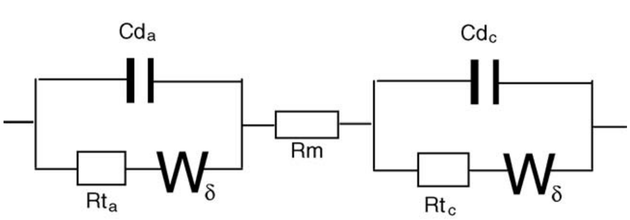

Fig. 2. Equivalent circuit of one single cell.

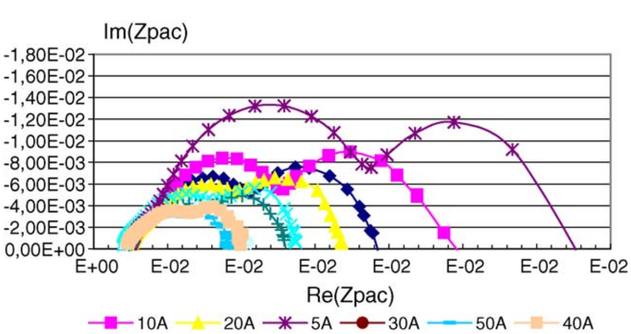

Fig. 3. Experimental impedance spectra of the fuel cell.

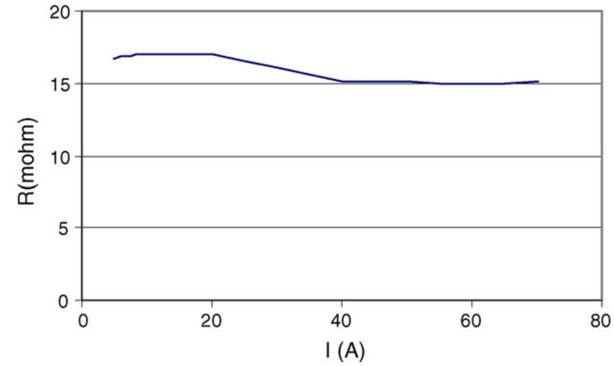

Fig. 4. Impedance of the studied 20-cell stack vs. the current for a fixed frequency of 50 kHz.

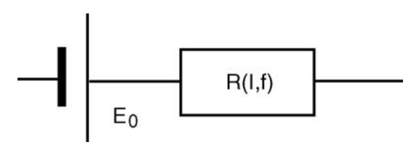

Fig. 5. Simplified model of the fuel cell stack for high frequencies.

computed impedance spectra and the measured ones are in good agreement [5].

Fig. 3 shows that for frequencies up to 10 kHz, the stack has a resistive behavior. The resistance variation is reported for an operating frequency of 50 kHz, which appears as a relevant frequency for the dedicated power converter (see Section 3.2) and for a current solicitation from 0 to 70 A, which corresponds to the current range of the fuel cell used in our application (Fig. 4).

The model can then be simplified for high-frequency solicitations as follows: the open circuit electromotive force E_0 in series with a resistance $R(I,f)$ depending on the current delivered by the fuel cell and the frequency range of the power converter (Fig. 5).

This simplified model of the fuel cell stack will be integrated now in the simulation program in order to have a global model of the power system composed of the fuel cell generators and the associated power converter.

3. Study of the power converter structure

3.1. Problematic and requirements of the power system

In order to increase the power required for stationary or transportation application, series and/or parallel association of fuel cell stacks seems to be the most efficient solution. To reach this aim, an important work has been done to find out a new modular power architecture. The study presented in this paper has been limited to two PEFC stacks having the same nominal output power 500 W. It is based on characteristics of stacks supplied by the ZSW Company, i.e. 20 cells, 100 cm^2 MEA area. The power system supplies a 42 V_{DC} bus, a voltage level, which will be used in automotive industry in mid-term.

The stack voltage varies between the open circuit voltages 20 and 9 V, which is the threshold value chosen to keep the stack safety. The maximal current density is around 0.7 A cm^{-2} and is fixed by the maximal gas flow that the test bench can provide.

Fig. 6. 5400 W–50 kHz PAYTON planar transformer.

