Hybrid Power Electronic Transformer Model for System-Level Benefits Quantification in Energy Distribution Systems

Federico Prystupczuk 1,*, Valentín Rigoni 1, Alireza Nouri 1, Ramy Ali 1, Andrew Keane 1 and Terence O'Donnell 1

1 UCD Energy Institute, School of Electrical & Electronic Engineering, University College Dublin, Dublin, Ireland

Correspondence*: Federico Prystupczuk federico.prystupczuk@ucd.ie

ABSTRACT

The Hybrid Power Electronic Transformer (HPET) has been proposed as an efficient and economical solution to some of the problems caused by Distributed Energy Resources and new types of loads in existing AC distribution systems. Despite this, the HPET has some limitations on the control it can exert due to its fractionally-rated Power Electronic Converter. Since various HPET topologies with different capabilities have been proposed, it is necessary to investigate the system benefits that they might provide in possible future scenarios. In order to conduct such system-level studies, adequate HPET models are needed, which are still not covered in the current literature. Consequently, this article presents a methodology to develop power flow models of the HPET that facilitate the quantification of controllability requirements for voltage, active power and reactive power. A particular HPET topology composed of a three-phase three-winding Low-Frequency Transformer coupled with a Back-to-Back converter is modeled as an example. The losses in the Back-to-Back converter are represented through efficiency curves that are assigned individually to the two modules. The model performance is illustrated through various power flow simulations that independently quantify voltage regulation and reactive power compensation capabilities for different power ratings of the Power Electronic Converter. In addition, a set of daily simulations were run with the HPET supplying a real distribution network modeled in OpenDSS. The results show HPET losses which are around 1.3 times higher than the conventional transformer losses over the course of the day. The proposed methodology offers enough flexibility to investigate different HPET features, such as power rating of the Power Electronic Converter, losses, and various strategies for the controlled variables. The contribution of this work is to provide a useful tool that can not only assess and quantify some of the system-level benefits that the HPET can provide, but also allow a network-tailored design of HPETs. The presented model along with the simulation platform are publicly available.

Keywords: Power Electronic Transformer, Hybrid Transformer, power flow simulation, energy distribution systems, transformer losses, inverter losses, power factor
1 INTRODUCTION

The growing presence of distributed generation such as small-scale PV systems and new types of controllable loads such as electric vehicles (EVs) or electric heat pumps is increasing the stress on existing distribution systems, creating problems such as voltage rise, thermal overload, higher presence of harmonics and higher system losses (Walling et al., 2008; Procopiou and Ochoa, 2017). Distribution networks have been traditionally designed under the assumption that the only source of power in the grid is the primary substation, and so, the presence of highly variable Distributed Energy Resources (DER) leads to operating situations that were not foreseen in conventional systems (Walling et al., 2008). In this respect, the distribution transformer, one of the most important and robust components operating at the interface between transmission and distribution systems, has limited capabilities to cope with the impact of these new technologies in the electric grid, resulting in potentially increased operational costs and losses (Aeloiza et al., 2003). Augmenting the network with smart and active control appears as a good option to deal with some of the envisaged issues and to potentially mitigate the need for network reinforcement (Bala et al., 2012; Navarro-Espinosa and Ochoa, 2015b). Nowadays, many of the solutions proposed for achieving a more flexible, controllable and stable grid rely on power electronic devices for their implementation, such as active filters, HVDC, FACTS-devices, electronic breakers, and particularly Power Electronic Transformers (PETs) (Liserre et al., 2016).

The PET is a relatively new device that utilizes power electronic converters to transform electrical power between not only different AC voltage levels but also different frequencies and forms (e.g. AC-DC and DC-AC conversion). Among the several different proposed topologies and implementations of Power Electronic Transformers, possibly the most researched approach is the three-stage PET due to its high level of controllability and flexibility (Wang et al., 2012; Yang et al., 2016; Ferreira Costa et al., 2017). The PET facilitates new active control functionalities for AC distribution networks in terms of, for example, power flow control, voltage regulation, and limitation of neutral and fault currents, which cannot be implemented by traditional iron-copper Low-Frequency Transformers (LFT) (She et al., 2013; Chen et al., 2019). Also, a more convenient integration of DC distributed generation, battery storage and DC loads becomes possible with the three-stage PET since those devices could be directly connected to the DC ports of the transformer, improving efficiency and reducing costs by eliminating conversion stages (Hunziker and Schulz, 2017). In a broader perspective, the PET offers opportunities for online automated control and decentralized operation in Smart Grids, reducing operational costs and improving the reliability of power systems under highly disruptive complex phenomena such as cascading failures (Pournaras and Espejo-Uribe, 2017).

Besides this, there are important aspects that should be considered when the full PET is compared with the conventional LFT. Although the topologies, control techniques, and technologies applied to the PET design are being continuously improved, its high cost and relatively low efficiency are still some of the problems that this device is facing to be extensively used in the current electric system (Huber and Kolar, 2014). The target maximum efficiency for state-of-the-art PET designs is between 95% and 98%, while for oil-immersed LFTs over 500 kVA it is normally above a 99% (She et al., 2013). As a consequence, the Total Cost of Ownership (TCO) of a PET is currently highly unfavourable compared to the LFT; the PET capital cost is estimated to be at least five times higher (Huber and Kolar, 2014), and the operation cost is expected to be also increased due to higher maintenance during the PET lifetime.

The hybrid version of the Power Electronic Transformer arises as a possible solution to some of the main limitations that the full PET has in AC grid applications. The Hybrid PET (HPET) is a special type of transformer resulting from the combination of a conventional Low-Frequency Transformer (LFT) with one or more electronic converters. In order to keep the efficiency as high as possible, the electronic converter
is designed to process only a fraction of the LFT rated power, providing some level of controllability while the overall efficiency is not considerably affected (Huber and Kolar [2019]; Burkard and Biela [2015]). The capital cost of the HPET is expected to be considerably lower than the PET capital cost and the improved efficiency causes an important decrease in the total losses over the HPET lifetime, resulting in a much more favourable Total Cost of Ownership. In addition, in case of a failure in the electronic converter, the HPET has the possibility of bypassing the electronic converter and remaining operational as a conventional transformer, providing higher reliability. The previously mentioned advantages make the HPET a viable alternative to the full PET in AC networks. However, clearly because of the reduced rating of the controllable power electronic part, the HPET will have more restrictive limitations on the control it can exert compared to the full PET.

