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ORIGINAL RESEARCH

Transformer-less unified power flow controller in medium voltage distribution networks

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Abstract
A transformer-less unified power flow controller (UPFC) is a power electronic device consisting of series and shunt voltage source converters (VSCs) that are not connected to a common DC bus. It can control power flow in medium voltage (MV) distribution networks without the need for interfacing transformers. Hence there is a significant reduction in size and cost compared to a conventional UPFC. This paper investigates the operating range of a transformer-less UPFC in an MV distribution network and the required power ratings of the series and shunt converters. The results showed that a transformer-less UPFC is able to provide active power control using partially rated converters. However, its ability to control reactive power is limited by the current ratings of the converters. The analysis was verified using software simulation and hardware experiment.

1 | INTRODUCTION

The growth of distributed generation, energy demand and energy storage requires continuous improvements of the controllability and automation of existing medium voltage (MV) electricity distribution networks. Such improvements are possible with the increasing use of power electronic devices capable of controlling power flow. An acknowledged trend is to transfer the Flexible AC Transmission Systems (FACTs) technology to MV network applications [1, 2]. This is reflected by the commissioning of several projects which use power electronics in MV distribution networks, such as Angle-DC project ± 27 kV, 30.5 MVA [3], Flexible Power Link project 33 kV, 20 MVA [4] and Active Response project 11 kV, 5 MVA [5]. These projects aim to control the power flow (e.g. transfer excess power generated by distributed generators (DGs) to other load centres), maintain the voltages and currents within limits, improve the utilisation of existing assets, and support the growth of low carbon technologies [6, 7].

Typical MV power electronic devices for power flow control are similar to MV motor drive systems [8, 9]. Such systems consist of multi-winding line-frequency transformers with multiple three-phase voltage source converters (VSCs) that are connected back-to-back (B2B) to a common DC link [10, 11]. The B2B configuration of VSCs processes all power transfers (i.e. fully rated converters). The main advantages of a B2B configuration of VSCs are: (1) Its ability to connect busbars that might have different voltage and vector groups, and (2) it does not significantly increase the fault level of a distribution network, and it limits fault propagation [12, 13]. The main disadvantages of B2B configuration of VSCs are the high cost and size of the fully-rated VSCs and the interfacing transformers.

In order to reduce the cost and the size of power electronic devices, they can be partially rated by using series-connected VSCs, similar to the conventional Unified Power Flow Controller (UPFC) in transmission networks. Figure 1 shows a conventional UPFC composed of partially rated series and shunt converters connected through a common DC link [14]. The converters are interfaced to an AC network using series and shunt interfacing transformers. In contrast to B2B VSCs configuration, the series connection of a UPFC offers a solution with lower rating converters and size [15]. However, a major challenge of using a conventional UPFC is the unique design characteristics of the series interfacing transformer described in [16].

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The size and cost of a conventional UPFC are further reduced in a transformer-less UPFC. The main advantage of a transformer-less UPFC over a conventional UPFC is the complete removal of interfacing transformers, reducing its size and cost significantly [17, 18]. Figure 2 shows the structure of a transformer-less UPFC. It has isolated series and shunt converters that are not connected to a common DC bus, similar to a STATCOM and a static series synchronous compensator (SSSC).

The converters within a transformer-less UPFC are based on cascaded H-bridge or half-bridge modules to meet the required voltage and power ratings for transmission applications [19]. By reducing the number of modules, such a device can be adapted for MV distribution networks at a low cost due to fewer semiconductor devices.

The low X/R ratio of distribution networks makes the analysis more complex than transmission networks. In addition, the main purpose of a transformer-less UPFC in a transmission network is to control active power and maintain reactive power flow to a minimal. However, this purpose might not be suitable for distribution networks, especially with the ongoing investigation to use distribution networks to provide a certain amount of controlled reactive power at grid side points (GSPs) [20, 21].

In [22], the capability of using a transformer-less UPFC to control active power in a transmission network was tested. It was shown that the total rating of the transformer-less UPFC was reduced to half of that of a B2B configuration when the reactive power was maintained unchanged. In [23], a transformer-less UPFC was investigated to increase the transfer capability of a transmission network by connecting two separate transmission networks with a large phase difference that could not be previously connected.

