End user voltage regulation to ease urban low-voltage distribution congestion

Gordon Connor, Catherine E. Jones, Stephen J. Finney

Department of Electronic and Electrical Engineering, University of Strathclyde, Royal College Building, 204 George Street, Glasgow, G1 1XW, UK
E-mail: gordon.connor@strath.ac.uk

Abstract: Owing to the increasing demand in the urban areas for new technologies such as heat pumps and electric vehicles (EVs), greater power capacity in low voltage (LV) distribution networks is becoming increasingly important. This study will investigate how to improve the power capacity through the implementation of point of use voltage regulation (PUVR). PUVR relies on a power electronics converter at each end-user. Most LV network cabling has a voltage limit of 1 kV, PUVR exploits this voltage rating to increase the network capacity. This study will describe and discuss the results from a viability study using data from a utility company, which shows that the capacity in the LV network could be increased by an additional 500 kVA. However, it was also found that PUVR using present off-the-shelf converters is not as cost-effective as replacing the LV network cables. Two power electronics topologies have been investigated in the simulation studies to date: the AC chopper circuit and the back-to-back inverter circuit. These two topologies were compared and the AC chopper was found to be a cheaper, more efficient topology. Therefore the AC chopper is more suitable for this application and may increase the viability of the PUVR.

1 Introduction

1.1 Need for point of use voltage regulation (PUVR)

In order for the UK to meet the 2020 and 2050 greenhouse gas emissions targets set by the European Union, immediate changes are required across all energy sectors [1]. Therefore it is expected that over the next 30 years ‘cleaner’ emerging technologies such as heat pumps [2] and electric vehicles (EVs) will be implemented in order to meet these targets. In addition, the price of fossil fuels is expected to rise significantly, possibly by up to as much as 30% in one year [3]. The increasing costs of fossil fuels and of new vehicles are likely to force higher population densities in urban areas, thereby reducing distance of travel to the work place. Therefore it is prudent to assume a large increase in load on urban distribution systems [4] in the future.

If the existing urban low-voltage distribution infrastructure is left unchanged, it is unlikely to be ready for this predicted increase in demand in urban areas, which is expected to be in the order of 1–2 GW in magnitude [4]. The aim of this paper is to show that end user voltage regulation is a potential solution to this problem. The concept of PUVR is to set the line-to-line voltage in the three-phase distribution cabling to be higher than the standard 415 V. At present, the insulation limit of the wiring allows a maximum of 1 kV [5]. Therefore it is clear that the distribution cabling is underutilised, but in order to make the power usable when it reaches the customer it must be transformed down to 230 V phase.

1.2 Advantages of using PUVR

1.2.1 Voltage rise: The voltage drop as current travels through a conductor is dependent on the impedance of the conductor [6]. Considering a street of houses in an urban distribution system, to ensure each house receives 230 V, including the housing at the end of the conductor, it is acceptable for the voltage to fluctuate within the limits of 230 V + 10−6% [7].

PUVR can be used to overcome this problem of fluctuating voltage, resulting in each house on the distribution network receiving exactly 230 V AC. This paper will demonstrate how this level of control can be achieved using power electronics whereas conventional distribution networks use transformers to control voltage amplitude.

1.2.2 Distributed generation: The integration of distributed generation on the distribution grid close to the point of use reduces transmission losses and helps to meet local power demand [8]. This is particularly useful during times of peak demand. However, during periods of off-peak demand where there is significant reduction in the local load, local distributed generation will contribute to the voltage rise. This can lead to the voltage rise exceeding
shows the results of this study. By inspection of Fig. 1a it can be seen that the main feeder is at 65% of its thermal capacity. This simulation result indicates that, without PUVR, a further 174 A could be drawn from the distribution network before the thermal limit of the main feeder reached 100% capacity. From the used assumptions this is the equivalent of 124 more houses.

If EVs or heat pump boilers were introduced to the present system it would more than double average household load [2, 18, 22]. The effect of doubling the average load at each household to 2 kW is shown in Fig. 1b. This indicates that the capacity of the network cannot be increased by increasing current levels because of the thermal limit of the network. Therefore to increase the capacity of the network, increasing the voltage level of the system must be considered. A realistic way to achieve this would be using PUVR.

2.3 Effect of implementing voltage regulation

The effect of increasing the voltage on the distribution network is shown in Figs. 1c and d. Fig. 1c has a network voltage level of 600 V, while in Fig. 1d the voltage level is increased further to 1 kV.
Although setting the network voltage at 1 kV would provide the most effective voltage regulation, it is only being shown here as a comparison. It is not a viable option because of the cable insulation limit of 1 kV. In reality the cable insulation limit will be below 1 kV because of factors such as tolerances, degradation and bends/twists in the cabling [23].