Previous works have studied the impact of the PET in LV and MV networks using simplified models in power flow simulations (Guerra and Martinez-Velasco [2017]; Hunziker and Schulz [2017]; Huber and Kolar [2019]). These studies concluded that while the PET is the most convenient option for DC and hybrid grids, it is necessary to further improve the efficiency and reliability for the PET to be a cost-effective alternative in AC systems. In this regard, similar studies could be carried out to investigate the system benefits that different HPET topologies may have in possible future scenarios. However, the development of the models that are necessary for that kind of analysis has not been covered yet in the current HPET literature. To address this gap, this work presents a methodology to develop simplified average power flow models of HPETs, and demonstrates the integration of those models into power flow simulations. These models facilitate the quantification of controllability requirements for voltage, active power and reactive power, becoming a new tool towards the identification of the most beneficial HPET features and topologies.

The proposed methodology has the flexibility to represent important characteristics of the electronic converter which impact at the system level, such as the different power ratings and losses for each of the converters and the various strategies for the controlled variables. By making small changes to the presented model, different circuit configurations and topologies of HPET can be represented, and afterwards tested in power flow simulations of distribution networks models. In this way, the proposed methodology for modeling of HPETs becomes a useful tool not only to assess and quantify some of the system-level benefits that can be obtained with these devices, but also to develop HPET network-tailored designs. The HPET model, along with the simulation platform created to obtain the results presented in this work, remain an open-source development in Python and are freely available for the academic community and distribution utilities (Prystupczuk et al. [2021]).

2 MATHEMATICAL MODELS AND SIMULATION TOOLS

In this section, the HPET concept is explained in detail and the mathematical description of a shunt-series combined topology is presented in the form of a sinusoidal steady-state representation. For the sake of clarity, lossless behaviour is assumed in all the presented equations of this section, but a representation of the HPET losses will be covered later in the next section. A single-phase schematic diagram of a shunt-series combined HPET is presented in Figure 1. This shunt-series combined topology consists of a combination of two electronic modules in a Back-to-Back (BtB) configuration with a three-winding LFT: Module 1 is electromagnetically coupled to the LFT in a type of shunt connection through the tertiary winding, while Module 2 is connected in series with the secondary winding. The complete functionality of this shunt-series topology can be better understood by first describing the modeling of the separate shunt and series configurations.
2.1 Shunt Connection with Direct Coupling

The connection of a DC-AC converter in parallel or shunt with the LV winding of the LFT (Figure 2), can provide reactive power to the LV grid for reactive power compensation or voltage support through reactive power injection, similarly to a D-STATCOM (Burkard and Biela, 2018; Hunziker and Schulz, 2017; Liu et al., 2009). The output voltage of the electronic converter is actually imposed by the transformer, so the converter can only act as a current source. Ignoring the small active power $P_C$ that flows to compensate for power losses in the converter, the electronic module supplies a controlled reactive power flow $Q_C$ from the capacitor.

Considering the space phasor $\vec{v}_{LV}$ of LV side voltage of the transformer as the reference voltage (1), the current $\vec{i}_{LV}$ in the LV side can be expressed by in-phase and in-quadrature components in the rotating dq-frame, as it is described in (2). In steady-state and assuming the $d$ axis is aligned with $\vec{v}_{LV}$ as it is stated in (1), the $q$ component of $\vec{i}_{LV}$ will be non-zero if the load in the LV side demands reactive power. This reactive power $Q_{LV}$ will be supplied from the primary side of the LFT unless the electronic converter compensates it by providing enough reactive current $i_{Cq}$. Therefore, the power rating of the converter defines the HPET reactive power compensation capability in the primary side.

\[ \vec{v}_{LVdq}(t) = v_{LVd}(t) + jv_{LVq}(t) = \vec{v}_{LV}(t)e^{-j\rho(t)} \]  
\[ \vec{i}_{LVdq}(t) = i_{LVd}(t) + ji_{LVq}(t) = \vec{i}_{LV}(t)e^{-j\rho(t)} \]  

where:
In this topology, the primary side reactive current $i_{MVq}$ will be compensated depending on the relationships presented in (5) and (6). The power factor in the primary side will remain equal to one while the reactive current demanded in the LV side $i_{LVq}$ is lower than the electronic converter current rating $i_{Cmax}$, i.e. $|Q_{LV}|/v_{LVd} \leq i_{Cmax}$. Although a full compensation is described in (6), the electronic converter could also inject a controlled amount of $Q_{MV}$ for voltage support in the primary side. In equations (3) - (6), the relationship between the reactive current in the LV and MV side is expressed as a function of the current supplied by the electronic converter, which is rated at a fraction $\alpha$ of the LFT power rating $S_{Tmax}$ (3). Also, an ideal transformer and a dq-frame controller working in steady-state condition are assumed:

$$S_{Cmax} = \alpha \cdot S_{Tmax} \Rightarrow i_{Cmax} = \alpha \cdot i_{Tmax}$$  \hspace{1cm} (3)$$

$$i_{LVq} = |Q_{LV}|/v_{LVd}$$  \hspace{1cm} (4)$$

$$i_{MVq} = \frac{n_2}{n_1} i_{Tq} = \frac{n_2}{n_1} (i_{LVq} - i_{Cq})$$  \hspace{1cm} (5)$$

$$i_{MVq} = \begin{cases} 0 & \text{if } i_{LVq} \leq i_{Cmax} \\ \frac{n_2}{n_1} (i_{LVq} - i_{Cmax}) & \text{if } i_{LVq} > i_{Cmax} \end{cases}$$  \hspace{1cm} (6)$$

where:

