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Research Article

Next generation of power electronic-converter application for energy-conversion and storage units and systems

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Abstract

By a rearrangement of the traditional supply-converter-load system connection, partial-power-processing-based converters can be used to achieve a reduction in size and cost, increase in system efficiency and lower device power rating. The concept is promising for different applications such as photovoltaic arrays, electric vehicles and electrolysis. For photovoltaic applications, it can drive each cell in the array to its maximum power point with a relatively smaller converter; for electric-vehicle applications, both an onboard charger with reduced weight and improved efficiency as well as a fast charger station handling higher power can be considered. By showing different examples of partial-power-processing application for energy-conversion and storage units and systems, this paper discusses key limitations of partial-power-processing and related improvements from different perspectives to show the potential in future power electronic systems.

Keywords: batteries; DC–DC converter; differential power processing; fuel cells; hydrogen production; partial-power processing; wide band-gap devices; fractional power processing

Introduction

Different sources for renewable-energy production are currently in use and more are being researched in order to bring them to the commercial level [1]. Photovoltaic (PV) panels, wind turbines and hydro power are a few examples of commercially available sources that are included in the power system and more are added to the mix every day. Other emerging renewable systems are enhanced geothermal, artificial photosynthesis, concentrated solar and cellulosic ethanol [2]. All of these sources can deliver electrical power but at different voltage levels, ranging from a few volts to kilo or mega volts, and either of the AC or DC type. Since some renewable-energy sources are intermittent, such as when the sun shines or the wind blows, an intermediate is needed to store the energy when there is too much energy in the power system.

A wide variety of storage systems are available for storing excess energy, for example batteries (many different chemical compositions), pumped hydro, flywheel, compressed-air energy storage and some emerging technologies at various stages: hydrogen systems (electrolyser and fuel-cell), superconducting magnetic-energy storage and electrochemical capacitors [3]. For the storage systems, as was the case for the sources of renewable energy, the input and output voltages range from a few volts to kilo or mega volts. Therefore, an interface between energy generation and storage is needed. Since the interface
needs to be used to both store and retrieve the power, it needs to be highly efficient.

The conventional way of interconnecting an energy-storage system (ESS) to a renewable-energy source could be through a DC bus, as shown in Fig. 1, where a positive terminal and a negative terminal of a bidirectional DC–DC converter are connected to the ESS while the other positive and negative terminals of the DC–DC converter are connected to the regulated DC bus. This means that the power (P) running into the DC–DC converter will also be the power supplied to the ESS (minus the losses of the DC–DC converter), thus the DC–DC converter has to be rated at the same power level as the ESS and the supply.

Instead of using the conventional way of interconnection, the next-generation power electronic-converter applications are proposed to use the idea of connecting the ESS in series to the DC–DC converter and the DC bus, which is shown in Fig. 2. The ESS is connected between the positive terminals of the DC–DC converter, while the DC bus is connected to a positive terminal and the reference of the DC–DC converter. In that manner and in accordance with Fig. 2, the voltage \( V_1 \) is set by the partial voltage between the DC bus and the ESS (\( V_2 - V_{ESS} \)), hence the DC–DC converter only processes the partial power between the DC bus and the ESS. The definition of \( V_1 \) and \( V_2 \) will be followed throughout the rest of the paper and their corresponding names in other figures will be pointed out. Here, it should be noted that, in the literature, this concept is known under at least the following names: differential/fractional/partial-power processing [4–6] and, for the rest of the paper, it will be known as partial-power processing (PPP).