Little research discussed transformer-less topologies of VSCs in MV distribution networks. Transformer-less STATCOM and SSSC were investigated to provide voltage regulation in distribution networks. A transformer-less UPFC is a hardware combination of a STATCOM and an SSSC that can be simultaneously controlled to provide power flow control in distribution networks. In [24], the performance of a 6.6 kV, 100 kVAR prototype transformer-less STATCOM was investigated to manage voltage in distribution networks. The results showed the capability of the transformer-less STATCOM to provide inductive and capacitive reactive power of 100 kVAR when connected to a 6.6 kV distribution network without an interfacing transformer. In [25], a transformer-less SSSC was examined to provide voltage regulation in an 11 kV distribution network with many DGs. The results showed that the SSSC maintained the network voltage within the permissible limits by injecting a series voltage of approximately 15% of the rated network voltage. In [26, 27] the series connection of a UPFC was realised using single-phase series converters directly connected to a distribution network without an interfacing series transformer.

Further investigation is required to assess the ability of a transformer-less UPFC to control both active and reactive power in distribution networks and the size of the series and shunt converters. This paper investigates the operation of a transformer-less UPFC in an MV distribution network with a low X/R ratio. It provides a detailed analysis of the operating range of a transformer-less UPFC considering both active and reactive power control. It also examines the magnitude of the shunt current required to change the power flow from various uncompensated active and reactive power to an arbitrary target active and reactive power. It highlights that the magnitude of the shunt current and, therefore, the ratings of the converters are small when a transformer-less UPFC is used to control active power. However, a transformer-less UPFC has limited capability to control reactive power due to the current ratings of the converters. The analysis was verified using simulation and a small-scale experimental setup.

2 | TRANSFORMER-LESS UPFC IN AN MV DISTRIBUTION NETWORK

Figure 3 shows the equivalent circuit of a transformer-less UPFC connected in a two-busbar distribution network. The series converter is modelled as a controlled voltage source and the shunt converter as a controlled current source. The voltage and current at busbar $\overline{V}_1'$ are given as:

$$\begin{cases} \overline{V}_1' = \overline{V}_1 + \overline{V}_{se} \\ \overline{I}_s = \overline{I} + \overline{I}_{sh} \end{cases}$$  (1)
The active and reactive power $P_2$ and $Q_2$ are given, as in (3).

\[
\begin{align*}
P_2 &= \frac{\left| V_1 \right| \cdot \left| V_2 \right| \cos(\delta_0 + \theta) - \left| V_2 \right|^2 \cos \theta}{\left| Z \right|} \\
Q_2 &= \frac{\left| V_1 \right| \cdot \left| V_2 \right| \sin(\delta_0 + \theta) - \left| V_2 \right|^2 \sin \theta}{\left| Z \right|}
\end{align*}
\]

Equation (3) shows that $V_{se}$ affects both $P_2$ and $Q_2$. However, if the transformer-less UPFC is deactivated (i.e. $V_{se} = 0$), the uncompensated active and reactive power $P_2'$ and $Q_2'$ are given, as in (4).

\[
\begin{align*}
P_2' &= \frac{\left| V_1 \right| \cdot \left| V_2 \right| \cos(\delta_0 + \theta) - \left| V_2 \right|^2 \cos \theta}{\left| Z \right|} \\
Q_2' &= \frac{\left| V_1 \right| \cdot \left| V_2 \right| \sin(\delta_0 + \theta) - \left| V_2 \right|^2 \sin \theta}{\left| Z \right|}
\end{align*}
\]

The difference between (3) and (4) is the controllable active and reactive power $P_c$ and $Q_c$ of a transformer-less UPFC (i.e. $P_c = P_2 - P_2'$ and $Q_c = Q_2 - Q_2'$), and are given as in (5).

\[
\begin{align*}
P_c &= \frac{\left| V_1 \right| \cdot \left| V_{se} \right| \cos(\delta_0 + \theta - \rho)}{\left| Z \right|} \\
Q_c &= \frac{\left| V_1 \right| \cdot \left| V_{se} \right| \sin(\delta_0 + \theta - \rho)}{\left| Z \right|}
\end{align*}
\]

By further simplifying (5) yields the expression of $V_{se}$ as given in (6).

\[
|V_{se}| = \left| \frac{|Z|}{|V_2|} \right| \sqrt{P_c^2 + Q_c^2}, \quad \rho = (\delta_0 + \theta - \tan^{-1}(\frac{Q_c}{P_c}))
\]

Equation (6) shows that $|V_{se}|$ is a function of $|Z|$, $P_c$, $Q_c$, and $|V_2|$. 

Figure 4 shows a phasor diagram developed using the equivalent circuit in Figure 3. It explains the role of the series and shunt converters, where voltage $V_1$ of Busbar 1 is taken as a reference and $\delta_0$ represents the power angle between $V_1$ and voltage $V_2$ of Busbar 2.

The role of the series converter in a transformer-less UPFC is similar to that in a conventional UPFC. It injects a controllable voltage $V_{se} = |V_{se}|Z \rho$. This voltage is added to $V_1$ making the resultant voltage $V'_1 = |V'_1|Z \delta_1$ whose magnitude and power angle are regulated to achieve the target active and reactive power $P_2$ and $Q_2$ as shown by the voltage phasors in Figure 4.