$S_{Cmax}$ electronic converter maximum apparent power
$S_{Tmax}$ LFT maximum apparent power
$i_{Cmax}$ electronic converter maximum current
$n_1, n_2, n_3$ Number of turns on each winding of the LFT

2.2 Shunt Connection with Magnetic Coupling

The magnetic-coupled shunt connection depicted in Figure 3 is an alternative that employs an LFT with an auxiliary winding, allowing different voltage-rated electronic converters to be connected and providing galvanic isolation. In Figure 3, the turns ratio $n_2/n_1$ is defined by the winding nominal voltages, as it is shown in (8), while $n_3/n_2$ can be adjusted for the electronic converter design to meet certain trade-offs between voltage and current. The current $i_{MV}$ in the primary side results from the sum of the currents in the secondary and auxiliary windings reflected to the primary winding, as it is described in (9) and (10).
Figure 3. Shunt-connected DC-AC converter with magnetic coupling.

\[ \alpha = \frac{S_{C_{\text{max}}}}{S_{LV_{\text{max}}}} \]  

\[ \frac{n_2}{n_1} = \frac{V_{LV_{\text{nom}}}}{V_{MV_{\text{nom}}}} \]  

\[ \tilde{i}_{MVdq} = \frac{n_2}{n_1} i_{LV} + \frac{n_3}{n_1} i_C \]  

\[ i_{MVd} + j i_{MVq} = \frac{n_2}{n_1} (i_{LVd} + j i_{LVq}) + \frac{n_3}{n_1} (i_{Cd} + j i_{Cq}) \]  

where:

- \( S_{LV_{\text{max}}} \): Nominal apparent power of the LFT secondary winding
- \( V_{MV_{\text{nom}}} \): Nominal voltage of the LFT primary winding
- \( V_{LV_{\text{nom}}} \): Nominal voltage of the LFT secondary winding
- \( \tilde{i}_{MVdq} \): Dq-frame vector of the primary side current

Neglecting the small active power flow \( P_C \) originating from losses in the electronic converter, the AC-DC converter will only inject reactive power, meaning that \( i_C \approx i_{Cq} \). Therefore, the dq-frame equation (10) can be rewritten as follows:

\[ i_{MVd} = \frac{n_2}{n_1} i_{LVd} \]  

\[ i_{MVq} = \frac{n_2}{n_1} i_{LVq} + \frac{n_3}{n_1} i_C \]  

\[ i_{MVq} = \begin{cases} 0 & \text{if } Q_{LV} \leq S_{C_{\text{max}}} \\ \frac{n_2}{n_1} \left( \frac{Q_{LV} - \alpha S_{LV_{\text{max}}}}{v_{LVd}} \right) & \text{if } Q_{LV} > S_{C_{\text{max}}} \end{cases} \]  

From (12), the reactive current \( i_{MVq} \) in the primary side can be controlled by adjusting \( i_{Cq} \), so \( i_{MVq} \) can either be compensated to obtain unity power factor or controlled for voltage support in the MV side. If the
goal is to obtain a unity power factor, the controller has to keep $i_{MVq}$ equal to zero, as it is expressed in (13).

The features of this connection are rather similar to the direct-coupled shunt connection previously analysed in Figure 2, in the sense that it can control the reactive power flow and cannot impose the voltage at the LV side. However, modeling the magnetic-coupled shunt topology provides a useful tool for analysing different trade-offs such as the electronic converter voltage rating, the compensation capabilities and costs.

### 2.3 Shunt-Series Combined Topology

In addition to the shunt connection, the combined shunt-series connection of the HPET provides a series path for the active power to flow through the electronic converter, allowing the HPET to simultaneously compensate reactive power in the primary side and regulate the voltage at the secondary side. Consequently, the addition of the series-connected DC-AC converter allows this HPET topology to independently impose and control both active and reactive power flows, unlike the shunt connections previously presented which can only provide reactive power. During normal or forward power flow operation, the shunt-connected Module 1 (Figure 1) operates as a DC-voltage power port that regulates the DC capacitor voltage by controlling the active power flow $P_{C1}$. That active power compensates for any decrease in the voltage of the DC capacitor caused by the active power $P_{C2}$ drawn by Module 2 as well as to compensate for losses in the whole electronic converter. At the same time, Module 1 can control the reactive power flow in the primary side of the HPET by independently adjusting $Q_{C1}$ in a similar manner as it was previously described in Subsection 2.2, the reactive power flows in Module 1 and Module 2 are decoupled thanks to the DC capacitor (Yazdani and Iravani [2010]). The series-connected Module 2 is a Voltage-Sourced Converter (VSC) in charge of regulating the voltage $\vec{v}_{LV}$ in the secondary side, since in this configuration both active and reactive power can be delivered from the DC link. In the combined topology, the current in the secondary winding and the current in Module 2 are the same due to the series connection. Hence, the fraction $\alpha$ can be expressed as per (14).

$$\alpha = \frac{S_{C2max}}{S_{Tmax}} = \frac{n_3}{n_2} \quad (14)$$

Since the combined topology can simultaneously regulate the secondary-side voltage and the primary-side reactive power flow, the ability for reactive power compensation will depend on the actual active power that the electronic converter is instantaneously delivering. This way, the equations for total reactive power compensation are the following:

$$Q_{C1avail} = \sqrt{(\alpha \cdot S_{Tmax})^2 - P_{C1}^2} \quad (15)$$

$$Q_T = Q_{LV} - Q_{C2} \quad (16)$$

$$i_{MVq} = \begin{cases} 
0 & \text{if } (Q_T \leq Q_{C1avail}) \\
\frac{n_2}{n_1} \left( \frac{Q_T - Q_{C1avail}}{v_{LVd}} \right) & \text{if } (Q_T > Q_{C1avail})
\end{cases} \quad (17)$$

Another shunt-series combined configuration, similar to the one of Figure 1, can be achieved using a two-winding LFT with a direct connection of the electronic converter. However, it is necessary to include an injection transformer to adapt the nominal voltage of the electronic converter to the desired series voltage...
in the LV terminal, as it is depicted in Figure 4. The injection transformer may also be connected between the secondary winding and Module 2, therefore Module 1 will be directly connected to the LFT. This variation will result in lower current and higher voltage ratings for the electronic converter. The advantage of this topology is that it can be implemented using a regular two-winding distribution transformer, allowing a practical enhancement of the devices with the connection of the BtB electronic converter.