Several different PPP schemes have already been described in the literature and here a couple of applications will be shown. The earliest configuration using PPP seems to be [7] from 1996, where it is called a Series Connected Boost Unit (SCBU). The intended use was for PV arrays supplying a battery, particularly in space use. The author specifies the idea as a ‘unique interconnect topology’ instead of a new DC–DC converter and suggests that many isolated DC–DC converters can be used. The topology is shown in Fig. 3, which shows the configuration used to further boost the output voltage by stacking the voltage of the PV cells on top of the converter output. Based on the numbers in Fig. 3, the efficiency of the system is calculated as

\[
\eta = \frac{P_{out}}{P_{in}} = \frac{V_{out} \cdot I_{out}}{V_{in} \cdot I_{in}} = \frac{28V \cdot 10A}{20V \cdot 14.7A} = 95.2\%\,,
\]

for a DC–DC converter efficiency of 85%. This showcases the higher-than-normal efficiency of the system view. The increase in power density is also calculated by [7] for the system in Fig. 3 as

\[
P_{d_{SCBU}} = \frac{V_{out}}{V_{boost}} \cdot P_{dc} = \frac{28V}{8V} \cdot 80W = 250\%\,.
\]

Another benefit of the SCBU according to the author is an inherent fault tolerance, which for space applications usually is covered by redundancy in the system. Reference [7] argues that the redundancy in the case of the SCBU can be a shorting of the output side, which would connect the PV array directly to the battery of this system. The usual requirement for redundancy in spacecraft applications is to have the required number of converters plus a backup converter, which translates to removing one converter from the spacecraft for both cost and weight savings. The last benefit worth mentioning is that an isolated DC–DC buck converter is used to achieve a boost converter, which is possible even with a lower-efficiency converter due to the increase in efficiency from the SCBU topology.

The limitations of the system given by [7] as a direct quote are

1. The SCBU is a boost converter and requires that the output voltage be greater than or equal to the input voltage at all times,
2. Galvanic isolation must not be required between input and output circuits, and
3. The input voltage source has a limited voltage range requiring only a small percentage (<50%) of voltage boost.

The last requirement has since been shown by others not to be a limitation, whereas the first two requirements are still a hindrance to the PPP scheme.

PPP has recently been gaining more attention than earlier, especially for PV arrays, where it is used for maximum power-point tracking for individual cells of the PV array. A recent paper [8] organizes the different techniques used for PPP together with PV arrays into two main groups: series-connected PV strings and parallel-connected PV strings, examples shown in Fig. 4a and b, respectively. Series-connected PV strings are used to achieve a larger voltage than a single PV cell can supply on its own, while the parallel-connected PV strings are used if the required voltage is only slightly larger than the PV cells can supply on their own. The use of PPP here is to ensure that each cell is working at its maximum power point by either supplying the cell with extra current from the bus or feeding excess current to the bus.

PPP has also been suggested in use for extreme fast-charging stations [9], where the drawing has been redrawn in Fig. 5 to reflect our style of drawing. Fig. 5 highlights another feature of PPP: the excess energy can be delivered back to the source or the load, depending on what would be most beneficial to the actual application. The DC–DC converter chosen for this application is a current-fed resonant full-bridge boost converter, which has a transformer to help boost the voltage between the input and the output. As in the other papers about PPP, the benefits are praised as lower initial cost and better efficiency than a full-rated converter, but here it is taken a step further and calculates what the improved efficiency means in kWh. A straightforward approach is used, where the loss over time is calculated as

$$e_{bus} = \int_0^T P_{loss}(t)dt.$$  \hspace{1cm} (3)

The full power processing is compared to the PPP approach for the same charging profile, which shows almost a reduction of a factor of 10 in used kWh for their example.

The trend in power systems is a move towards distributed energy-production and storage system [10], which translates to a need for more converters placed close to the production or storage. PPP is a promising concept in that regard, since it is an effective way to minimize the physical size, which is due to a lower power requirement. At the same time, the initial and running costs of converters will also be reduced, which is of great benefit when the installation of more converters is required.

1 PPP examples

Different prototypes have been created at the Technical University of Denmark and will here be reproduced as examples showing the application of PPP.

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Fig. 4 Example of (a) a series-connected string of PV cells controlled by PPP and (b) a parallel string of PV cells controlled by PPP [8]. The power is flowing from the PV panels to the bus; thus, with reference to Fig. 2, $V_{bus}$ is equal to $V_{ESS}$.