The role of the shunt converter in a transformer-less UPFC is different from that in a conventional UPFC. The shunt converter ensures zero active power exchange between both the converters within a transformer-less UPFC and the connected AC network (i.e. $P_w = 0$ and $P_{sh} = 0$). To achieve this, the shunt current $I_{sh}$ is controlled to be perpendicular to $V'_1$ (i.e. $I_{sh} \perp V'_1$), and it must make the series current $I_{se}$ perpendicular to $V_{se}$ (i.e. $I_{se} \perp V_{se}$) as shown by the current phasor in Figure 4.

The distribution feeder is represented by a series impedance $Z = |Z|Z \theta$. The current through the distribution feeder can be obtained as $\bar{I} = (\bar{V}'_1 - \bar{V}'_2)/|Z|Z \theta$. Therefore, the apparent power $\bar{S}_2$ at Busbar 2 is given as in (2).

\[
\bar{S}_2 = \bar{V}'_2 \cdot \bar{I}^* = \bar{V}'_2 \left( \frac{\bar{V}'_1 - \bar{V}'_2}{|Z|Z \theta} \right)^* = P_2 + j Q_2
\]
The current at busbar $I_1'$ is obtained as in (7), where $\phi$ is the angle between $\overline{V}_1'$ and $I$. Note that the series current $I_s$ is the resultant of the shunt current and the current of the distribution feeder (i.e. $I_s = I_{sh} + I$).

$$|I_{sh}| \angle (\delta + 90^\circ) = |I_s| \angle (\rho - 90^\circ) - |I| \angle \phi$$  \hspace{1cm} (7)

Equation (7) is used to obtain an expression of $I_{sh}$, as in (8). Detailed derivation of (8) is provided in the Appendix.

$$I_{sh} = \frac{\cos(\rho - \phi)}{\sin(\rho - \phi)} |I_{ss}| \angle (\delta - 90^\circ)$$  \hspace{1cm} (8)

Equations (6), and (8) are used to calculate the reference voltage and current $\overline{V}_{ss}$ and $I_{sh}$ for the series and shunt converters. As the feeder's impedance is known, a transformer-less UPFC relies on the measurements of $\overline{V}_{ss}$ and $\overline{I}$ to calculate its $\overline{V}_{ss}$ and $I_{sh}$. $\overline{V}_1$ is measured locally, while $\overline{V}_2$ requires communication.

3 OPERATING RANGE OF A TRANSFORMER-LESS UPFC IN MV DISTRIBUTION NETWORKS

The operating range of a transformer-less UPFC was investigated based on the modelling conducted in Section 2. It describes the capability of a transformer-less UPFC to control active and reactive power in an MV distribution network, and it is directly related to the power ratings of the series and shunt converters.

The series and the shunt converters' power ratings must fulfil the maximum apparent power $|\overline{V}_{ss}|$ and $|\overline{I}_{sh}|$ exchanged between the converters and the connected AC network (i.e. $|\overline{V}_{ss}| \cdot |\overline{I}_{sh}| \leq |\overline{V}_s| \cdot |\overline{I}_s| \leq |\overline{V}_{ss}||\overline{I}_{sh}|$).

3.1 Series converter

The power rating of the series converter is estimated by calculating $|\overline{V}_{ss}|$ using (6). Note that $|\overline{V}_{ss}|$ is advantageously smaller in MV distribution networks than in transmission networks due to the smaller impedance. Assuming $|\overline{V}_s| = 0.95$ p.u., the term $\sqrt{P_s^2 + Q_s^2}$ is 2.0 p.u. (e.g. the series converter can reverse the active power from 1.0 to -1.0 p.u., while the reactive power was maintained to zero) and impedance $|\overline{Z}|$ ranges between 5% to 10%, then the range of $|\overline{V}_{ss}|$ is calculated to be between 0.105 to 0.210 p.u. As current $|\overline{I}_{ss}|$ is 1.0 p.u., the power rating of the series converter also ranges between 0.105 to 0.210 p.u.

3.2 Shunt converter

The shunt converter has full network voltage applied across its terminal. The power rating of the shunt converter is determined based on $|\overline{I}_{sh}|$. Therefore, it is required to calculate the maximum shunt current required to ensure zero active power exchange between each of the series and shunt converters and the connected AC network.

An algorithm was developed to calculate the shunt current as shown in Figure 5. It calculates $|\overline{I}_{sh}|$ when the power flow changes from various uncompensated active and reactive $P_s'$ and $Q_s'$ (i.e. prior to connecting the transformer-less UPFC) to an arbitrary target active and reactive power $P_s$ and $Q_s$.