From Fig. 1c, it can be observed that the main feeder is now 86% utilised under double average load. This is a decrease from 136% in the results presented in Fig. 1b. This means that no cables need to be replaced and a further 24 houses could be placed on the system. This is an increase of 200 kVA in available capacity compared to the present system (Fig. 1a). Fig. 1d shows a further decrease from 136 to 51% utilisation, 84 new houses could be placed on this system. This is an increase of 500 kVA in available capacity compared to the present system (Fig. 1a).

Therefore these studies indicate that PUVR will significantly increase the load capacity of urban distribution networks.

2.4 Consideration of losses in a point of use regulation system

In Section 2.3, PUVR has been shown to be an effective means of increasing the capacity of an urban distribution network. However, the losses attributed to end-user conversion in a PUVR system must be considered. The two main sources of loss are cable losses and converter losses.

2.4.1 Cable loss: From the heat maps in Fig. 1, it is clear that PUVR lowers the thermal losses present in the cabling because of the lower current levels in the network. Table 1 summarises the different thermal losses for the urban distribution network.

![Fig. 1 Heat maps of power loss: darkest areas show 0 W loss, palest show 2 kW loss](image)

- **a** Average loading
- **b** Double average loading conditions
- **c** Double average loading at 600 V
- **d** Double average loading at 1 kV

Table 1 Summarises the different thermal losses for the urban distribution network

|                      | 415 V average load (Fig. 1a) | 415 V double average load (Fig. 1b) | 600 V double average load (Fig. 1c) | 1 kV double average load (Fig. 1d) |
|----------------------|-----------------------------|------------------------------------|-----------------------------------|-----------------------------------|
| Cable loss, %        | 3.1                         | 6.74                               | 1.26                              | 0.16                              |
| (a) Cable loss at average load and double average load at each voltage level |                            |                                    |                                   |
| Cumulative loss (cable and conversion) with the best and worst case conversion loss for each voltage level |
| Converter loss, %    | 600 V (+2% conversion)      | 1 kV (+2% conversion)              | 600 V (+8% conversion)            | 1 kV (+8% conversion)             |
| (b)                   | 3.26                        | 2.16                               | 9.26                              | 8.16                              |
|                      | (a)                         |                                    |                                   |                                   |
distribution network considered in Fig. 1 operating at different voltage levels.

The present urban distribution network, drawing the maximum average from all loads simultaneously, loses 3.1% of its transmitted power as heat in the cabling. At the estimated future maximum average load, 6.74% of the power transmitted is lost. Transmission of power at 600 V decreases this loss at maximum load to 1.26% and transmission at 1 kV further reduces this to 0.16%. These losses were calculated by using the following equation

\[
\% \text{cableloss} = \frac{\sum S_{\text{cableloss}}}{S_{\text{in}}} \times 100
\]  

(1)

2.4.2 Converter loss: When using PUVR, the voltage level must be stepped down at the end-user. In the case of the urban network, this would take place at each house connected to the distribution network.

This voltage conversion will not be 100% efficient, and therefore extra losses will be introduced to the network. Existing power electronic inverters on the market have a maximum efficiency of 98% [24].

The best and worst case scenarios are shown in Table 1. The best case considered was an efficient single conversion process of 2%, with one AC to AC converter. For example, a single phase AC chopper or matrix converter, as shown in Fig. 2a [25]. The worst case considered was an inefficient conversion of 4% using a back-to-back inverter topology [26], as shown in Fig. 4a; this requires two conversions and would, therefore, give an 8% conversion loss.

2.5 Cost benefit

The approximate cost of implementing PUVR is shown in Table 2. The costs of transformer and cable replacement including excavation and reformation were taken from the Scottish and Southern Energy (SSE) 2012 Statements, Methodology, Charges and Connection document [27].

Using this document and the diagram gained from industry partners which specify cable length and type (see Section 2.2) an estimation of the cost of replacing the distribution cables was made. The cost of the converters was estimated using the cost of present off-the-shelf converter units [28, 29]. A transformer replacement was considered for the cable replacement method as it is possible that the voltage rise because of the distributed generation issue would give cause to replace this transformer (see Section 1.2.2); a replacement was not deemed necessary for this study.

It was found that, at present, the PUVR method has a greater cost and that a 23 kW converter would need to cost between £460 and £2100 (worst case and best case, respectively) to be equivalent to replacing the cables. However, the costing for these converters was for individual units and it is expected that the price would reduce significantly if ordered in bulk (in this case 220 units). It is also expected that when PUVR is taken into consideration semi-conductor costs would be lower than they are at present as the cost of semi-conductor devices decreases over time [30].