![Figure 4. Single-phase diagram of the shunt-series combined HPET topology with direct coupling.](image)

### 2.4 Power Flow Simulations

Power flow simulations incorporating the HPET models are performed using the Open Distribution System Simulator OpenDSS which is an open-source simulation tool for power distribution systems. This tool can perform almost all the sinusoidal steady-state analyses that are commonly used in distribution systems studies, such as unbalanced multi-phase power flow, quasi-static time-series, fault analysis, harmonic analysis, flicker analysis, etc. A Component Object Model (COM) interface is also provided to facilitate new types of studies and custom solution modes and features from external software. For example, OpenDSS can be entirely driven from external programs written in Python or Matlab, allowing advantage to be taken of all OpenDSS features inside the external software (Dugan and Montenegro, 2020). For these reasons, OpenDSS was chosen as the tool in which to develop the different PET models that are intended to be studied, with the possibility of applying the various OpenDSS analyses in order to quantify of the system-level benefits of PETs in the distribution system.

Different types of transformer models are also provided in the OpenDSS platform. While the software offers dedicated definitions for conventional multi-phase multi-winding transformers, different variations can be made by connecting several of these transformers to form a single transformer. For instance, a three-phase transformer can be modeled by using its dedicated definition or also with three single-phase transformers, connecting each winding properly. This approach is useful to perform the unconventional series connection of the secondary winding of the HPET in Figures 4 and 1. OpenDSS also provides representation of core and winding losses in the transformer through the parameters \(\%Noloadloss\) and \(\%Loadloss\), respectively. The parameter \(\%Noloadloss\) represents the percent losses at nominal voltage with no load, and causes a resistive parallel branch to be added in the transformer model. The parameter \(\%Loadloss\) represents the percent losses at rated load, and adds a percent resistance for each winding on the rated kVA base. The percent magnetising current can be also modeled by using the parameter \(\%imag\), which includes an inductance in parallel with the resistive branch that represents core losses. All these parameters are finally embedded within the transformer model as the primitive Y matrix (a nodal admittance formulation of the transformer model), is being computed (Dugan and Montenegro, 2020).
3 METHODS. HPET MODEL FOR POWER FLOW CALCULATIONS

In this section, the complete development of an average model of the three-phase HPET is presented. The objective of the model is to serve as a tool in power flow studies of distribution systems aimed to assess the capabilities of the HPET from a system-level perspective. This new model has been developed in OpenDSS by implementing the series-shunt combined topology of Figure 1 and builds on the work presented by Guerra and Martinez-Velasco (2017). The schematic diagram of the model is shown in Figure 5 in a three-phase representation. The Back-to-Back converter has been modeled by a combination of a three-phase controlled load and a three-phase controlled voltage source. As it can be seen in Figure 5, the three-phase Load element sets the active and reactive power flows $P_{C1}, Q_{C1}$ in the auxiliary winding, while the $V_{source}$ element establishes the magnitude and phase of the voltage $\vec{v}_{C2}$, and delivers $P_{C2}, Q_{C2}$. Both Load and $V_{source}$ elements are linked by the active power flow, as it is described in (18) and (19). This way, the Load and $V_{source}$ elements emulate the behaviour of Module 1 and Module 2 respectively, in the BtB converter of Figure 1. On the other hand, $\vec{v}_{C2}$ and $Q_{C1}$ are control variables that are decided according to the adopted control strategy.

Figure 5. Complete three-phase model of the magnetically coupled series-shunt combined HPET.

The three-phase three-winding iron-copper transformer included in the HPET of Figure 5 has been modeled using three single-phase three-winding transformer models in OpenDSS. Those models include a representation of winding and core losses by means of the parameters %LoadLoss and %NoLoadLoss respectively, as well as the transformer percent reactances through the parameters $X_{12}, X_{23}$ and $X_{13}$ (Dugan and Montenegro 2020). In the case of real iron-copper transformers, all those parameters can be normally found in manufacturer specification sheets or catalogs (Siemens AG, 2017).

In addition, a representation of the electronic converter losses is included in the model by assigning an efficiency curve to each of the two electronic Modules of Figure 1. This is one of the most important aspects of the proposed model for studying the extra losses incurred by the HPET, and a proper loss model is the only way to quantify this effect. The efficiency curve may be a function of different factors, such as load level, temperature, switching frequency, DC link voltage, etc., depending on the depth needed in the modeling. The load level is the parameter that has the strongest influence on the electronic converter efficiency, and is the one which is considered in the power flow model.

The model can deal with bidirectional power flow, where for reverse power, the Load element of Figure 5 becomes negative, injecting active power into the transformer (Guerra and Martinez-Velasco 2017). In
(18) and (19), the active power in the electronic converter is expressed for forward and reverse power flow operation. The reactive power flows $Q_{C1}$ and $Q_{C2}$ are decoupled and can be independently controlled by each module of the electronic converter.