Fig. 5 PPP for use in an extreme fast-charging station. (a) Charging the ESS, (b) discharging the ESS.
Before getting into the examples, a short explanation of the gain of PPP is given. When using PPP, there will be an efficiency ($\eta$) of the DC–DC converter and a different efficiency for the overall system. The efficiency of the system can be written as [4]

$$\eta_{\text{system}} = \frac{1}{1 + k \cdot (1 - \eta_{\text{DC–DC converter}})},$$

where

$$k = \frac{P_{\text{DC–DC converter}}}{P_{\text{ESS}}} = \frac{V_2 \cdot I_{\text{ESS}}}{V_{\text{ESS}} \cdot I_{\text{ESS}}} \approx \frac{V_1 - V_{\text{ESS}}}{V_{\text{ESS}}},$$

$V_1$ is the DC bus voltage, $V_2$ is the converter input voltage and $V_{\text{ESS}}$ is the ESS voltage, thus $V_1 - V_{\text{ESS}}$ is the DC–DC converter input voltage. This definition of voltages comes from Fig. 2.

Fig. 6 shows the system efficiency as a function of $k$ and a function of converter efficiency. For $k = 0$, the system is 100% effective, which is expected, since, at $k = 0$, the converter is not processing any power from the system. This requires that $V_1$ is 0 V, which requires infinite gain to get the required output voltage and is thus hard to achieve. At the other extreme of $k = 1$, meaning the converter processes the full power, there is a small improvement if a 90% converter is used, but an improvement of 17% for a 50% efficient converter. $k = 1$ means that $V_{\text{ESS}}$ is equal to $V_2$ and thus only half of the system power is being processed. This shows that the best way to operate a PPP system is to have a small voltage difference between the energy source and the ESS. One approach to achieving a high voltage at the input of the converter and a low voltage at the output is the so-called input-series-output-parallel concept or, in reverse, the input-parallel-output-series for a low-input voltage and a high-output voltage.
1.1 Alkaline electrolyser cell converter

The first prototype was made for an alkaline electrolyser cell and the system specifications are shown in Table 1, while the relationship between the power processed by the DC–DC converter versus the power fed into the electrolyser cell at different output voltages is shown in Fig. 7. There is no linear relationship between the two, which is due to the I-V characteristic of the electrolyser cell. The converter can be seen in Fig. 8a [11, 12], the system setup is shown in Fig. 8b and the system diagram is shown in Fig. 8c. An example of a positive load step is shown in Fig. 9a and a negative load step is shown in Fig. 9b. Both load steps occur with no overshoot and the negative load step is faster than the positive load step.

The converter is made for a maximum operating power of 733 W, while the maximum system power is 3.5 kW. The highest k factor is achieved when the input to the DC–DC converter is 2 V and the output is 48 V (corresponding to a V_{ESS} of 48 V), resulting in $k = 0.04$. This k factor occurs at the same time as the efficiency of the DC–DC converter itself is low, as seen in Fig. 10a. Fig. 10a shows the efficiency of the DC–DC converter at different $V_1$ levels, giving the worst-case DC–DC converter efficiency when $V_1$ is the lowest. In Fig. 10b, the calculated system efficiency is shown. All the efficiencies are within 0.5% and the highest efficiency is achieved when the converter efficiency is lowest, which is attributed to the fact that the k factor is lowest for this.

Table 1 Alkaline electrolyser system specifications [7]

| Specification          | Value       |
|------------------------|-------------|
| V_{ESS}                | 35 – 48 V   |
| I_{ESS}                | 0 – 72 A    |
| V_1                    | 58 – 50 V   |
| $V_2 = V_1 - V_{ESS}$  | 23 – 2 V    |
| Maximum system power, $P_{system}$ | 3456 W |
| Maximum dc converter power, $P_{DC-DC}$ | 733 W |
| k                      | 0.21        |

Fig. 8 (a) DC–DC converter made for an alkaline electrolyser cell using the partial-power concept. (b) The DC–DC converter connected to an alkaline electrolyser system. (c) System diagram of the DC–DC converter and the ESS, which, in this case, is an electrolyser cell (EC) [11, 12]. Reprinted from [12] with permission from IEEE.