2.6 Summary

The studies carried out have strongly indicated that PUVR would be effective in easing congestion of low-voltage urban distribution systems by increasing capacity of the network without exceeding thermal/current limits of the cables. A potential disadvantage of implementing PUVR using power electronic converters is that conversion losses are introduced to the system. However, the studies and Tables 1a and b have shown that this additional loss is compensated for by the lower losses in the conductors because of the lower current levels. It was found that PUVR is not as cost-effective as replacing the LV distribution cables. It is expected, however, that future decreases in semi-conductor costs and bulk orders will bring the cost to a comparable level with the cable replacement method.

3 Proposed technology options for PUVR

If the distribution network voltage is raised above 415 V line to increase network capacity, then this voltage must be regulated at each end user on the network to an acceptable level, typically 230 V phase. This paper proposes two different power electronic circuits to carry out the voltage regulation: the AC chopper and the back-to-back inverter.

3.1 AC chopper for PUVR

Fig. 2a shows the initial design of the AC chopper, which is the single phase form of the matrix converter [25], the circuit \( V_{\text{in}} \) is 346 V AC (from 600 V line to single phase) which is pulse-width modulated at 10 kHz by the IGBT switching arrangement S1–S4.

Activation of switches S1 and S2 will connect the load to the source voltage, while activation of S4 and S3 will apply zero voltages to the load. Modulation of these states allows the load voltages to be controlled as shown in Fig. 2b. The resulting output is then filtered by a low-pass filter shown in Fig. 2a as an inductance ‘L’. The final output is a controlled 230 V AC waveform at 50 Hz shown in Fig. 2c.

3.1.1 Filter design: The AC chopper introduces harmonics to the input current, output voltage and output current in the form of multiples of the switching frequency (10 kHz) each at 50% total harmonic distortion (THD). To reduce this distortion, the output voltage and current must be filtered in order to meet acceptable power quality standards [26]. Therefore an inductive first-order filter with a cut-off frequency of 75 Hz was designed.

As a filter with this cut-off frequency is able to filter the high frequency harmonics of the switching and additionally filter lower frequency harmonics because of non-linear loading, which typically are at odd multiples of the fundamental [31]. The open-loop transfer function for the first-order filter is given as follows

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R}{R + sL}
\]  

(2)

\[
\omega_c = \frac{R}{L}
\]  

(3)

The cut-off frequency of the filter was chosen to be 75 Hz as this is between the fundamental and second harmonic frequencies ensuring the third harmonic is filtered. This is represented in angular frequency by \( \omega_c = 471 \text{ rads}^{-1} \) and using an average household load of \( R = 53 \Omega \) (taken from the earlier three bedroom household consumption average of 3500 kWh/year, Section 2.2) using (3) the optimum value for \( L \) was calculated to be 112.5 mH.
3.1.2 AC chopper results: Fig. 2c demonstrates the steady-state operation of the AC chopper; it is clear that the circuit successfully lowers a voltage of 346 to 230 V. A phase shift of 32° between the waveforms can also be observed, this is, because of the inductance in the low-pass filter (see Fig. 2a). This phase shift is not detrimental to the operation of the circuit.

To improve the design of the AC chopper, firstly, the filter was redesigned as a second-order filter, which included a capacitor, therefore increasing the response time of the filter.
and decreasing the magnitude of any passed higher frequencies (see Section 3.2.3). Secondly, the switching frequency was adjusted to 33 kHz minimising voltage harmonics in the output (see Section 3.2.4). Thirdly an input filter was introduced to the AC chopper, to minimise current harmonics at the input caused by non-linear loading, see Fig. 2d.

3.1.3 Second-order low-pass filter design: The transfer function of a second-order low-pass filter (Fig. 3a) is given in (4). In order to tune this filter to give the desired response, the transfer function in (4) was manipulated to have the form of a standard second-order transfer function as shown in (5). By comparison of (4) with (5) the values for the inductance and capacitance for a given cut-off frequency can be calculated, using (6) and (7)

\[
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{\omega_n^2}{s^2 + 2\omega_n\xi s + \omega_n^2} \tag{5}
\]

\[
\omega_n = \sqrt{\frac{1}{LC}} \tag{6}
\]

\[
2\omega_n\xi = \frac{1}{RC} \tag{7}
\]

Since \( R = 53 \ \Omega \), \( \omega_n = 471 \ \text{rads}^{-1} \) and \( \xi = 1 \) using (6) and (7) the optimum values for \( L \) and \( C \) were calculated to be: \( L = 225 \ \text{mH} \) and \( C = 20 \ \mu \text{F} \).

It was found that the new filter design is an improvement as, post cut-off frequency, the first-order filter has a slope of 19.2 dB/decade and the second-order filter has a slope of 37.3 dB/decade.