Forward power flow: $P_{C1} = P_{C2} + P_{\text{loss}}$ \hspace{1cm} (18)

Reverse power flow: $P_{C1} = P_{C2} - P_{\text{loss}}$ \hspace{1cm} (19)

Once the HPET model is integrated into a distribution network model in OpenDSS, a series of calculations must be solved in a sequential way to obtain the solution for each time step, as it is described in the flow diagram of Figure 6. Initially, the $V_{\text{source}}$ and $\text{Load}$ elements are initialised, meaning that $\vec{v}_{C2} = 0$, $P_{C1} = 0$ and $Q_{C1} = 0$. Hence, in the first time step only the primary and secondary windings of the LFT transfer power. For any new time step, all the values obtained in the previous solution will be already set in OpenDSS (step 1), and so the demand corresponding to the current time step has to be updated (step 2). The solution in step 3 will provide the new demand and the resulting voltages at each transformer winding. In step 4, the secondary voltage is regulated by modifying the voltage of the $V_{\text{source}}$ element of Figure 5 according to the adopted voltage regulation strategy. The calculation of the required voltage is implemented as an algorithm in the external software (see Subsection 3.1) and the obtained values are uploaded to the $V_{\text{source}}$ element configuration in OpenDSS. Then, a new power flow analysis (step 5) is needed to find the new resulting demand and voltages in the circuit. At this point, the $P_{C1}, Q_{C1}$ values for the $\text{Load}$ element of Figure 5 are calculated by an algorithm in the external software according to the adopted reactive power compensation strategy (see Subsection 3.2). The calculated $P_{C1}, Q_{C1}$ values also account for losses in the electronic converter, obtained through the efficiency model described in Subsection 3.3. A new solution is run in step 7 using the new set points in OpenDSS. Steps 4 to 7 are repeated until the voltage and reactive power relative incremental errors, $\epsilon_V$ and $\epsilon_Q$ respectively, are below a certain limit (0.01 in this case).
3.1 Voltage Regulation at the Secondary Terminal

In this subsection, the algorithm for regulating the voltage phasor at the secondary terminal of the HPET is described. The calculations are independently executed on each phase, therefore all the voltages expressed in this subsection are per-phase quantities. The voltage phasor $\bar{V}_{C2}$ can be controlled using the $V_{source}$ element (Figure 5) to bring the secondary voltage $\bar{V}_{LV}$ to a defined target value. In Figure 7, $\bar{V}_T(t-1)$ and $\bar{V}_{C2}(t-1)$ represent the voltage phasors inherited from the previous time step. During step 3 of the simulation workflow (Figure 6), a new power flow solution resulting from the current time step demand provides a new value for the secondary voltage that has to be regulated, indicated as $\bar{V}_{LV}(\text{step 3})$ in Figure 7. On step 4, the new phasor $\bar{V}_{C2}(t)$ is calculated as it is shown in (20) and (21) to bring $\bar{V}_{LV}$ to its target value.
\[ \bar{V}_T(t) = \bar{V}_{LV}(\text{step 3}) - \bar{V}_{C2}(t - 1) \]  
\[ \bar{V}_{C2}(t) = \bar{V}_{LV\text{target}} - \bar{V}_T(t) \]  

where:

- \( \bar{V}_T(t) \) Resulting voltage phasor at the secondary winding for the current time step
- \( \bar{V}_{C2}(t) \) Resulting voltage phasor at the Vsource element for the current time step
- \( \bar{V}_{C2}(t - 1) \) Voltage phasor at the Vsource element calculated in the previous time step
- \( \bar{V}_{LV}(\text{step 3}) \) Voltage phasor at the HPET secondary terminal calculated at the intermediate step 3
- \( \bar{V}_{LV\text{target}} \) Desired voltage phasor at the HPET secondary terminal

\[ \bar{V}_{LV}(\text{step 3}) = \bar{V}_{C2}(t - 1) - \bar{V}_T(t) \]

\[ \bar{V}_{C2}(t) = \bar{V}_{LV\text{target}} - \bar{V}_T(t) \]

\[ \bar{V}_T(t - 1) \]

\[ \bar{V}_{C2}(t - 1) \]

\[ \bar{V}_{LV}(t) = \bar{V}_{LV\text{target}} \]

**Figure 7.** Per-phase phasor representation of the output voltage regulation algorithm.

### 3.2 Reactive Power Compensation

In this subsection, the primary-side reactive power compensation algorithm is described. This algorithm corresponds to the calculations that are performed in step 4 of the flow chart described in Figure 3. The reactive power regulation strategy is aimed to provide compensation in order to maintain unity power factor at the primary side whenever it is possible. As it is explained in Section 2.3, the shunt-connected Module 1 (Figure 1) can control \( Q_{C1} \) independently from \( Q_{C2} \) due to the decoupling provided by the DC-link capacitor. The reactive power available for compensation depends on the power rating \( S_{C1\text{max}} \) of Module 1 and the actual active power \( P_{C1} \) delivered to the DC link, as it is described in (22). In the circuits of Figure 1 and Figure 3, the reactive power injected by the electronic converter should be the negative of the reactive power delivered by the secondary winding to compensate reactive power in the primary side, as it is described in (24).

\[ Q_{C1\text{avail}} = \sqrt{S_{C1\text{max}}^2 - P_{C1}^2} \]  
\[ Q_T = Q_{LV} - Q_{C2} \]  
\[ Q_{C1} = \begin{cases} 
-Q_T & \text{if } (|Q_T| \leq Q_{C1\text{avail}}) \\
\frac{|Q_T|}{Q_T}Q_{C1\text{avail}} & \text{if } (|Q_T| > Q_{C1\text{avail}})
\end{cases} \]
3.3 Loss Modeling in the Electronic Converter

In most of the corresponding literature, the loss representation is obtained by multiplying the active power by the converter efficiency at the operating point, with the efficiency being a function of the load level and the power factor (Guerra and Martinez-Velasco, 2017; Rocha et al., 2019; Longo et al., 2020; Qin and Kimball, 2010). While this approach can provide accurate results in simulations with high values of power factor, it can lead to unrealistically low losses in situations of low power factor, since it only considers the active power flow as a source of losses inside the converter. In the case of the presented HPET model, the Load element of Figure 5 will be operating at a very low power factor most of the time when it is compensating reactive power. Consequently, a different loss modeling approach is needed in this case.