Firstly, various operating conditions of $P_s'$ and $Q_s'$ are generated by hypothetically changing $|\overline{V}_2|$ and $\delta_2$, while maintaining $|\overline{V}_1|$ and $\delta_1$ constant at 1.0 p.u. 0.0 and Busbar 1 was taken as a stiff busbar to demonstrate the inherent capability of a transformer-less UPFC. Note that a non-stiff busbar adds further limitations on the operating range of the transformer-less UPFC. For example, an increase in voltage at the point of connection reduces the reactive power the shunt converter can supply. $P_s'$ and $Q_s'$ are calculated using (4), and are stored in matrices $[P_s'[\text{MV}], Q_s'[\text{MV}]] \times \delta_2$, where $M$ and $N$ are the range of $|\overline{V}_2|$ and $\delta_2$. For example, $|\overline{V}_2|$ is changed from 0.95 to 1.03 p.u. and $\delta_2$ from $-5^\circ$ to $+5^\circ$ such as $\sqrt{(P_s')^2 + (Q_s')^2} \leq \delta_2$ where $\delta_2$ is the nominal apparent power of the distribution feeder.

Secondly, an arbitrary target power $P_s$ and $Q_s$ is chosen such as $\sqrt{(P_s)^2 + (Q_s)^2} \leq \delta_2$. Finally, voltage $|\overline{V}_s|$ and current $|\overline{I}_{sh}|$ and current $|\overline{I}_s|$ are calculated using (6)–(8).

Figure 6 shows the mapping of $|\overline{I}_{sh}|$ against $P_s'$ and $Q_s'$. The base apparent power and voltage were 10 MVA and 12.66 kV. The impedance of the distribution feeder was 8%, and the X/R was 2.0. A circle of 1.0 p.u. radius represents all the values of $P_s'$ and $Q_s'$. The colour map provides the shunt current's magnitude at every power $P_s'$ and $Q_s'$ to the target power of (0.6 p.u., 0.2 p.u.) such as, dark blue area represents zero shunt current, while dark red area represents 1.0 p.u. shunt current. The areas with black circles and red crosses are inoperable as either $|\overline{I}_{sh}|$ and $|\overline{I}_s|$ exceeded 1.0 p.u. or $|\overline{I}_{sh}|$ exceeded 1.0 p.u.

Three cases were selected to demonstrate the shunt current's magnitude by changing the uncompensated power "A", "B" and "C" to the same target power. These cases are:

Case A: The change of power flow from A (0.2 p.u., 0.2 p.u.) to target power (0.6 p.u., 0.2 p.u.), where the per-unit values in each bracket are the active and reactive power.

Case B: The change of power flow from B (0.6 p.u., 0.2 p.u.) to target power (0.6 p.u., 0.2 p.u.).
1- Generate various power flow operating conditions $P_2^\prime$ & $Q_2^\prime$:

Using Equation (4), calculate: $[P_2^\prime]_{MxN}$ & $[Q_2^\prime]_{MxN}$

2- Choose an arbitrary target power flow $P_2$ & $Q_2$ where $\sqrt{P_2^2 + Q_2^2} = S_2$

3- Using Equations (6)-(8), calculate $[\vec{V}_{sc}]_{MxN}$, $[\vec{I}_{sh}]_{MxN}$, and $[\vec{I}_{se}]_{MxN}$.

4- Check constraints

Case C: The change of power flow from C (0.2 p.u., 0 p.u.) to target power (0.6 p.u., 0.2 p.u.).

It can be observed that in case A, $|\vec{I}_{sh}|$ was only 0.1 p.u. when the power flow changed from A to the target power (i.e. step change of active power from 0.2 to 0.6 p.u., while the reactive power was maintained constant). In case B, the change of power flow from B to the target power (i.e. step change of reactive power from 0 to 0.2 p.u. while the active power was maintained constant) was in the area with black circles as $|\vec{I}_{sh}|$ and $|\vec{I}_{se}|$ exceeded 1.0 p.u. In case C, the change of

FIGURE 5 The algorithm used to determine the shunt current
power flow from C to the target power (i.e. step change of active power from 0.2 to 0.6 p.u. and reactive power from 0 to 0.2 p.u.) was in the area with red crosses as $|I_{sh}|$ exceeded 1.0 p.u.

Note that in all cases, the power flow was changed from either “A”, “B” or “C” to “Target Power” by injecting the corresponding series voltage $V_{se}$. While $|I_{sh}|$ is required to guarantee zero active power exchange between each of the series and shunt converters and the connected AC network.