3.1.4 Switching frequency against harmonic distortion: In order to optimise the size of the filter an

| Table 2 | Cost benefit results |
|---------|----------------------|
| Proposed method | Cost of transformer replacement, £ | Cost of cable replacement, £ | Cost of converters, £ | Total cost, £ |
| | Min | Max | Min | Max | Min | Max | Min | Max |
| PUVR method | 13 800 | 69 200 | N/A | N/A | 621 500 | 1 335 800 | 635 300 | 1 405 000 |
| Cable replacement method | 169 700 | 476 600 | N/A | N/A | 169 700 | 476 600 | N/A | N/A |

Fig. 4 Circuit topology for the back-to-back inverter

a Circuit diagram of back-to-back inverter
b Switching pattern of the inversion stage
c Back-to-back inverter initial input and output
d Back-to-back inverter steady-state phase compensated
analysis of harmonic distortion and switching frequency was carried out. The focus was to minimise harmonic content caused by the introduction of the AC chopper while also trying to minimise filter size. A higher switching frequency will increase the frequency of the harmonics, therefore the size of the filter can decrease [31]. The filter was redesigned to filter the 3rd, 5th, 11th and 21st harmonics of the fundamental. These new filter values were tested against differing switching frequencies the result of this is shown in Fig. 3b. The British standards (Energy Networks Association – G5/4) limit for THD is 5% [31].

From Fig. 3, a filter designed to filter out the 21st harmonic of the fundamental combined with a switching frequency of 33 kHz was chosen as optimal. From the results shown in Fig. 3 this allows the use of a small filter without the distortion becoming greater than 5%. The new value of $L_1/L_2$ is 2 mH and the new value of $C_1/C_2$ is 0.6 μF.

The final circuit arrangement for the AC chopper is shown in Fig. 2d; note that an input filter of equal magnitude has been added. This filter limits the harmonics present in the input current. For further information on harmonics see Section 4.2.

3.1.5 Back-to-back inverter: Fig. 4a shows the circuit topology for the back-to-back inverter. As with the improved chopper, it is proposed that the switching frequency is 33 kHz, with an input voltage level of 346 V single phase AC. The back-to-back inverter consists of an active rectifier and inverter.

The inversion process is shown in Fig. 4b, it can be observed that the output contains switching frequency components therefore a filter is required to smooth the signal, shown in Fig. 4a as inductance $L_2$ and capacitance $C_2$.

3.1.6 Capacitor sizing and design of input and output filters: The size of the DC-link capacitor has an effect on voltage ripple on the DC section of the topology. Large size of the DC-link capacitor has an effect on voltage ripple (600 V), where $L_1/L_2$ is 2 mH and $C_1/C_2$ is 0.6 μF.

The inversion process is shown in Fig. 4b, it can be observed that the output contains switching frequency components therefore a filter is required to smooth the signal, shown in Fig. 4a as inductance $L_2$ and capacitance $C_2$.

$$ V_{\text{ripple}} = \frac{V_{\text{peak}}}{2 \times R_{\text{load}}} \times C_1 \times \frac{T}{2} $$

where $T$ is the switching period (20 ms), $V_{\text{peak}}$ is the highest voltage point (600 V), $R_{\text{load}}$ is the load resistance (53 Ω) and $V_{\text{ripple}}$ is the ripple in the DC voltage. It is known that (8) becomes increasingly inaccurate for a voltage ripple higher than 10% [34]. Hence minimum DC-link capacitance required for a 10% ripple was calculated to be 1.88 mF. The sizing and importance of the input inductance is described in Section 4.2.

For the output filter, the same process of filter choice was used as described in Section 3.2.4. Therefore the values used in the back-to-back inverter output filter were $L_2 = 2$ mH and $C_2 = 0.6$ μF at a switching frequency of 33 kHz.

3.1.7 Back-to-back inverter results: Fig. 4c illustrates the input and output voltage from the back-to-back inverter. By inspection of Fig. 4c it can be seen that the output voltage is shifted by 171° leading. Unlike the AC chopper, which pulse-width-modulates the input voltage and draws a chopped version of the output current. The back-to-back inverter deconstructs the voltage into DC.

The back-to-back inverter can then synthesise an AC voltage of any phase, magnitude and frequency. Therefore the control of the input and output stage are decoupled. The phase shift can be compensated for in the control, this is shown in Fig. 4d.

4 Comparison of the AC chopper and back-to-back inverter for PUVR

The two topologies presented in the previous section have been tested in simulation and results for their performance in several areas compared. They were compared in the following areas:

- Losses
- Power quality
- Complexity
- Control
- Transient behaviour
- Protection

4.1 Losses

The conduction loss for the AC chopper and back-to-back inverter was calculated and is shown in Table 3. These results were calculated using the data in the device datasheets [35, 36] and the loss calculation methods used in [26, 37, 38].