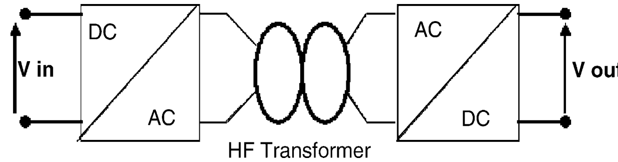

Fig. 7. Global structure of the converter.

A stack delivers then a 70 A maximal current. These characteristics determine constraints on the output power converter architecture. The structure should allow a series or a parallel coupling.

In the case of our study, the parallel coupling is in fact a "*pseudo-parallel*" connection mode, which consists in operating both stacks separately (Fig. 8). There is no real addition of each fuel cell current to the DC bus as required for a real electrical parallel connection of the fuel cell sources. Moreover, this structure authorizes an asymmetric control for the stacks.

The power converter architecture should take into account the different interaction problems resulting from these connection modes. The final converter working conditions impose significant requirements and limitations on the choice of components and their packaging.

Different converter topologies have been studied and compared, from the simplest one like a buck or boost converter [6,7] to high-frequency transformer based converters [8–10]. All these power electronic structures have been developed in order to use only one fuel cell stack as an input source to the system. Furthermore, they do not take into account degraded running modes or generator failure, which must be considered in transport applications for safe operation. The structure presented in this paper is an original one. It is based on the use of a high-frequency PAYTON planar technology transformer [11–13] as shown in Fig. 6. This one allows a better integration and compact structure of the power system than using a classical high-frequency transformer.

A working frequency of 50 kHz appears as a good compromise between power losses and the transformer volume.

3.2. Converter topology

The chosen power converter structure (Fig. 7) is constituted of two stages linked by the high-frequency transformer.

The first stage of the converter is an inverter, which generates square-shaped voltage from fuel cell source; it is based on the use of two separated half bridges using Trench MOSFET technology [14]. This converter structure is able to associate the fuel cell stacks either in pseudo-parallel or in series connection modes. Fig. 8 shows the pseudo-parallel connection mode. V_1 and V_2 represent, respectively, the two fuel cell voltages.

To realize this association, a two-separated input winding transformer is needed. With such a configuration, an asymmetric power management of the stacks can be tested. As a matter of fact, the power delivered by each stack can be different, depending on the gas feeding and the temperature regulation. The asymmetry can be either voluntarily imposed or can be the response of the power system to a degraded operation of one stack.

Fig. 9 shows the converter topology when two fuel cell stacks are connected in series. The resulting input voltage is $V_1 + V_2$.

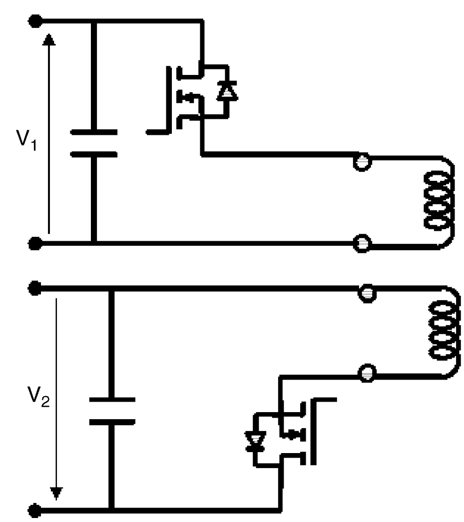

Fig. 8. Converter topology for a "pseudo-parallel" association of the stacks, V_1 and V_2 are voltages delivered by the two stacks.

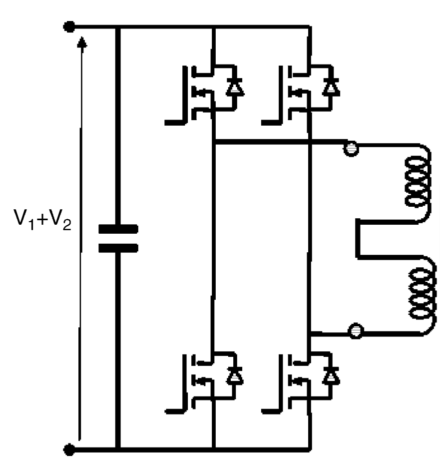

Fig. 9. Converter topology for a series association of the stacks.