A horizontal line labelled as “Active power control” was drawn to the target power where $P_2'$ changes while $Q_2'$ is constant (i.e. active power control). The points along the horizontal line show a maximum shunt current’s magnitude of 0.1 p.u. This demonstrates the ability of the transformer-less UPFC to control active power using a small shunt current. Similarly, a vertical line labelled as “Reactive power control” was drawn to the target power where $Q_2'$ changes while $P_2'$ is constant (i.e. reactive power control). The vertical line is entirely in the areas with red crosses and black circles, hence the transformer-less UPFC is inoperable.

Table 1 shows steady-state voltages and currents of the series and shunt converters for Case B and Case C when the transformer-less UPFC was inoperable. These values were calculated using (1), (6) and (7). Figure 7 shows scaled phasor diagrams developed using Table 1 where cases B and C are inoperable due to current constraints.

### 3.4 Analysis of the shunt current

Simplified expressions of $|I_{sh}|$ obtained in two cases:

1. Active power control (i.e. $Q_2 = 0$), and
2. Reactive power control (i.e. $P_2 = 0$).

Firstly, an approximate expression of $|I_{sh}|$ can be obtained from (8) by neglecting angle $\delta$, which is usually small in MV distribution networks, as in (9).

$$|I_{sh}| = |I| \cdot \frac{\cos(\phi)}{\tan(\rho)} + \sin(\phi)$$  \hspace{1cm} (9)

Secondly, approximate expressions of $P_2$ and $Q_2$ can be obtained from (5) by neglecting the angle $\delta_0$, as in (10), where $V_d$ and $V_q$ are the direct and quadrature components of $V_{se}$.

$$\begin{cases} P_2 \approx \frac{V_2 R}{Z^2} V_d + \frac{V_2 X}{Z^2} V_q \\ Q_2 \approx \frac{V_2 X}{Z^2} V_d - \frac{V_2 R}{Z^2} V_q \end{cases}$$  \hspace{1cm} (10)

When $Q_2 = 0$, then substituting in (10) obtains $V_q/V_d = X/R$ or $\tan(\rho) = X/R$. In this case, $|I_{sh}|$ can be approximately
FIGURE 8 Shunt current’s magnitude mapped against $P_2'$ and $Q_2'$ for several target power; (a) $\Lambda$ (0.6 p.u., 0.2 p.u.), (b) $\Lambda$ (−0.6 p.u., −0.2 p.u.) and (c) $\Lambda$ (−0.6 p.u., 0.2 p.u.)

rewritten, as in (11).

$$|\tilde{I}_{sh}| \approx \frac{|I|}{R/X} \left( \cos(\phi) + \sin(\phi) \right)$$ (11)

The feeder is utilised for active power control, and so $\phi$ is close to zero. Therefore, $|\tilde{I}_{sh}|$ is a fraction of $|\tilde{I}|$ considering a distribution feeder of an X/R greater than 1.0.

Similarly, when $P_0 = 0$, then substituting in (10) obtains $V_q/V_d = -R/X$. In this case, $|\tilde{I}_{sh}|$ can be rewritten, as in (12).

$$|\tilde{I}_{sh}| \approx |\tilde{I}| \cdot \left( \frac{\cos(\phi)}{R/X} + \sin(\phi) \right)$$ (12)

Equation (12) demonstrates that $|\tilde{I}_{sh}|$ is very likely to exceed 1.0 p.u. especially as the X/R ratio of a distribution feeder increases.

The above analysis demonstrates that a transformer-less UPFC can control active power with a partially rated shunt converter. Equations (11) and (12) show that various values of feeder’s X/R ratio will affect the shunt current magnitudes, consequently the operating range of a transformer-less UPFC.

Assume a full-load operation of $|\tilde{I}|$, $\phi$ is zero and the X/R ratio is 2.0, using (11), the power rating of the shunt converter is 0.5 p.u. when used to control active power. Note that the rating of the series converter is 10–20% of the nominal apparent power, as given in Section 3.1. The ability of a transformer-less UPFC to control reactive power is limited by the converters’ current ratings.