The switching losses for both of the topologies were calculated, using a switching frequency of 33 kHz. The energy loss for each time the devices switched was taken from the device datasheet. The results of these calculations are shown in Table 3. In order to validate the calculations the back-to-back inverter and AC chopper were both modelled in PLECs. The models calculated the conduction and switching losses; with a thermal profile for each device created from information in the device datasheets [35, 36]. These results indicate that the back-to-back inverter generates approximately 6–7% more total loss than the AC chopper.

4.2 Power quality

Equation (9) [39] is used to describe the transmission of real power between two sources linked by a series inductance. Examining Fig. 4a it can be said that because of the

| Table 3 Summary table of device losses: switching and conduction |
|------------------|------------------|-----------------|------------------|------------------|------------------|
| Loss             | $P_{\text{conduction}}$, W | $P_{\text{switching}}$, W | Total, W         | Total, %         |
|                  | Calculation      | PLECS           | Calculation      | PLECS           | Calculation      | PLECS           |
| back-to-back inverter, per arm | 2.01            | 2.7            | 10.3            | 9.3            | 98.5            | 96             | 9.8            | 9.6            |
| AC chopper, per arm | 2.2             | 3.2            | 4.5             | 5.9            | 27              | 36.4           | 2.7            | 3.6            |

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inductive element between the grid and the rectifier (9) is true for the back-to-back inverter

$$ P = \frac{V_1 \times V_2}{X} \times \sin(\delta_1 - \delta_2) $$  

(9)

where $V_1$ is the voltage of the primary source at angle $\delta_1$ (346 V$_{rms}$), $V_2$ is the voltage of the secondary source at angle $\delta_2$ (425 V$_{rms}$) and $X$ is the reactance of the inductance $L$ (0.02 H) multiplied by the angular frequency (100$\pi$). Therefore from (9), we can state that the real power bandwidth between the grid and the back-to-back inverter rectification stage is 0–23 kW dependant on the phase difference between the two.

4.2.1 Total harmonic distortion: Two Matlab models using idealised lossless devices were implemented to study the effect of non-linear loads on system power quality. Table 4 is a summary of the effects of THD on both topologies. First the THD of both topologies was found with a standard linear load of 53 kW. Table 4 shows that conducted harmonic emissions from the output to the input.

Table 4 Summary table of THD on both topologies

| Device and configuration | $V_{in}$, THD, % | $I_{in}$, THD, % | $V_{out}$, THD, % | $I_{out}$, THD, % |
|--------------------------|------------------|-----------------|------------------|------------------|
| AC chopper (linear load) | 0                | 0.81            | 0.44             | 0.44             |
| AC chopper (non-linear load) | 0                | 58.9            | 16.1             | 58.8             |
| back-to-back inverter (linear load) | 0                | 0.29            | 0.17             | 0.17             |
| back-to-back inverter (non-linear load) | 0                | 3.05            | 3.45             | 69.9             |

For the back-to-back inverter (see Fig. 4a) the initial rectifying stage can be controlled in order to gain the necessary power for the rest of the circuit.

This decouples the source and the load; with the DC-link capacitor acting as a buffer. Therefore it is reasonable to expect that in terms of power quality the back-to-back inverter will perform better as the AC chopper has no similar function, see Fig. 2d.

4.2.2 Non-unity power factor loading: The effect of reactive loading on the idealised models of both topologies can be shown in Table 5. Each topology was examined with a resistive load ($R$) of 53 $\Omega$ (see Section 3.1.1) and then subsequently tested with the same resistive load in series with an inductive load ($L$) of 17.2 mH. The value of reactive load was chosen to give a power factor in the region of 0.9.

It was observed that under reactive loading the AC chopper demands the extra 100 VAr required for the load directly from the source. In contrast the back-to-back inverter topology requires no additional reactive power from the source. Based on these observations, the back-to-back inverter is the superior topology with regard to power quality as it has been shown to reject load harmonics and load reactive power draw.

4.2.3 Loading extremes: Although an average load of 1 kW has been assumed it is far more likely that load will erratically vary over the course of the day. The maximum power that can be drawn in a UK household is 23 kW. Table 6 shows that conducted emissions from the converter can be controlled, via the use of filters, to be within the boundaries issued in G5/4 (<5% THD [31]).