Fig. 9 Load-step response of the PPP system. (a) is a positive step and (b) a negative. The shown waveforms are identical between (a) and (b), and are as follows from top to bottom: $V_{gs}$ is the gate voltage (10 V/div), $V_1$ is the converter input voltage (5 V/div), $I_{ESS}$ is the ESS current (2 A/div) and $I_L$ is the inductor current (20 A/div), Rogowski coil (100 mV/A). Time scale is 6.4 ms/div [11, 12]. Reprinted from [12] with permission from IEEE.
V. The measured system efficiency is shown in Fig. 10c and, again, the efficiency is flat at higher powers and the highest efficiency is obtained at the highest power level. This showcases one of the benefits of PPP, which is that the usual worst-case operating mode for the DC–DC converter (high voltage gain) is suddenly turned into a highly efficient mode, since the $k$ factor becomes low.

### 1.2 Solid-oxide electrolyser/fuel-cell converter

The second prototype is of a solid-oxide electrolyser cell (SOEC)/solid-oxide fuel-cell (SOFC) setup [13, 14], which can be seen in Fig. 11a and the system diagram in Fig. 11b. The drawing of the system diagram is changed from the first prototype, but the functionality of the two is equal. The SOEC/SOFC system is in the background of Fig. 11a, while the converter is shown in the front. The I-V curves of the used SOEC/SOFC can be seen in Fig. 11c and the overall system specifications can be seen in Table 2. The $k$ factor for the charging is in the low end and, as shown in Fig. 6, the expected system efficiency is above 90% regardless of the efficiency of the DC–DC converter. For the discharging case, the benefit is reduced due to the higher $k$ but, with a converter efficiency of 90%, the system efficiency is still improved to ~94%. Fig. 12 shows the converter and system efficiency, while discharging (SOEC mode). The efficiency on the system level improves by around 2% and the system efficiency curve is relatively flat, which is usually hard to achieve since the control reduces the efficiency at low power levels and conduction losses reduces efficiency at high power levels.

### 1.3 Electric-vehicle converter

The last prototype is a DC–DC converter designed for charging a battery in an electric vehicle [4]. The DC–DC converter is shown in Fig. 13a, the setup is shown in Fig. 13b and Table 3 lists the specifications of the system. The system diagram is shown in Fig. 13c and it can be seen that the configuration is the same as in the first prototype. Table 3 shows that the voltage difference between the ESS and the supply is smaller than the earlier prototypes, which leads to a larger $k$ factor and therefore a smaller improvement in the efficiency. The converter and system efficiency for $k = 0.4$ is shown in Fig. 14a and, for the lowest converter efficiency, the system efficiency is improved by 8%, while it is improved by around 4% for the rest of the
The efficiencies for $k = 0.9$ is shown in Fig. 14b, where the lowest converter efficiency is improved by 2% at the system level and the rest of the efficiencies are improved by around 1%. This comparison shows the benefit of having a big difference between the voltages of the ESS and the source, leaving only a small part of the processed power to the DC–DC converter and thus improving system efficiency.

### Table 2 SOEC/SOFC system specifications [6]

| VESS [V] | Charging | Discharging |
|----------|----------|-------------|
| VESS     | 450–540 V| 360–450 V   |
| IESS [A] | 0–60 A   | 30–0 A      |
| $V_1$ [V]| 600 V    | 600 V       |
| $V_2 = V_1 - V_{ESS}$ | 150–60 V | 240–150 V |

Maximum system power, $P_{system}$: 32.4 kW for charging, 10.8 kW for discharging.

Maximum DC–DC converter power, $P_{DC–DC}$: 3.6 kW for charging, 7.2 kW for discharging.

The range of the voltages and currents are from 2 to 600 V and from 0 to 72 A, respectively, but can in theory go both lower and higher than that. The converter power level compared to the system power level also ranges by a factor of 10 (from 733 W to 7.2 kW), which can also vary more for the right applications.

