Development and Efficiency Test of a 3 MVA Four-port Power Electronic Transformer

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Abstract. The development of a 3 MVA four-port, i.e. 10 kV ac port, 380 V ac port, ±750 V dc port, and ±375 V dc port, power electronic transformer (PET) for an integrated energy system is described. For this four-port PET, the efficiency test is a complex problem as each port-to-port efficiencies should be tested. To solve this problem, this paper proposes a data fitting method using only the converter efficiency in each port. The experimental results show a high accuracy of the proposed testing method. The test results of this four-port PET are also analyzed and the efficiency under different power flow directions is explained.

1. Introduction
A power electronic transformer (PET) can realize the power interface between a medium-voltage (MV) system and a low-voltage (LV) system, in which galvanic isolation is provided using medium-frequency transformer [1-4]. An ocean of researches have been done to analyze the losses of the PET, and numerous soft-switching strategies to improve efficiency. However, the definition of the efficiency for multiport PET rarely attracts much attention.

In this paper, a 3 MVA four-port, i.e. 10 kV ac port, 380 V ac port, ±750 V dc port, and ±375 V dc port, power electronic transformer (PET) for an integrated energy system is developed. The capacity of each port is AC 10kV-3MVA, 380V-0.5MVA, ±750V-2.2MW, ±375V-0.3MW, respectively. To some degree, the 3 MVA four-port PET can be envisioned as an energy router, transforming different voltage levels and connecting to various AC or DC micro-grids, for providing all kinds of load with the corresponding form of electrical energy. In order to get all the efficiency in the various operation modes of the multiport PET, a new method is proposed. The experiment result shows the high accuracy of the test method.

2. The Structure of PET
It is shown in figure 1, which is comprised of three parts: the high voltage (HV) cascaded H-bridge (CHB), the dual-active bridge (DAB), the low voltage (LV) DC-DC convertor and the DC-AC convertor. The HV side CHB converts the HV AC voltage into LV DC voltage and vice versa, as CHB is a bidirectional converter. The dual-active bridge performs the function of DC voltage transformation and it is also a bidirectional converter. The LV DC-AC convertor consists of a buck circuit and the LV DC-AC convertor is comprised of a conventional three-phase inverter using a
three-level NPC structure. LV DC side can be a DC load, DC source (photovoltaic battery, energy storage battery, etc. for instance), or DC grid, and the LV AC side can connect to the AC grid or can be an AC source.

Each part of the PET is controlled separately. The CHB side adopts the conventional double-loop control strategy, as it is presented in the right of the figure 2. The average LV-DC bus value is controlled by using the d-axis current of the conventional d- and q-axis vector control in the synchronously rotating reference frame [5]. Both positive converters and negative converters are controlled by the same strategy. The dual-active bridge adopts an open-loop serial-resonance control strategy. The DC-DC converter is realized by voltage closed-loop control to provide a constant DC voltage(For brevity, control strategy diagrams of DC-DC converter and DAB are omitted in figure 2). The DC-AC converter can work as an AC source or a three-phase grid-connected inverter as they are presented in figure 2. The cascaded H-bridge multilevel converters can successfully operate in a low frequency with the interleaved carrier phase-shifted PWM, offering significantly better output waveforms. In this paper, a method to automatically unlock the pulses of the HV and LV sides’ IGBTs in the DAB converter by detecting the power-flow direction is proposed by which higher efficiency could be reached.

![Figure 1. Topology of the 4-ports PET.](image-url)
3. Efficiency Definition of the PET

Few kinds of research about multi-port PETs give a normative method for efficiency-test. For two-port PETs, much easier it becomes to cope with the efficiency that can be measured and calculated in the limited dimensions. However, it becomes very difficult when multiport PETs are composed of several terminals. PET with four ports, two ACs, and two DCs, of which the efficiency is to be tested, needs lots of measuring devices yet timing synchronization problem should be considered.