Table 5 Summary table of power with and without reactive load

| Device and configuration | $P_{in}$, W | $Q_{in}$, VAr | $P_{out}$, W | $Q_{out}$, VAr | $V_{in}$, THD, % | $I_{in}$, THD, % | $V_{out}$, THD, % | $I_{out}$, THD, % |
|--------------------------|-------------|----------------|--------------|-----------------|-----------------|------------------|--------------|------------------|
| AC chopper ($R$)          | 1 000       | 15             | 1 000        | 0               | 3.98            | 0.48             | 0.48         |
| AC chopper ($R + L$)      | 990         | 86             | 990          | 100             | 3.12            | 1.83             | 1.83         |
| back-to-back inverter ($R$) | 997       | 0              | 997          | 0               | 0.81            | 0.44             | 0.44         |
| back-to-back inverter ($R + L$) | 988     | 0              | 988          | 101             | 0.29            | 0.17             | 0.17         |

Table 6 Power draw results from varying the load

| Power draw, W | Device | $P_{in}$, W | $Q_{in}$, VAr | $P_{out}$, W | $Q_{out}$, VAr | $V_{in}$, THD, % | $I_{in}$, THD, % | $V_{out}$, THD, % | $I_{out}$, THD, % |
|--------------|--------|------------|---------------|--------------|-----------------|-----------------|------------------|-----------------|------------------|
| 100          | AC chopper | 100       | −32.2         | 100          | 0               | 3.98            | 0.48             | 0.48         |
|              | back-to-back inverter | 100      | −0.2          | 100          | 0               | 3.12            | 1.83             | 1.83         |
| 1000         | AC chopper | 1000     | 15            | 1000         | 0               | 0.81            | 0.44             | 0.44         |
|              | back-to-back inverter | 997      | 0             | 997          | 0               | 0.29            | 0.17             | 0.17         |
| 10 000       | AC chopper | 10 000   | 1700          | 10 000       | 0               | 0.77            | 0.42             | 0.42         |
|              | back-to-back inverter | 10 000  | −1           | 9973         | 0               | 2.03            | 0.11             | 0.11         |
| 20 000       | AC chopper | 20 000   | 7100          | 20 000       | 0               | 1.15            | 0.61             | 0.61         |
|              | back-to-back inverter | 20 010  | 2480         | 19 960       | 0               | 4.98            | 0.06             | 0.06         |
Radiated electromagnetic interference (EMI) is a problem associated with the use of power electronics; however at these power levels well established rules for enclosures, connection layout and semi-conductor gate drive devices can be used to ensure EMI is minimised [31].

### 4.3 Complexity and cost

From Figs. 2d and 4a, it is clear that the AC chopper is much less complex. Table 7 provides a cost estimate comparison of the two solutions based on the principal components in both converter topologies. The costs are based on the power semi-conductors used in Section 4.1 and include values for the power filters [40–42].

From the results, in Table 7 it is clear that the cost of using the back-to-back converter topology to outfit the physical system demonstrated in Section 2.1 is more expensive than outfitting the system with the AC chopper topology. Looking at Section 2.5, the cost reduction in using the AC chopper over the back-to-back inverter will make PUVR more viable in terms of cost benefit.

| Device                  | 1 Bridge arm, £ | 1 module, £ | Cost to convert an urban area, £ |
|-------------------------|----------------|-------------|---------------------------------|
| AC chopper              | 9.60           | 520         | 111 800                         |
| back-to-back inverter   | 5.76           | 1070        | 228 300                         |

### 4.4 Control

#### 4.4.1 Development of closed-loop control for the AC chopper

In order to improve dynamic performance, a closed voltage feedback control loop was placed around the AC chopper. Fig. 5a shows the block diagram for this control. The response of the closed-loop control was tested by applying a load step to the output of the chopper. Fig. 5b shows that when the load is doubled from 0.5 to 1 kW after 1.35 s the chopper output voltage remains at 230 V and the current doubles from 2.1 to 4.2 A. After 1.55 s the load is further doubled to 2 kW. The output chopper voltage remains at 230 V AC and the current rises to 9 A. In response to the load steps, the output voltage was observed to dip slightly by 1.3 and 1.7 V over 0.03 s for the first and second load steps, respectively, which as a percentage of load is a dip of −0.4 and −0.5%. These dips are caused by the change in load which increases current demand. This results in a voltage dip because of the relationship between voltage and current. The PI controller then adjusts the PWM of the switches to match the demand. The dips are within the British standards for voltage sag, which is 230 V + 10−6% [7].

A block diagram for the AC chopper is shown in Fig. 5c, with values taken from the filter design section. The closed-loop transfer function was found to be cubic, shown in (10). Fig. 5d is a control diagram of the closed loop, the reference is compared with the output then passed to the PI control. The new output of the inverter is then passed through the plant and the cycle continues. In order to tune

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**Fig. 5** Closed voltage feedback control loop was placed around the AC chopper

a Block diagram of improved chopper with control
b Output voltage and current of the AC chopper
c Block diagram of AC chopper
d Control of the AC chopper
the third-order equation the good gain method was used [43].
Using this method to find approximate values then manual
tuning, the ideal values for $K_p$ and $K_i$ were found. See
Appendix 3 for all calculated values of controller gain

$$\frac{V_{out}}{V_{in}} = \frac{\left(\frac{K_p}{L_2C_2}\right)s + \left(\frac{K_i}{L_2C_2}\right)}{s^3 + \left(\frac{1}{R_{load}C_2}\right)s^2 + \left(\frac{K_p+1}{L_2C_2}\right)s + \left(\frac{K_i}{L_2C_2}\right)}$$