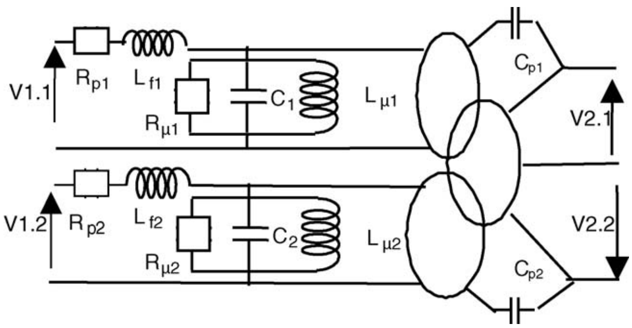

Fig. 10. High-frequency transformer model.

In this case, a transformer with only a single primary winding can be used. It is fed by a full bridge composed of four power Mosfet switches.

This second topology (Fig. 9) can be obtained from the same planar transformer (Fig. 8) by connecting both transformer primary windings. This specific connection of the transformer causes a modification of the transformer ratio m from 1 to 0.5, and consequently, the output voltage level is the same in the series coupling as in pseudo-parallel connection mode.

3.3. High-frequency transformer model

In order to simulate the global operation of the converter, it is necessary to establish a model of the high-frequency transformer (Fig. 10).

The parameters of the transformer model have been evaluated by impedance spectroscopy and implemented using the Matlab Simulink® software.

3.4. Simulation results

According to the model presented Fig. 10, input and output voltage response of the transformer has been calculated. Figs. 11 and 12 show the response of the two primaries windings of the transformer for a current solicitation. The peaks on the voltage waveforms are due to the switching of the Mosfet transistors. A snubber circuit will be added in order to limit the over-voltage variations during commutations.

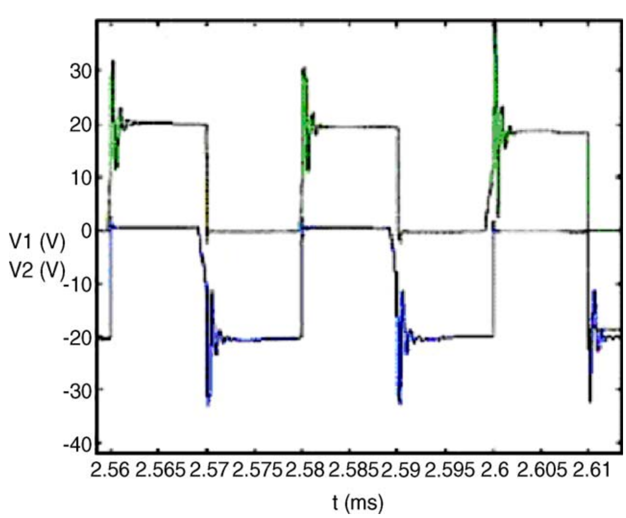

Fig. 11. Primary winding voltages for the parallel connection mode.

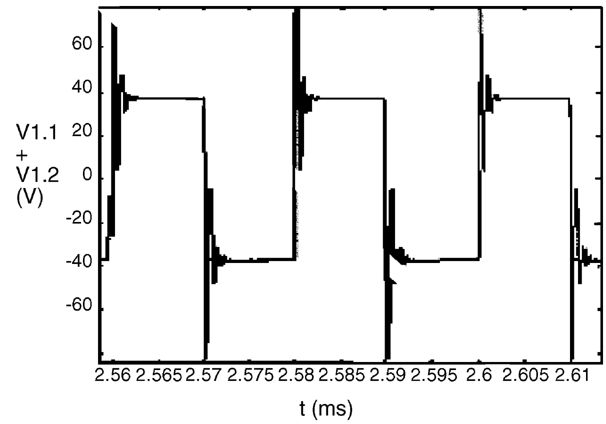

Fig. 12. Primary winding voltages for the series connection mode.

Different output power converter topologies can be chosen like sinusoidal or square power modulation converters, multi-level converters or simply a boost converter.

In this study, we have chosen a boost converter to adapt the output voltage of the transformer to a 42 V_{DC} bus as shown in Fig. 13.

The operation of the converter structure (Fig. 14) can now be fully simulated.