For the four-port PET efficiency test, since the four ports are a whole part, it is no longer a separate three power electronic converters. Considering the efficiency between the two ports alone does not explain the efficiency of the whole machine, the four ports must be tested in the same period of time and the overall calculations must be carried out to obtain the overall operating efficiency of the four-port PET. The efficiency should be defined as the specific value of all the output power with the input power in a certain period of time.

4. Efficiency Test Method and Results Analyses

Up to know, PET can be divided into several power conversion units in which each efficiency can be tested alone. Positive and negative power flow direction is defined in figure 3. The experiment prototype is shown in figure 5. And the equipments of measurement in the efficiency test is shown in figure 6 in which the efficiency of all ports under different power flow conditions is measured using a power analyzer (WT-1800).

The experimental efficiency data from 10kV port to ±750V port can be uploaded into the Matlab. With the same method, we can get the efficiency of the DC-DC and DC-AC converters and upload them into the software. Using the data fitting tool in the Matlab, as is presented in figure 4, we can get the linear-poly function of the PET in which the different efficiency of different power flow direction and power transfer unit can be represented. They are listed as follows:

\[
\eta_{10kV \rightarrow 750V} = 0.002681x^3 + 0.02447x^2 + 0.07521x + 0.8912
\]
\[ \eta_{750\_V\_104V} = 0.002743x^3 + 0.02571x^2 + 0.08467x + 0.8596 \]  
(2)

\[ \eta_{750\_V\_375V} = 2.9910x^3 + 2.5342x^2 + 0.7251x + 0.9132 \]  
(3)

\[ \eta_{375\_V\_750} = 1.4791x^3 + 1.6097x^2 + 0.5548x + 0.9294 \]  
(4)

\[ \eta_{750\_V\_380V} = 0.6458x^3 + 0.9122x^2 + 0.4351x + 0.9034 \]  
(5)

\[ \eta_{380\_V\_750} = 0.5207x^3 + 0.7801x^2 + 0.3945x + 0.9147 \]  
(6)

With the fitting functions of the PET from (1)-(6), any kind of running state of the multiport PET can be calculated. In the left of figure 3, the efficiency of the PET could be derived as:

\[ \eta_{104V\_V\_750V} = \frac{P_{380\_in} + P_{375\_in} + P_{750\_in}}{P_{104V\_in}} \]  
(7)

\[ \eta_{PET} = \frac{P_{380\_in} \times \eta_{380\_V\_380V} + P_{375\_in} \times \eta_{375\_V\_375V} + P_{750\_in} \times \eta_{750\_V\_750V}}{P_{104V\_in}} \]  
(8)

By using the power parameters in figure 3 and substituting them into (1), (7) can be rewritten as follows:

\[ P_{104V\_in} = \frac{2.4}{0.002681 \times 2.4^3 + 0.02447 \times 2.4^2 + 0.07521 \times 2.4 + 0.8912} = 2.48 MW \]  
(9)

By substituting (3) (5) and (7) into (8), the efficiency can be calculated as \( \eta_{PET} = 0.9638 \). With the same method, in the right of figure 3, the efficiency of the PET could also be derived as:

\[ \eta_{750\_V\_104V} = \frac{P_{380\_out} + P_{375\_out} + P_{750\_out}}{P_{104V\_out}} \]  
(10)

\[ \eta_{PET} = \frac{P_{380\_out} \times \eta_{380\_V\_380V} + P_{375\_out} \times \eta_{375\_V\_375V} + P_{750\_out} \times \eta_{750\_V\_750V}}{P_{104V\_out}} \]  
(11)

Given the length of the article, with (2) (4) (6) (10) and (11) to be calculated, the efficiency in this running state is directly given as \( \eta_{PET} = 0.9655 \).

**Figure 3.** The power flow direction defined for each port and the examples of the power flow.
For proving the correctness of the efficiency test method proposed in this paper, the efficiency of the PET is measured again under different power flow condition, where efficiency is defined as $\int_0^T p_{out} \, dt / \int_0^T p_{in} \, dt$. (T is a cycle of fundamental wave). From data in the table 1, the experiment results suit the results from the proposed method well, which indicates the effectiveness and high accuracy of the proposed method.