4 | SIMULATION STUDY

4.1 | Control scheme of the simulated transformer-less UPFC

Figure 9 shows the test system implemented in MATLAB Simulink to validate the theoretical analysis in Section 3. A transformer-less UPFC was connected to a 10 MVA, 12.66 kV distribution feeder whose impedance was 8%, X/R ratio of 2. The base apparent power and voltage were 10 MVA and 12.66 kV. The series converters were implemented using single-phase two-level VSCs, while the shunt converter was implemented using a three-phase, two-level VSC. The DC-link capacitance of the series and shunt converters are 12 mF and 0.5 mF and were calculated from $C_{se} \geq \frac{s_{se} \omega V_{dc,se} \Delta V_{dc}}{2}$ and $C_{sh} \geq \frac{s_{sh} \omega V_{dc,sh} \Delta V_{dc}}{2}$, where $\Delta V_{dc}$ is the ripple component of the DC voltage [29, 30]. Selection criteria for the DC-link capacitors can be found in [31]. The parameters of the transformer-less UPFC model are summarised in Table 2.
### Parameters of the transformer-less UPFC model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series converter</td>
<td></td>
</tr>
<tr>
<td>Nominal power, $S_s$</td>
<td>1.5 MVA</td>
</tr>
<tr>
<td>DC voltage, $V_{dc,s}$</td>
<td>1750 V</td>
</tr>
<tr>
<td>DC capacitance, $C_{se}$</td>
<td>12 mF</td>
</tr>
<tr>
<td>Filter inductance, $L_{se}$</td>
<td>20 mH</td>
</tr>
<tr>
<td>Shunt converter</td>
<td></td>
</tr>
<tr>
<td>Nominal power, $S_{sh}$</td>
<td>10 MVA</td>
</tr>
<tr>
<td>DC voltage, $V_{dc,sh}$</td>
<td>30 kV</td>
</tr>
<tr>
<td>DC capacitance, $C_{sh}$</td>
<td>0.5 mF</td>
</tr>
<tr>
<td>Filter inductance, $L_{sh}$</td>
<td>20 mH</td>
</tr>
</tbody>
</table>

4.1.1 Overall control

The transformer-less UPFC was operated to control active and reactive power $P_2$ and $Q_2$ at Busbar 2 independently. Figure 10 shows the overall control structure [28]. In stage 1, the desired active and reactive power at Busbar 2 $P_2^*$ and $Q_2^*$ were used to calculate the reference voltage $\bar{V}_{se0}^{*}$ of the series converter and the reference current $\bar{I}_{sh0}^{*}$ of the shunt converter according to (6) and (8). When $\bar{V}_{se}$ and $\bar{I}_{sh}$ are regulated effectively, $P_2$ and $Q_2$ will be maintained close to $P_2^*$ and $Q_2^*$. In stage 2, the DC voltage control loops of the series and shunt converters are found. Their outputs are $\Delta \bar{V}_{se}$ and $\Delta \bar{I}_{sh}$ which are added to $\bar{V}_{se0}^{*}$ and $\bar{I}_{sh0}^{*}$. In stage 3, the series and shunt converters generate the switching signals of the IGBTs.

4.1.2 Individual control of the series converter

Figure 11 shows the control loop of the single-phase series converter.

In total, three identical control loops were used for the series converters. The DC voltage controller (in the red dash box) maintains the DC voltage $V_{dc,se}^{*}$ of the series converter at its reference value $V_{dc,se}^{*}$. The PI controller eliminates the error between $V_{dc,se}$ and $V_{dc,se}^{*}$ and generates an output power $P_{se}$ which equals the power losses of the converter (i.e. $P_{se} = P_{loss}$). This ensures the active power is balanced within the converter. The output $P_{se}$ is then divided by $I_{se}^{2}$ to obtain a virtual resistance $R_{se}$ that is equal to the equivalent resistance of the converter. $R_{se}$ is further mul-

![FIGURE 10](image1)

![FIGURE 11](image2)

![FIGURE 12](image3)

![FIGURE 13](image4)
tiplied by the vector $\hat{I}_d$ to obtain the AC voltage drop across the converter $\Delta V_{ad}$ caused by the equivalent resistance of the converter. $\Delta V_{ad}$ needs to be added to $V_{ad}^*$ to compensate for the AC voltage drop. The sum $V_{ad}^* + \Delta V_{ad}$ is the reference voltage $V_{ad}^*$ that is forwarded to the PWM block, generating the switching signals ($S_1 \rightarrow S_6$).

### 4.1.3 Individual control of the shunt converter

Figure 12 shows the current control loops of the three-phase shunt converter. The DC voltage controller (in the red dash box) maintains the DC voltage $V_{dc,sh}$ of the shunt converter at its reference value $V_{dc,sh}^*$. It has similar control structure to the DC voltage controller of the series converter.

The shunt current is regulated in the dq frame using $abc$ to $dq$ transformation. The dq current errors ($I_{sh,d} - I_{sh,d}^*$) and ($I_{sh,q} - I_{sh,q}^*$) are sent to the PI controllers of the current control loops [32]. The PI controllers minimise the dq current errors and generate the reference dq voltage signals $V_{sh,d}$ and $V_{sh,q}$ which are then transformed into $abc$ frame using $dq$ to $abc$ transformation. The PWM block generates the gate signals of the IGBTs ($S_1 \rightarrow S_6$).