We have simulated the converter behavior for the two different connection modes (series and pseudo-parallel) in order to demonstrate by simulation that such a structure is applicable and reliable for fuel cell dedicated to transport or automotive applications. This power electronic structure is able to test the fuel cells for different operating conditions. The stacks can be unbalanced and the control strategy, which is applied to the fuel

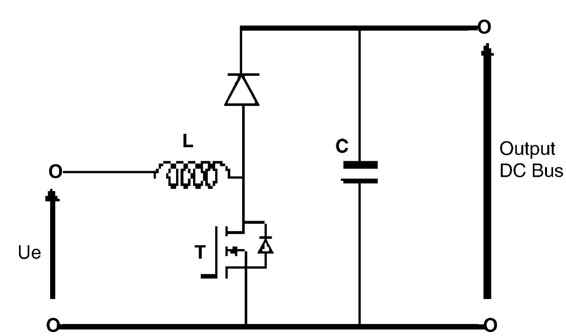

Fig. 13. Boost structure of the output converter.

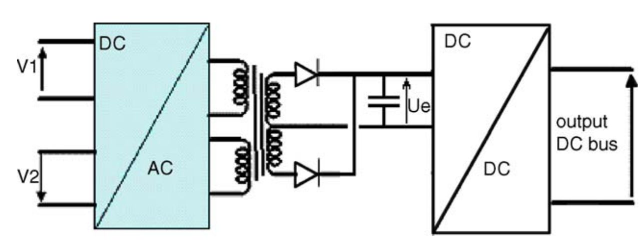

Fig. 14. Simplified structure of the global power converter.

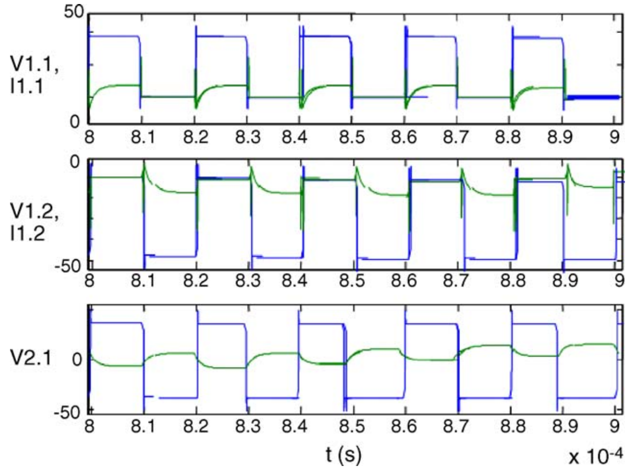

Fig. 15. Simulation result for the parallel connection mode.

cells can be asymmetric. Adding a DC filtering input capacitor at the first stage of the power converter (Fig. 8) allows limiting the over-shoot during the start-up of the power system. This capacitor behaves like a power buffer regarding the fuel cell and consequently protects the stack from high-frequencies over-currents.

Fig. 15 shows the voltages and currents waveforms for the primary winding ($V_{1.1}$, $V_{1.2}$, $I_{1.1}$ and $I_{1.2}$) of the HF transformer when the pseudo-parallel connection mode for the fuel cell stacks is used.

The simulation results show that the frequency is imposed and no significant over-shoot appear on the waveforms (see Fig. 16 and Table 1).

V_{out} is the output voltage of the transformer (secondary winding), V_{in} is the input voltage of the transformer when the two stacks are connected in series.

Fig. 17 shows the output voltage of the transformer when the stacks are connected in parallel. The peak voltages due to commutation are filtered.

Results shown in Fig. 18 are obtained for a current ripple imposed of 12 A and for the maximal amplitude of the fuel cell current. In that particular case, the current has not been limited in order to test the fuel cell for its extreme operating conditions. This result does not take into account the fluid flow limitation of the testing bench.

It can be seen in Fig. 18 that the filtering capacitors play their role of power buffer and avoid each fuel cell to have a prejudicial discontinuous behavior.