A benefit that has not been mentioned yet is that, due to a high-voltage/low-current side and a low-voltage/high-current side of the converter, the components used does not need to be rated for both high voltage and high current as is usually the case for DC–DC converters converting voltages that are close between the source and the ESS. For example, take the system specifications in Table 1, which, for a traditional converter, would need devices rated at 48 V/72 A on one side and 58 V/~69 A on the other side. For the system employing PPP, those ratings would change to 48 V/72 A on one side and 58 V/~69 A on the other side. This might lead to more options of switching devices, lower-cost devices, less copper on the printed circuit board and reduced costs for the magnetic and capacitive components.

So is this configuration the new way for all applications? Certainly not. PPP has its limitations, as mentioned earlier, which are: (i) best performance obtained for a voltage difference between the source and load close to zero, (ii) source voltage greater than load voltage and (iii) no galvanic isolation. One use of isolated DC–DC converters is normally that they provide galvanic isolation, which provides safety to both the source and the ESS, but also to any eventual human interaction with the devices. For the three cases here, galvanic isolation has either not been a desired feature or it has been implemented in a different manner.

A difficulty that seems to occur in some DC–DC converters/some PPP configurations is that non-active power is circulating and erodes the benefits of the PPP [15, 16], the idea being that the reactive element of the DC–DC converter is storing non-active energy and losing a bit of that energy every switching cycle.

### 3 Conclusions

The concept of PPP fits into the decentralization trend of society and thus of power electronics moving to distributed systems, where smaller converter units are used close to the source/load instead of bigger centralized units.
several benefits of using PPP, which include a lower initial price, higher efficiency (and thus lower operational cost), lower-rated devices (voltage, current and/or power) and smaller size. As always in electrical engineering, nothing comes for free and the tradeoff for PPP is the requirements of no galvanic isolation and higher source voltage than load voltage. For many applications, the voltage requirement is no problem by default or the system can be set up in such

![DC-DC converter efficiency](image1)

![System efficiency](image2)

**Fig. 12** Converter and system efficiency. $V_{\text{ESS}} = 300–450$ V and $P_{\text{ESS}} = 10$ kW [14].

![Converter and system efficiency](image3)

### Table 3 Electric-vehicle system specifications [3]

| Parameter                        | Specification         |
|----------------------------------|-----------------------|
| $V_{\text{ESS}}$                 | 288 – 403 V           |
| $I_{\text{ESS}}$                 | 10 A                  |
| $V_1$                            | 489 – 566 V           |
| $V_2 = V_1 - V_{\text{ESS}}$     | 201 – 163 V           |
| Maximum system power, $P_{\text{system}}$ | 4 kW     |
| Maximum dc converter power, $P_{\text{DC-DC}}$ | 2.8 kW     |
| $k$                              | 0.70                  |

![Battery efficiency](image4)

**Fig. 13** (a) DC–DC converter for charging of batteries in electric vehicles, (b) DC–DC converter connected to batteries for testing and (c) system diagram of the proposed system. Reprinted from [4] with permission from IEEE.

![Battery efficiency](image5)

**Fig. 14:** Efficiency curves for the DC–DC converter of the electric-vehicle charging and the system efficiency. Operating conditions (a) $V_{\text{ESS}} = 273$ V, $V_1 = 400$ V, $k = 0.4$ and (b) $V_{\text{ESS}} = 273$ V, $V_1 = 540$ V, $k = 0.9$. Reprinted from [4] with permission from IEEE.
a way as to be no problem. Left is the question of galvanic isolation, which again might be of no consequence or can be solved with a fuse, digital instrumentation or some other smart ideas.

It has been shown through examples that PPP is suitable for electrolyser cells, fuel cells, battery storage and, from a literature example, PV arrays. The impact of using PPP compared to the traditional method has been quantified through the use of k factor for the improvement in efficiency and an example calculation of a battery-charging session for the saved energy.