(10)

4.4.2 Closed-loop back-to-back inverter: A block diagram for the back-to-back inverter is shown in Fig. 6a.
In order for the back-to-back inverter to be able to operate correctly $V_{out}$ must not vary with load. To solve this, a
feedback loop was placed in the system which measures the $V_{out}$, compares with a set point of 230 V AC and passes this
difference to a PI controller. This controls the switching of the house side inverter (HSI) semiconductors (Fig. 4b)
and changes the modulation index of the H bridge dependant on what is required.

The closed-loop HSI was tested using the same means as the AC chopper, demand changes from 0.5 to 1 to 2 kW.
The results are shown in Fig. 6b. It is observed that the back-to-back inverter can supply the load with a steady
230 V AC at the different loads. In response to the load steps, the output voltage was observed to dip slightly by
1.9 and 2.1 V over 0.03 s for the first and second load
steps, respectively, which as a percentage of load is a dip of
$-0.6$ and $-0.65\%$, this is within the British standards for
voltage sag, which is $230 V \pm 10-6\%$ [7]. Both topologies
perform well within industry standards. See Section 4.2 for
more information on power quality.

It can be observed that the inversion stage of the back-to-back inverter in Fig. 6b is identical to the output of the
AC chopper in Fig. 5c but with different values of $L_2$
and $C_2$. Therefore Fig. 5d and (10) can be used to describe
the control of the inversion stage.

It is worth noting that the initial rectification stage can only ‘boost’ the $V_{dc}$, therefore the voltage is not able to go below
the peak $V_{in}$ of 490 V. This means the modulation index of the inverter stage will be low and this will lead to more loss
in the switching of the HSI [44].

In order to control the power flow into the back-to-back inverter from the distribution grid, an additional control
loop is required at the grid side rectifier (GSR) as shown as
controller 2 in Fig. 6c.

The power flow from the grid to the back-to-back inverter is controlled via two, classic cascaded control loops, where
the outer control loop regulates the DC-link voltage and the inner loop regulates the current flowing from the grid
through the rectifier. In order to tune controller 2, the speed
of the inner and outer loop PI controllers were set to be an
order of magnitude apart. This allowed the two control
loops to be decoupled and hence operate independently of
each other [45, 46]. Therefore the outer control loop was
 treated as a standard second-order control loop as described
in (5) in Section 3.2.3.

Using Fig. 6d, (11) which describes the outer loop and (12)
which describes the inner loop (where $R$ is a small line
resistance of $1 m\Omega$) the controller gain vales were
calculated. Appendix 3 catalogues the calculated values of
controller gain. It was found that these calculated values

![Fig. 6](https://example.com/image6.png)

**Fig. 6** Block diagram for the back-to-back inverter

a) Output of the back-to-back inverter
b) Block diagram of the back-to-back inverter
c) Back-to-back inverter with second controller
d) Control of the back-to-back inverter rectifier
had an overshoot response despite being tuned for over-damping ($\xi = 1$), this is because the ignored differential term in the numerator of (11) and (12). Therefore the GSR controllers were manually tuned by increasing $K_{p2}$ and $K_{p3}$, the result of this is shown in Fig. 7b. The final control values are catalogued in Appendix 4.

The step response for (10)–(12) is shown in Fig. 7b. This demonstrates the speed of the controllers to be sufficiently different, to allow them to be considered decoupled from each other.

The response of the AC chopper is shown in Fig. 7c. In order to demonstrate the stability of the controllers the poles of the control loops were plotted in Fig. 7d

$$
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{(K_{i2}/C_1)}{s^2 + (K_{p2}/C_1)s + (K_{i2}/C_1)}
$$

(11)

$$
\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{(K_{i3}/L_1)}{s^2 + ((R + K_{p3})/L_1)s + (K_{i3}/L_1)}
$$

(12)

4.5 Transient behaviour

The time taken to reach steady state was found to be 0.1 s for the back-to-back inverter compared to 0.05 s for the AC chopper shown in Figs. 7b and c. Both topologies are sufficiently fast.

4.6 Protection

The proposed converter location is shown in Fig. 8. To ensure that the breaker on the main feeder does not activate in case of a fault on the converter hardware, the converter must be placed after the fuses on the distribution network. This will prevent a fault in any single converter causing a trip on an entire street.

However, this means that any present protection system must be rated higher than 346 V phase, otherwise it must be replaced. This will not be problematic as British Standards fuses have a voltage rating of up to 1 kV line AC [47].