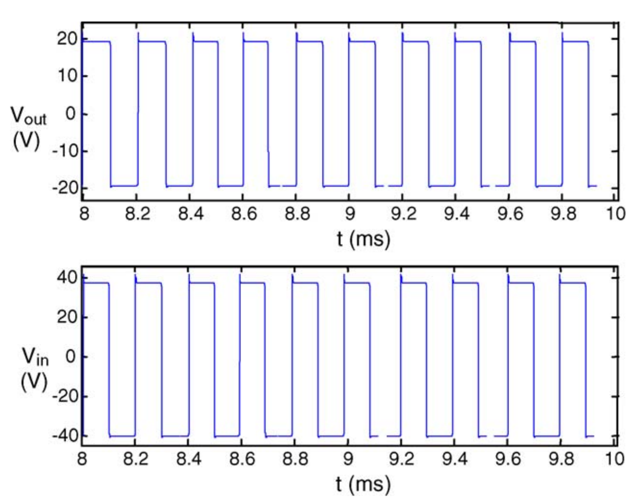

Fig. 16. Simulation result of the series connection mode.

Table 1
High-frequency transformer model parameters

R_{p_1}, R_{p_1}	Equivalent resistance of the primary coil
L_{f_1}, L_{f_2}	Equivalent leakage inductance of the primary and secondary coils
C_1, C_2	Equivalent coil capacitances
L_{μ_1}, L_{μ_2}	Magnetizing inductances of the transformer
R_{μ_1} R_{μ_2}	Magnetic core losses equivalent resistances
C_{p_1}, C_{p_2}	Primary to secondary equivalent capacitances

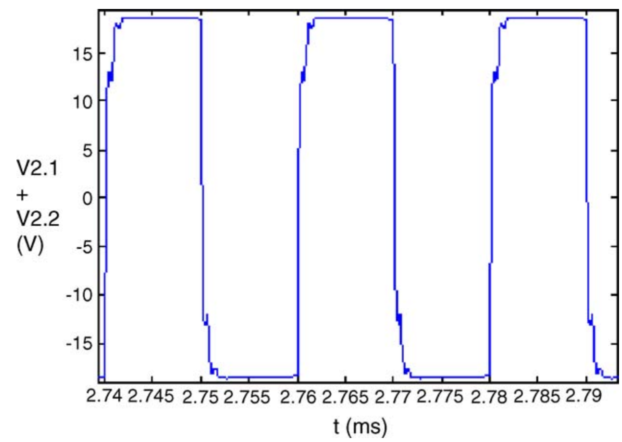

Fig. 17. Output voltage of the HF transformer for the pseudo-parallel connection mode.

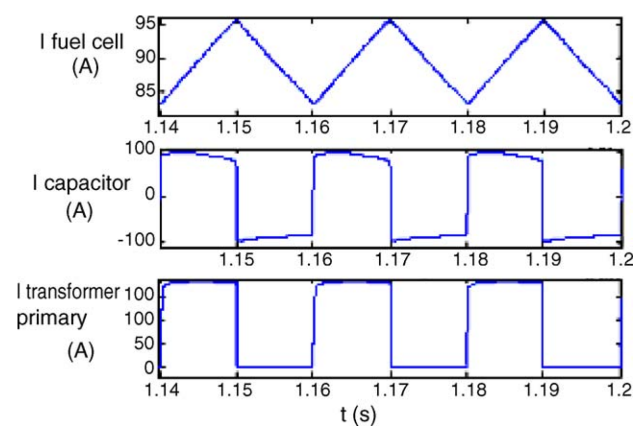

Fig. 18. Current responses of the fuel cell, filtering capacitor and transformer primary winding for the pseudo-parallel connection mode.

4. Conclusion

This paper has presented the advantages of using a HF power chain, based on the use of a HF transformer to adapt fuel cell voltage for future power traction applications. In the first step of the work, a fuel cell stack model has been established, valid at high frequency with the aim of coupling it with the power electronic converter. The second step has concerned the definition of a power converter architecture, which enables the electrical association of two PEFC stacks. The originality of such structure consists in the possibility for the fuel cell stacks to operate either in normal or in degraded mode and the control management can be asymmetric. Simulation results of the complete power chain confirmed that such a structure is a promising way to transfer the energy between the fuel cell to the power engine.

Different topologies for the output power converter could be chosen like sinusoidal or square power modulation converter, multi-level converter or simply a boost converter as shown in this study. A testing bench has been designed in order to validate the simulation results. The first results should confirm and validate the choice of a HF transformer based power converter. The study presented in this paper has been limited to two fuel cell stacks only. However, future investigations should demonstrate the possibility for such a power converter structure to associate multi-stacks in order to increase the power required for transportation applications and test their functionality.

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