The examples shown here have a moderate power level of 700 W to 7 kW, but both lower and higher power levels would be of interest to investigate in the future and have been shown in the literature with PV panels and the extreme fast electric-vehicle charger. Therefore, the application of the PPP idea is suggested to enable cheaper, lighter and more efficient charger systems. Overall, PPP will be one of the key power electronics systems enabling technologies for next-generation energy-conversion and storage units and systems.

Conflict of Interest: None declared

References

[1] Gielen D, Boshell F, Saygin D, et al. The role of renewable energy in the global energy transformation. Energy Strateg Rev 2019; 24:38–50.

[2] Hussain A, Arif SM, Aslam M. Emerging renewable and sustainable energy technologies: state of the art. Renew Sustain Energy Rev 2017; 71:12–28.

[3] Gürg. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. Energy Environ Sci 2018; 11:2696–767.

[4] Kanstad T, Lillholm MB, Zhang Z. Highly efficient EV battery charger using fractional charging concept with SiC devices. In: Proceedings of Applied Power Electronics Conference 2019 (APEC), Anaheim Convention Center, Anaheim, CA, 2019, 1601–8.

[5] Rojas J, Renaudineau H, Kouso S, et al. Partial power DC–DC converter for electric vehicle fast charging stations. In: Proceedings IEC, 2017–43rd Annual Conference of the IEEE Industrial Electronics Society, China National Convention Center, Beijing, China, 2017, 5274–9.

[6] Levron Y, Clement DR, Choi B, et al. Control of submodule integrated converters in the isolated-port differential power-processing photovoltaic architecture. IEEE J Emerg Sel Top Power Electron 2014; 2:821–32.

[7] Button RM. An advanced photovoltaic array regulator module. In: IECEC 96. Proceedings of the 31st Intersociety Energy Conversion Engineering Conference, 1996; 1:519–24. Washington, DC.

[8] Jeong H, Lee H, Liu YC, et al. Review of differential power processing converter technologies for photovoltaic applications. IEEE Trans Energy Convers 2019; 34:531–60.

[9] Iyer VM, Gulur S, Gohil G, et al. Extreme fast charging station architecture for electric vehicles with partial power processing. In: Conference Proceedings—IEEE Applied Power Electronics Conference and Exposition—APEC, San Antonio, TX, 2018, 659–65.

[10] Fonseca JD, Camargo M, Commenge JM, et al. Trends in design of distributed energy systems using hydrogen as energy vector: a systematic literature review. Int J Hydrogen Energy 2019; 4:9486–504.

[11] Mira MC, Zhang Z, Andersen MAE. Analysis and comparison of dc/dc topologies in partial power processing configuration for energy storage systems. In: 2018 International Power Electronics Conference, IPEC-Niigata—ECCE Asia, Niigata Convention Center, Niigata, Japan, 2018, 1351–7.

[12] Mira MC, Zhang Z, Jørgensen KL, et al. Fractional charging converter with high efficiency and low cost for electrochemical energy storage devices. IEEE Trans Ind Appl 2019. doi: 10.1109/TIA.2019.2921295.

[13] Tomas-Manez K, Anthon A, Zhang Z. High efficiency power converter for a doubly-fed SOEC/SOFC system. In: 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach Convention & Entertainment Center, Long Beach, CA, 2016, 1235–42.

[14] Tomas-Manez K. Advances in Bidirectional DC–DC Converters for Future Energy Systems. Technical University of Denmark, 2018.

[15] Zientarski JRR, Pinheiro JR, Martins MLDS, et al. Understanding the partial power processing concept: a case-study of buck-boost dc/dc series regulator. In: 2015 IEEE 13th Brazilian Power Electronics Conference and 1st Southern Power Electronics Conference (COBEP/SPEC), Fortaleza, Brazil, 2015, 1–6.

[16] Zientarski JRR, Da Silva Martins ML, Pinheiro JR, et al. Evaluation of power processing in series-connected partial-power converters. IEEE J Emerg Sel Top Power Electron 2019; 7:343–52.