A standard three bedroom home will have a series of fuses with upstream reclose devices on the main feeder or breakers on the local transformer [48]. Use of either converter increases the fault level substantially, consider a short circuit across the load of 0.1 $\Omega$ and (13) [49]

$$
P_f = \frac{V_{\text{rms}}^2}{R_f}
$$

(13)

With the present system where $V_{\text{rms}} = 230$ V the resulting fault level, $P_{f}$, is equal to 0.53 MW. With $V'_{\text{rms}} = 346$ V the resulting fault level is 1.2 MW, an increase of 0.7 MW.

Therefore both converter types share this common disadvantage. However, if the installation follows IET wiring standards, which considers low voltage to be under
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8 Appendix

8.1 Appendix 1
See Table 8.

8.2 Appendix 2
See Table 9.

8.3 Appendix 3
See Table 10.

8.4 Appendix 4
See Table 11.

Table 8 Power world cable data

| Cable resistance, Ω | Cable reactance, jΩ | Cable thermal limit, MVA |
|---------------------|---------------------|--------------------------|
| 1                   | 0.006992            | 0.003118                 | 0.34431 |
| 2                   | 0.00564             | 0.0021                   | 0.22877 |
| 3                   | 0.00189             | 0.0007                   | 0.22877 |
| 4                   | 0.012               | 0.00555                  | 0.28841 |
| 5                   | 0.01128             | 0.0042                   | 0.22877 |
| 6                   | 0.049556            | 0.00646                  | 0.12822 |
| 7                   | 0.01222             | 0.00455                  | 0.22877 |
| 8                   | 0.01122             | 0.00455                  | 0.22877 |
| 9                   | 0.00583             | 0.00076                  | 0.12822 |
| 10                  | 0.014575            | 0.00019                  | 0.12822 |
| 11                  | 0.014575            | 0.00019                  | 0.12822 |
| 12                  | 0.0112              | 0.007                    | 0.22877 |
| 13                  | 0.0188              | 0.007                    | 0.22877 |
| 14                  | 0.016               | 0.00074                  | 0.28841 |
| 15                  | 0.016               | 0.00074                  | 0.28841 |
| 16                  | 0.0216              | 0.00999                  | 0.28841 |
| 17                  | 0.0216              | 0.00999                  | 0.28841 |
| 18                  | 0.0192              | 0.00441                  | 0.18354 |
| 19                  | 0.0064              | 0.00147                  | 0.18354 |
| 20                  | 0.00564             | 0.00076                  | 0.12822 |
| 21                  | 0.01055             | 0.000026                 | 0.22877 |
| 22                  | 0.008745            | 0.00114                  | 0.18354 |
| 23                  | 0.008745            | 0.00114                  | 0.18354 |
| 24                  | 0.000376            | 0.00014                  | 0.22877 |
| 25                  | 0.02256             | 0.0084                    | 0.28841 |
| 26                  | 0.0224              | 0.005125                 | 0.18354 |
| 27                  | 0.00846             | 0.00315                   | 0.22877 |
| 28                  | 0.00752             | 0.0028                    | 0.22877 |
| 29                  | 0.016               | 0.0074                    | 0.28841 |
| 30                  | 0.0008              | 0.00037                   | 0.28841 |
| 31                  | 0.0008              | 0.00037                   | 0.28841 |
| 32                  | 0.00188             | 0.00007                    | 0.22877 |
| 33                  | 0.00188             | 0.00007                    | 0.22877 |
| 34                  | 0.0216              | 0.00999                   | 0.28841 |
| 35                  | 0.0094              | 0.0035                    | 0.22877 |
| 36                  | 0.00583             | 0.00076                   | 0.12822 |
| 37                  | 0.0047              | 0.00175                   | 0.22877 |
| 38                  | 0.00953             | 0.00076                   | 0.12822 |
| 39                  | 0.01166             | 0.00152                   | 0.12822 |
| 40                  | 0.008745            | 0.00114                   | 0.12822 |

Table 9 Non-linear power draw data from devices

| DC power draw | Voltage, V | Current, A |
|---------------|------------|------------|
| laptop        | 19         | 4.74       |
| TV            | 66.7       | 1.5        |
| games console | 12         | 3.7        |
| PC            | 12         | 17         |
| monitor       | 66.7       | 1.5        |

Table 10 Calculated values of controller gain

| Kp1 | Kp2 | Kp3 | Kp4 | Kp5 |
|-----|-----|-----|-----|-----|
| AC chopper | 120 | 0.077 | 0.8 | 0.85 | 860 |
| back-to-back inverter | 120 | 0.077 | 0.8 | 0.85 | 860 |

Table 11 Final manually tuned values of controller gain

| Kp1 | Kp2 | Kp3 | Kp4 | Kp5 |
|-----|-----|-----|-----|-----|
| AC chopper | 120 | 0.1 | 0.8 | 50 | 860 |