In order to develop a more accurate loss representation, accounting for the loss dependence on reactive power flow, a three-leg inverter model composed by six VMO1200-01F IXYS power MOSFETs was developed in Matlab/Simulink including the semiconductor losses and thermal model presented by Giroux et al. (2021). A series of simulations were conducted for different load levels varying the power factor at constant apparent power. The obtained results can be observed in Figure 8, where the apparent power $S_{out}$ delivered by the inverter and the inverter losses $P_{loss}$ are measured at the different load levels. Since it can be observed in the resulting curves that the variations for different power factors are negligible, and since at unity power factor the quantity $S_{out} / (S_{out} + P_{loss})$ is equal to the inverter efficiency, then a single efficiency curve can be used to calculate the input power plus losses, even when the inverter is delivering mostly reactive power. This leads to the loss modeling approach described by equations (25) - (30) and Figure 9 for the case of forward power flow operation.

![Figure 8](image)

**Figure 8.** $S_{out} / (S_{out} + P_{loss})$ curves obtained for different power factors at constant apparent power.
\[ \eta_1 = f(P_{dc}, Q_{C1}) \]  
\[ \eta_2 = f(S_{C2}) \]  
\[ P_{loss2} = S_{C2} \left( \frac{1}{\eta_2} - 1 \right) \]  
\[ P_{dc} = P_{C2} + P_{loss2} \]  
\[ P_{loss1} = \sqrt{P_{dc}^2 + Q_{C1}^2} \left( \frac{1}{\eta_1} - 1 \right) \]  
\[ P_{C1} = P_{dc} + P_{loss1} \]  

4 RESULTS

In order to characterize the range of voltage regulation and reactive power compensation capabilities as a function of the PET module rating, two test cases have been carried out, and the corresponding results are shown in this section. In both simulations, an 800 kVA, 10 kV - 400 V Hybrid PET is used. In Subsection 4.1, the voltage regulation and reactive power compensation capabilities of the developed HPET model are characterized using the simple setup of Figure 10 in OpenDSS. The simulations consist of independently sweeping \( \vec{v}_{MV} \) and \( Q_{LV} \) over ranges that are considerably wider than the normal operation in a real distribution network, and these sweeps are repeated for different power ratings \( \alpha \) of the BtB converter (see Figure 1). The behaviour of the HPET when both the voltage regulation and the reactive power compensation capabilities are exceeded is shown in Figure 11.

In Subsection 4.2, a time series power flow simulation is performed using one of the distribution network models developed by the University of Manchester for the project LVNS, obtained from GIS data of real distribution grids in England (Navarro-Espinosa and Ochoa, 2015a). This second simulation has been used to compare the performance of the developed HPET model of Figure 5 with an existing model of PET (Guerra and Martinez-Velasco, 2017) and a conventional LFT model provided in OpenDSS, in terms of voltage regulation and power factor correction, and losses. The results of a power flow simulation with a daily load profile are shown in Figure 13 regarding voltage regulation, power factor correction and losses in the transformers.

The models, scripts and all data mentioned in this section used to obtain the presented results are publicly available in the HPET_POWERFLOW_MODEL GitHub repository (Prystupczuk et al., 2021).
4.1 Test Case 1. Standalone Voltage Regulation and Reactive Power Compensation

Using the setup of Figure 10 the voltage regulation algorithm presented in Subsection 3.1 is tested by linearly sweeping the amplitude of $\vec{v}_{MV}$ between 1.0 pu and 0.6 pu while the reactive power injected by the electronic converter into the LFT auxiliary winding is kept to zero. The three-phase load connected to the secondary terminal is kept constant so that it demands the HPET nominal power. In Figure 11A, the obtained results are presented in terms of the LV voltage amplitude (which ideally is to be regulated to 1 pu) for different power rating ratios $\alpha$ of the electronic converter. The curves show how the HPET regulates $\vec{v}_{LV}$ when $\vec{v}_{MV}$ starts to decrease: the secondary voltage is successfully regulated as long as the maximum power and voltage capabilities of the electronic converter are not exceeded. In this case where the demand is set to be constant, when the electronic converter reaches its maximum voltage, the HPET cannot regulate the voltage and $\vec{v}_{LV}$ results in a value lower than the nominal. The plotted values correspond to measurements taken using OpenDSS monitor elements connected directly to the HPET terminals.

The reactive power compensation algorithm presented in (24) has been similarly tested by linearly sweeping the reactive power $Q_{LV}$ demanded at the secondary terminal from 0.0 pu to 0.6 pu. In this simulation, the input voltage at the primary side $\vec{v}_{MV}$ is kept to 1 pu, meaning that the secondary voltage does not need to be compensated. Consequently, no active power is drawn by Module 2 and the ability of the electronic converter for reactive power compensation is maximum, as it is indicated in (22). In Figure 11B, the relationship between the reactive power at primary and secondary sides for different power ratings $\alpha$ of the electronic converter is plotted. The curves show how the HPET compensates $Q_{MV}$ when $Q_{LV}$ starts to increase from zero: the primary side reactive power is successfully compensated as long as the maximum power capability of the electronic converter is not exceeded, i.e. $Q_{LV} \leq S_{C1}_{max}$. It is worth recalling at this point that the fraction $\alpha$ is defined as the ratio between the power rating of the LFT secondary winding $S_T$ and the electronic converter power rating $S_{C2}$, as it is stated in equation (14).

Since in Figure 11 the basis for the per-unit notation used is the total HPET power rating (i.e. the sum of the LFT and electronic converter power ratings), it can be seen that a 30% rated electronic converter will provide less than 0.3 pu of reactive power compensation. This is also the reason for the non-uniform spacing between the traces of Figure 11B, while the difference between the electronic converter power ratings is uniform.