### 4.2 Simulation results

The same three cases (Case A, Case B and Case C) shown in Figure 6 were simulated.

#### 4.2.1 Case A

Figure 13 shows the voltages and currents of the series and shunt converters when a step change of active power occurred at $t = 0.2$ s in response to a change in active power control signal. Before $t = 0.2$ s, the uncompensated active power was 0.2 p.u. and the uncompensated reactive power was 0.6 p.u. was maintained constant at 0.6 p.u. in steady state.

Figure 13a shows that $P_2$ was increased from 0.2 to 0.6 p.u., while $Q_2$ was maintained unchanged at 0.2 p.u. in steady state. In response to this step change of reactive power, $I_{sh,q}$ increased to 1.31 p.u. and $I_{sh,d}$ to 1.21 p.u. in steady state as shown in Figure 14b,c. Both $|\overline{I}_{ab}|$ and $|\overline{I}_{ad}|$ exceeded 1.0 p.u. These magnitudes match with case B in Section 3 and the phasor diagram in Figure 7a.

#### 4.2.2 Case B

Figure 14 shows the voltages and currents of the series and shunt converters when a step change of active power occurred at $t = 0.2$ s in response to a change in active power control signal. Before $t = 0.2$ s, the uncompensated active power was 0.6 p.u. and the uncompensated reactive power was zero.

Figure 14a shows that $Q_2$ was increased from zero to 0.2 p.u. while $P_2$ was maintained constant at 0.6 p.u. in steady state. In response to this step change of reactive power, $|\overline{I}_{ab}|$ was increased to 1.31 p.u. and $|\overline{I}_{ad}|$ to 1.21 p.u. in steady state as shown in Figure 14b,c. Both $|\overline{I}_{ab}|$ and $|\overline{I}_{ad}|$ exceeded 1.0 p.u. These magnitudes match with case B in Section 3 and the phasor diagram in Figure 7a.

#### 4.2.3 Case C

Figure 15 shows the voltages and currents of the series and shunt converters when a step change of active and reactive power occurred at $t = 0.2$ s in response to changes in active and reactive power control signals. Before $t = 0.2$ s, the uncompensated active power was 0.2 p.u. and the uncompensated reactive power was zero.

Figure 15a shows that $P_2$ was increased from 0.2 to 0.6 p.u. and $Q_2$ was increased from zero to 0.2 p.u. in steady state. Figure 15b,c shows that current $|\overline{I}_{ab}|$ was increased to 0.64
1.06 p.u. Although \( |I_{sh}| \) was below 1.0 p.u., \( |I_{se}| \) exceeded 1.0 p.u. These results match with case C in Section 3 and the phasor diagram in Figure 7b.

5 | EXPERIMENTAL RESULTS

5.1 | Experimental equipment

A physical experiment was used to demonstrate the shunt current's magnitude of a transformer-less UPFC, as shown in Figure 16. It consists of:

1. An Imperix power electronic rig,
2. Two power amplifiers, and
3. A series impedance.

The Imperix power electronic rig has half-bridge modules that were connected to form the single-phase series converters and the three-phase shunt converter of a transformer-less UPFC. Two half-bridge modules were used to implement each two-level single-phase series converter and were directly connected to Busbar 1. Three half-bridge modules were used to implement a two-level three-phase shunt converter interfaced through a filter inductance \( L_{sh} \).

Power amplifiers were used to emulate Busbar 1 and Busbar 2, and both were controlled using an OPAL-RT digital simulator. Series impedance represents the distribution feeder connecting Busbar 1 and Busbar 2. Table 3 shows the parameters of the test setup.

5.2 | Tests and results

The start-up of the experiment required starting the series converters and shunt converter and both are physically connected to the same point (i.e. busbar \( V_{1}' \)). Then, synchronisation
procedures were followed to connect Busbar 1 and Busbar 2.
For simplicity, the experiment was conducted at low voltage.
Figure 17 shows the DC voltage across the DC buses of
the series and shunt converters from start-up until steady
state. In Step 1, the series converters were connected and
charged through the anti-parallel diodes. In Step 2, the DC
current controllers of the series converters were activated, and
$V_{dc,sa}$, $V_{dc,se}$, and $V_{dc,sc}$ were maintained constant at 20 V. In
Step 3, the shunt converter was connected and charged through
the anti-parallel diodes. In Step 4, the DC voltage controller
of the shunt converter was activated, and $V_{dc,sh}$ was maintained
constant at 150 V. Figure 18 shows the experimental waveform
of $V_1'$ after closing the Switch “S”.