Table 1. The Comparison of actual and theoretical values.

| Running State          | Experiment Results (From figure 6) | By the fitting method (Proposed Method) |
|------------------------|-------------------------------------|----------------------------------------|
| The Left in figure 2   | 96.32%                              | 96.38%                                  |
| The Right in figure 2  | 96.47%                              | 96.55%                                  |

Take experimental efficiency data from 10kV port to ±750V port as an analysis case: from the efficiency data, the conclusions can be drawn that the efficiency is higher when the power flow is
positive. Because the dual-active bridges convert HVDC to LVDC by a medium-frequency transformer. The switching loss of the HV-side IGBTs becomes much higher than that in the LV-side, the switching loss is mainly correlated to the IGBTs in the HV-side (ABB 5SND 0500N330300). When the CHB side worked as a rectifier, the IGBTs of the LV-side in the DAB will be locked to decrease the switching loss. And when the CHB side worked as an inverter, the IGBTs of the HV-side in the DAB will be locked as well, the switching loss is correlated to the IGBT in the LV-side (Infineon FF600R12ME4C_B11). Obviously, the efficiency between HV-side and LV-side of the DAB using the method described above will be improved compared to the conventional method in which IGBTs are all locked. The experimental DAB resonance waveforms in different flow directions are shown in figure 7(a-b):

![Figure 7](image)

**Figure 7.** (a) Voltage and high-frequency current in the LV-side and HV-side ($u_{HV}$, $u_{LV}$, $i_{r}$) in rectifying mode. (b) Voltage and high-frequency current in the LV-side and HV-side ($u_{HV}$, $u_{LV}$, $i_{r}$) in inverting mode. (c) Voltage and high-frequency current in the LV-side and HV-side ($u_{HV}$, $u_{LV}$, $i_{r}$) during switching instant in rectifying mode. (d) Voltage and high-frequency current in the LV-side and HV-side ($u_{HV}$, $u_{LV}$, $i_{r}$) during switching instant in inverting mode.

The reason for the efficiency difference in the two modes is that, in the DAB parts, the concentration of carrier in the N- area of the HV-side IGBT is much higher than that of the LV-side IGBT, thus, more time is necessary for the recombination of its carriers. Figure 7(c-d) points out that magnetizing current for transformer accelerates the LV-side IGBT carrier recombination speed during dead time $T_{dead}$ in order for the voltage of the device becomes zero, however, it is not sufficient for carrier recombination of the HV-side IGBT, thus the voltage of it keeps nearly constant. As a result, the loss for inverting mode of PET is much lower than rectifying mode as shown in experiment results. It is also revealed the correctness of the efficiency test method.

### 5. Conclusions and Future Work

One challenge of multiport PET is the efficiency test. In this paper, the efficiency definition of the multiport PET is given and a fitting method for calculating efficiency is proposed. In this proposed method, the efficiency for any running state of the multiport PET can be calculated without a complicated experiment test again when the efficiency of each transfer power unit is tested.
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References
[1] McMurray W 1998 The thyristor electronic transformer: A power converter using a high-frequency link IEEE Trans. Ind. Gen. A. IGA-7(4): 451–457.
[2] Steiner M and Reinold H 1998 Antriebsschaltung Fur Ein Schienenfahrzeug German Patent DE 198 27 872 A 1. (in German)
[3] Zhao C, Dujic D, Mester A, Steinke J K, Weiss M, Lewdeni-Schmid S, Chaudhuri T and Stefanutti P 2014 Power electronic traction transformer—medium voltage prototype IEEE Trans. Ind. Electron. 61(7): 3257–3268.
[4] Kieferndorf F, Drofenik U, Agostini F and Canales F 2016 Modular PET,two-phase air-cooled converter cell design and performance evaluation with 1.7kV IGBTs for MV applications Proc. IEEE Applied Power Electron. Conf. and Expo. (APEC), Long Beach, CA, USA.
[5] Choi J W and Sul S K 1998 Fast current controller in three-phase AC/DC boost converter using D-Q axis cross coupling IEEE Trans. Power Electron. 13(1): 179–185.