In Figure 11C, the primary and secondary power factors that result from the sweep simulation are presented, where the measured values (solid lines) are compared with theoretically calculated values (dashed lines) from equation (13). In the case of the primary side power factor, $P_{F_{MV}}$, a difference is observed as a consequence of the losses that are present in the LFT, which cause the power factor in the MV side to be higher due to the higher active power flow. The results obtained in this test case demonstrate
that the developed model can effectively and accurately represent the behaviour of a Hybrid PET under a wide range of operating points. They also show in a quantitative way the limitations imposed by the factional power rating of the electronic converter.

Figure 11. Output voltage regulation results in terms of $|\vec{v}_{LV}|$ vs. $|\vec{v}_{MV}|$ while $Q_{C1} = 0$ (A). Primary-side reactive power compensation while $V_{MV} = 1$ pu (B). Primary side power factor vs. secondary side power factor while $V_{MV} = 1$ pu (C). The dashed lines show the theoretical values obtained with (13).

4.2 Test Case 2. Power Flow Simulation on a Distribution Network Model

In order to illustrate how the HPET model can be included in a power flow simulation of a distribution network, the network model No 12 developed by the University of Manchester for the project LVNS (Navarro-Espinosa and Ochoa, 2015a) has been employed. The utilised network model and other 24 network models are publicly available at Electricity North West (2014). This test case is aimed at demonstrating the performance of the developed HPET model, and comparing the capability and performance of the HPET for voltage regulation and reactive power control to those of a full PET model presented by Guerra and Martinez-Velasco (2017). The results using a conventional LFT model (no voltage regulation or reactive power compensation) available in OpenDSS are also included for comparison. The technical features of the three used transformer models are shown in Table 1.

| Parameter                  | LFT        | PET        | HPET       |
|----------------------------|------------|------------|------------|
| Transformer power rating   | 800 kVA    | 800 kVA    | 800 kVA    |
| Converter power rating     | -          | 400 kVA    | 80 kVA     |
| Primary-side voltage       | 10 kV (∆)  | 10 kV      | 10 kV (∆)  |
| Secondary-side voltage     | 400 V (Y)  | 400 V      | 400 V      |
| Percent reactance X12      | 6.0        | -          | 3.5        |
| Percent reactance X23      | -          | -          | 5.0        |
| Percent reactance X13      | -          | -          | 1.3        |
| %LoadLoss                  | 0.875      | -          | 0.875      |
| %NoLoadLoss                | 0.08125    | -          | 0.08125    |
| Converter efficiency $\eta_{max}$ | - | 0.975 | 0.9837 |

Table 1. Parameters used in the different transformer models.

To model PET and HPET losses, the loss model presented in Subsection 3.3 has been used, but the simulated curve of Figure 8 has been replaced by the efficiency curve of a commercially available inverter (Figure 12) for more realistic results. In the case of the HPET, the same curve has been assigned to both
Module 1 and Module 2 of the BtB converter (Figure 1), so the resulting BtB efficiency is the product of the efficiency of each Module; e.g. since the curve peak efficiency for the inverter is equal to 0.9918, the peak efficiency of the whole BtB converter is 0.9837. For the full PET, just one curve is used to represent the whole PET efficiency, in accordance with the model presented by Guerra and Martinez-Velasco (2017). But since this is a three-stage device (AD-DC, DC-DC, and DC-AC), a lower efficiency level should be expected and so the curve of Figure 12 has been scaled to get a peak efficiency of 0.975 for the utilized PET model, which is in accordance with the experimental results obtained by Ferreira Costa et al. (2017).

It is important to mention that in the presented power flow simulation, the LFT and the HPET are rated at 800 kVA, while the PET is rated at 400 kVA. Conventional iron-copper transformers are normally rated based on the peak load method, which considers the highest demand during, for instance, the last year, resulting in oversized transformers that operate most of the time close to their maximum efficiency point (Luze, 2009). In the case of the full PET, adopting the same power rating would imply that the electronic converters will be most of the time operating in the lower part of the efficiency curve, resulting in increased losses in comparison with the LFT. Therefore, by sizing the PET at half the size of the LFT, the load level in this power flow simulation swings between a 15% and an 80% for the PET, and between a 10% and a 40% for the LFT and the HPET cases, approximately.

Figure 12. Efficiency curve of the 125 kVA KACO Blueplanet 125 TL3 inverter (KACO New Energy, 2021)

The LVNS distribution network No. 12, which has been employed to conduct the power flow simulation with the three different transformer models, consisted originally in a radial LV network with 330 residential customers and a single 800 kVA, 10 kV - 400 V transformer. In order to allow voltage variations in the primary side of the transformer, the original network has been augmented with a 10 km long MV line that connects the transformer to a substation, indicated in OpenDSS as the slack bus of the system. A set of load profiles consisting of ZIP coefficients with a 5-minutes resolution, obtained from Rigoni and Keane (2020), are used to model the demand at each time step from each of the 330 customers. The simulation platform used for this second test case has been developed using Python and OpenDSS, building on the Open-DSOPF model presented by Rigoni and Keane (2020). Open-DSOPF is an open-source Python-based model, integrated with OpenDSS, for the formulation of unbalance three-phase optimal power flow problems in distribution grids.
The obtained results can be observed in Figure 13. The voltage at the secondary side of the transformers is plotted for the three phases in Figure 13A. In this simulation, the adopted strategy for voltage regulation seeks to maintain the secondary voltage at 1 pu, although a different voltage target could be used depending on the needs of the study. As it can be seen, both the PET and HPET models provide perfect voltage regulation over the entire time.

In Figure 13B, the resulting reactive power flow in the MV side is shown. The adopted compensation strategy consists in keeping the primary power factor at unity. The green curve shows the total reactive power (i.e. the sum of the three phases) that flows through the MV line when the conventional LFT is used. The PET model provides total reactive power compensation during the whole simulation. On the other hand, the HPET model, provided with an electronic converter rated at $\alpha = 0.1$, is not able to compensate the whole reactive power flow at some points in the time series simulation, where the ability of the HPET to compensate reactive power is limited by the actual active power that is being processed by the electronic converter. The reason for this behaviour is explained in equation 22 and can be observed in Figure 13, where the uncompensated reactive power of Figure 13B appears at the moments of higher active power in Figure 13F.