Figure 19 shows the experimental results of the Transformer-
less UPFC in response to a control signal to step change the
active power flow. Figure 19a shows the measured active power
$P_2$ at Busbar 2. $P_2$ was increased from 0.36 to 0.8 p.u., while
the reactive power $Q_2$ was maintained unchanged at 0.12 p.u. Figure 19b shows a small shunt current of approximately 0.63 A rms (i.e. 0.13 p.u.) provided by the shunt converter.

Figure 20 shows the experimental results of the transformer-
less UPFC in response to a control signal to step change the
reactive power flow. Figure 20a shows that $Q_2$ was increased
from 0.12 to 0.3 p.u. while $P_2$ was kept unchanged at 0.36 p.u.
Figure 20b shows a large shunt current of 5.16 A rms (i.e. 1.03 p.u.).

It is worth noting that the lower voltage used in the experiment
did not provide the same operating points as in the
simulation results section. For example, the series converter
controls the power flow by injecting series voltage up to 5 V
(approximately 10% of the phase voltage). It was challeng-
ing to replicate the results in the simulation results section,
considering the voltage drop of the wires, the IGBTs, and
other passive components. However, the experiment highlights
the most important findings of this work. These are; (1) a
small shunt current when a transformer-less UPFC controls
active power (see Figure 19b), and (2) a large shunt current
when a transformer-less UPFC controls reactive power (see Figure 20b).

The control schemes presented in Figures 11 and 12 provided the required power flow control of the transformer-less UPFC. Further analysis is required to optimise the operation of the transformer-less UPFC when connected to various types of AC systems [33].

6 CONCLUSION

A transformer-less UPFC can provide power flow control in MV distribution networks using series and shunt converters that are not connected to a common DC-link and with complete removal of the interfacing transformers. Its operation relies on controlling the series and shunt converters together such that both converters exchange only reactive power with the AC network. The shunt current of the transformer-less UPFC was found to be small when it was used to control active power. In contrast, the use of the transformer-less UPFC to control reactive power required a large shunt current (i.e. > 1.0 p.u.). This makes a transformer-less UPFC a good choice for applications that require controlling active power. However, its ability to control reactive power is limited by the converters’ current ratings.

AUTHOR CONTRIBUTIONS

Mohamed Abdelrahman: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. Sheng Wang: Conceptualization, Writing - review & editing. Wenlong Ming: Conceptualization, Project administration, Resources, Supervision, Writing - review & editing. Jianzhong Wu: Project administration, Supervision, Writing - review & editing. Nick Jenkins: Conceptualization, Investigation, Supervision, Writing - review & editing.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

REFERENCES

APPENDIX

Derivation of Equation (8):

\[ |\bar{I}_{ar}| \rho - 90^\circ = |\bar{I}| \phi + |\bar{I}_{sh}| \delta + 90^\circ \]  \hspace{1cm} (A1)

Using Equation (A1), then

\[ |\bar{I}_{sh}| = \left| \frac{\bar{I} \cdot \cos(\phi) - |\bar{I}_{ar}| \cdot \sin(\rho)}{\sin(\delta)} \right| \hspace{1cm} \text{(A2)} \]

\[ P_{sh} = 0, \text{then } \text{real}(\bar{V}_1^* \cdot \bar{I}_{sh}) = 0 \hspace{1cm} \text{(A3)} \]

Using Equation (A3),

\[ (\bar{V}_1 + \bar{V}_{ar}) \cdot (\bar{I}_{ar} - \bar{I}) = 0 \hspace{1cm} \text{(A4)} \]

From Equation (A4), the current \(|\bar{I}_{ar}|\) is given in (A5).

\[ |\bar{I}_{ar}| = \left| \frac{\bar{I} \cdot \cos(\phi) + |\bar{V}_{ar}| \cdot |\bar{I}| \cdot \cos(\rho - \phi)}{|\bar{V}_1| \cdot \sin(\rho)} \right| \hspace{1cm} \text{(A5)} \]

Substitute Equation (A5) into (A2),

\[ |\bar{I}_{sh}| = - \left| \frac{|\bar{V}_{ar}| \cdot |\bar{I}| \cdot \cos(\rho - \phi)}{|\bar{V}_1| \cdot \sin(\delta)} \right| \hspace{1cm} \text{(A6)} \]

Using \(|\bar{V}_1| = |\bar{V}_1 + \bar{V}_{ar}|\), then

\[ |\bar{V}_1| = \left| \frac{\sin(\rho) \cdot \cos(\delta)}{\sin(\delta)} - \cos(\rho) \right| \hspace{1cm} \text{(A7)} \]

Substitute Equation (A7) into (A6)

\[ \bar{I}_{sh} = \left| \frac{\cos(\rho - \phi)}{\sin(\rho - \delta)} \right| (\delta - 90^\circ) \hspace{1cm} \text{(A8)} \]