Finally, the transformer losses and the resulting active power flow in the MV line are respectively presented in Figure 13C and 13D. Additionally, a computation of energy and losses at different points of the system is presented in Table 2. As expected, the case with the full PET results in the highest level of losses (around 7.9 times higher than the conventional LFT), and the case with the HPET gives losses slightly above the losses of the conventional LFT case (around 1.3 times higher), as can be seen from the results in Table 2. The total system losses, i.e. the losses in the distribution transformer plus line losses, are 3.1 times higher for the PET and 1.1 times higher for the HPET. In Figure 13D, the active power flow in the MV line is plotted for the three-phases, demonstrating the balancing effect of the reactive power compensation from the PET and HPET, and the higher power level that flows through the MV line to compensate for the higher losses of the PET.

In Figures 13E and 13F, the active and reactive power flows through the electronic converter of the HPET are displayed. As it can be seen, while Module 2 is all the time operating at a very low load level, Module 1 is delivering large amounts of reactive power to keep the primary side power factor at unity. It is evident from Figure 13E that a loss modeling approach that only considers the power factor and the active power flow would not provide an accurate representation of the losses caused by the large reactive currents that take place in Module 1. Hence the need for the proposed loss model presented in Subsection 3.3. It can also be observed in Figure 13E that, between the 10th and 12th hours and also between the 18th and 20th hours of the time series simulation, the reactive power compensation of Module 1 reaches its maximum, leading to the red spikes of Figure 13F. The reactive power compensation capability can be augmented by increasing the power rating of Module 1, with a possible increase in the BtB losses.

|                          | LFT     | PET     | HPET    |
|--------------------------|---------|---------|---------|
| Energy from Substation [kWh] | 3263.3  | 3320.8  | 3273.7  |
| Energy from Transformer [kWh] | 3232.0  | 3261.9  | 3262.0  |
| Transformer Losses [kWh]   | 21.8    | 172.0   | 29.3    |
| Total System Losses [kWh]  | 71.4    | 222.1   | 79.1    |

Table 2. Resulting computations of energy and losses in the power flow simulation.
The results presented in this section demonstrate the usefulness of the developed model towards the quantification of system-level benefits of including Hybrid Power Electronic Transformers in the distribution system. In this brief example, it can be seen that an HPET equipped with a 10% rated BtB converter can provide voltage regulation and power factor correction to almost the same extent that the full PET can, but with considerably lower losses. The power flows presented in Figures 13E and 13F show that there is a large mismatch between the power delivered by Module 1 and Module 2 in the proposed scenario (see Figure 1). This suggests that a possible optimal BtB configuration may be found by sizing the two BtB Modules differently.

Regarding the possible limitations and improvements of the presented HPET model, as it can be seen in the workflow of Figure 6, several power flow snapshots are needed to get one final solution for each time step, possibly making the modeling approach inadequate for long-term studies or high-resolution simulations. A possible improvement that could give faster solutions is to create a custom HPET module in OpenDSS, taking advantage of the open-source nature of the tool by embedding the equations and
algorithms described in this work into the OpenDSS public code. This way, the algorithms that represent the HPET behaviour are solved into a single snapshot.

It is also important to mention that further improvements may be done regarding the efficiency modeling of the full PET, since in this presented case an optimistic single efficiency curve is used for the whole PET. A more realistic approach could consider a modular implementation of the PET in which its power rating is allowed to change by enabling and disabling internal modules in accordance with the actual demanded power (Andresen et al., 2016).

5 CONCLUSION

Smart and active control in the distribution network appears as a good option to deal with some of the envisaged issues created by the growing presence of distributed generation and new types of controllable loads, which are increasing the stress on the electric grids. There is a growing interest in the possibilities of replacing the passive distribution transformers by active, smart power-electronics-based devices such as the Power Electronic Transformers (PETs). However while these devices offer a high level of controllability and flexibility to the network, their cost, losses and reliability are still the main obstacles that prevent their widespread integration in the grid. It is necessary to adequately quantify the net benefits that full and hybrid PETs can provide, using transformers and grid models to conduct simulations in different future network scenarios.

For that reason, a modeling approach for Hybrid Power Electronic Transformers for power flow studies is presented in this work along with a new representation of losses in the power electronic converters. The HPET power flow model depicted in Section 3 allows simulation of the steady-state behaviour of this power electronic device working in the distribution grid, and this enabling different system-level studies aimed at quantification of the net system benefits. The loss modeling presented in Subsection 3.3 provides accurate results even in cases of low power factor, as well as a practical way of simulating the losses of different converter topologies using an efficiency curve, that is easily integrated into the presented HPET model.

Finally, the presented results demonstrate how the HPET model works under different ranges of voltage, active power and reactive power, as well as how is the HPET model integrated into a network simulation facilitates comparisons between different types of transformers. This work contributes a useful tool that allows complete network studies to be conducted, which can quantify the system-level benefits of Hybrid PETs in terms of voltage management, network loss reduction, congestion management and load reduction, and it is freely available as an open-source development (Prystupczuk et al., 2021). Although the presented development has been done using the OpenDSS power flow solver and some of its modelling solutions, such as the LFT model, the proposed methodology is valid for any other power flow analysis solver.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

FP, VR, AN, and TO contributed to conception and design of the study. FP developed the HPET model, developed the inverter loss model, developed the power flow simulation platform and conducted the simulations, and wrote the manuscript. RA developed the Simulink inverter model used in the presented loss model. All authors contributed to manuscript revision, read, and approved the submitted version.
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The datasets generated for this study can be found in the HPET_PowerFlow_Model GitHub repository: https://github.com/fprystupczuk/HPET_PowerFlow_Model

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