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Four-Legs D-STATCOM for Current Balancing in Low-Voltage Distribution Grids

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ABSTRACT The fast deployment of distributed energy resources (DERs) is creating a series of challenges that should be addressed in the coming years. In particular, distribution grids are playing an increasingly important role in the electricity system. Moreover, the three-phase four-wire structure of this network contribute to the appearance of imbalances and a series of problems derived from them. In this context, distribution system operators (DSOs), as the main responsible for the distribution grid, must ensure the quality of supply to consumers. This paper takes advantage of a four-legs D-STATCOM to remove current imbalances in low-voltage power lines. A 35-kVA prototype has been developed and installed in an urban distribution grid. The effect of the D-STATCOM has been analyzed during its first month of operation, studying and measuring the advantages of providing DERs the ability to perform active balancing to the utility grid. The results show a reduction in current imbalances from 21 % to 0 % and neutral current from 10.3 A to 0.4 A. In addition, a 13 % decrease in cable losses has been estimated and a slight improvement in voltage unbalance factor can be noted.

INDEX TERMS Distributed energy resources, four-legs D-STATCOM, neutral current, three-phase four-wire network, unbalance compensation.

I. INTRODUCTION

The gravity of the climate crisis has already initiated a process of electrification of the energy system, increasing the use of electrical energy, maximizing the penetration of renewable energies and the deployment of clean, safe and connected mobility, among others [1], leading to a change in the electric grid as we know it today.

Since 2012, most of the new installed energy capacity has been renewable worldwide, achieving a net addition record of 83 % in 2020 [2]. Moreover, the renewable energies share in Europe reached 23.8 %, surpassing the nuclear energy and making Europe the first region where renewable energies are the dominant power generation source [3].

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The rapid deployment of renewable energy sources (RES) to replace the traditional large combustion power plants is producing a change, from the current centralized electricity model, to a distributed model where distributed energy resources (DER) are becoming especially relevant, as well as the importance of the distribution network in this process. Furthermore, the growing importance of the distribution network is being increased by changes in the consumption habits of the population, usually connected to the low voltage network. The substitution of gas and oil heating systems by HVAC systems and petrol vehicles by electric vehicles (EV) [4], together with the current profitability of small photovoltaic (PV) installations [5], is evidencing a change in our energy consumption.

In addition, single-phase and three-phase devices coexist in the low-voltage distribution grid, which are supplied by a three-phase four-wire (3P-4W) network, usually connected to the medium-voltage grid through a delta-wye configured distribution transformer (DT). In this way, single-phase currents return to the DT through the neutral wire, where the three neutral currents are usually canceled.

On the contrary, if the consumption in each of the phases is different the resulting neutral current will increase, and in the worst cases it can be higher than the current in any of the phases. Moreover, the increase in electricity demand, combined with the variability of RES, contributes to the occurrence of unbalanced currents with higher frequency and magnitude. The wide variety of problems caused by imbalances that can compromise the operation of the distribution grid are deeply analyzed in [6], and the most important are listed below:

- Neutral conductor overload: if current is decomposed into its symmetrical components, the neutral current is equal to three times the zero sequence component. If this current is large enough, it can cause heating and degradation of the cable and even failures [7].
- DT overheating: the zero-sequence-current magnetic flux closes via the fuel tank wall of the DT that generates heat, increasing losses and reducing equipment lifetime [8].
- Voltage quality reduction [9], [10].
- Line losses increase: produced by neutral line losses and a non-optimal distribution of phase currents [11].
- Abnormal vibration and malfunction in induction equipment such as rotatory machines [12]–[14].
- Mal-operation of protection relays [14].
- Neutral to ground voltage (NGV) increase [7], [15].

Consequently, the distribution system operator (DSO), as the main responsible for the low voltage grid must guarantee the power supply, and also ensure its power quality. In this way, a wide variety of parameters used to quantify imbalances can be found in the literature [6], [10], [16], [17]. Possibly the most common way to evaluate imbalances is through the unbalance factor (UF), which is defined by decomposing the network into its symmetrical components. Thus, if only positive and negative sequence are considered, the UF is usually expressed as:

$$UF = \frac{|G_{neg}|}{|G_{pos}|} \quad (1)$$

where G can be current or voltage quantities. However, for 3P-4W networks, the zero sequence should be taken into account in the previous definition, leading to the following expression:

$$UF_0 = \frac{\sqrt{|G_{zero}^2| + |G_{neg}^2|}}{|G_{pos}|} \quad (2)$$

Usually, these parameters are preceded by a V when they refer to voltages or by a C when they are calculated from current values. Since most of the problems for consumers are caused by voltage imbalances and not current imbalances, the most important standards define the voltage unbalance factor (VUF) and their limits. ANSI [18] recommends VUF values lower than 3% since IEC [19] and CIGRE [20] set the limit at 2%, allowing to reach 3% in networks with a high presence of single-phase customers, to ensure the quality of supply. The negative sequence has direct consequences on the malfunctioning of induction machines. However, zero sequence produce neutral currents and heating in electric machines [21], [22], especially in transformers, which reduces the life time of the equipment and can even lead to breakdowns. For this reason, more references to VUF_0 than to VUF are found in academia and research [23]–[25]. Moreover, the current unbalance factors (CUF and CUF_0) can be defined in the same way as for voltage. Finally, the neutral current ($|\bar{I_n}|$) is sometimes used as a representative parameter of the line unbalance:

$$|\bar{I_n}| = |\bar{I_a} + \bar{I_b} + \bar{I_c}| \quad (3)$$

To minimize the impact of imbalances, and thus improve the power quality and reliability of supply, several authors propose different methods that can be grouped into two categories [6]. Reconfiguration techniques consist in acting on the switches located in the network to achieve a better distribution of the power flow. In turn, two different methods can be distinguished in this technique: distribution feeder reconfiguration [26], [27] is a method to alter the topological structure of the grid by changing the switch status; whereas phase balancing technique [28], [29] alters the phase connection among phases (known as phase swapping).

The second category mitigates network imbalance by adding special current compensating devices. This category is further classified into three approaches. The first one, reduce the impact of imbalances in the grid by increasing power rating capacity of equipment: oversizing protections, DT and wires or separating the neutral conductor [30]. The next step consists in introducing more resistant to inbalances special transformer configurations e.g. Scott transformer, T-connected transformer and star-hexagon transformer, or by adding active filters to the DT [31]–[34]. Unlike the previous ones, the third technique does not mitigate the consequences of imbalances, but rather combats their origin by installing purpose-built shunt-connected active power filters (APF). The most commonly used APF topologies are three single-phase H-bridge, 3P-4W capacitor midpoint and 3P-4W four legs (4L) topologies [35]–[37].

The aim of this paper is to discuss the effect of removing current imbalances in an urban grid. For this purpose, a D-STATCOM has been designed and installed in a residential area of the Spanish city of Malaga. The remainder of this paper is organized as follows. Section II details the power converter characteristics, including the topology and control algorithms used for current balancing. Section III analyzes the results obtained during one-month field tests. The consequences of the installation of the D-STATCOM are discussed in Section IV. Finally, the conclusions of this paper are drawn in Section V.

II. PROPOSED SOLUTION

In order to achieve a DER which allows to mitigate the current imbalances in a low-voltage distribution grid, this paper analyses the installation of a D-STATCOM prototype in an urban line where imbalances are frequent. The developed D-STATCOM is a 3P-4W 4L APF. This topology has been chosen due to it reach a greater performance than 3P-4W capacitor midpoint topology and a smaller size and number of components than three single-phase H-bridge converters [38]. In addition, in order to improve the harmonic content and reduce the size and cost of the grid filter, the three-level neutral-point-clamped (NPC) I-type topology [39], shown in Fig. 1a, has been chosen. Moreover, 3P-3W NPC topologies are widely used in vehicle-to-grid (V2G) EV chargers [40], [41], battery energy storage systems and photovoltaic inverters [42], and can be slightly modified to add a fourth leg and improve its performance allowing unbalanced operation. The developed power converter is based on Si IGBTs with a switching frequency of 20 kHz, making its operation completely noiseless. Thus, the prototype shown in 1b has been designed to perform a rated power of 35 kVA with a maximum balancing capacity of 70 A.

In addition, Fig. 2 shows the control scheme implemented in the D-STATCOM to perform the balancing of the line. Firstly, active and reactive power in the grid are measured (P_i^{down}, Q_i^{down}) and the power references to balance the grid are calculated. The DC-link voltage (V_{dc}) is regulated by the D-STATCOM without any external source, therefore a PI controller estimates the power required to maintain a constant voltage in the DC side (P_{dc}^{comp}). Then, a SOGI filter [43] is applied to obtain single-phase instantaneous direct and quadrature components from the grid voltages, that are used to determine current references (I_i^{ref}) from active and reactive power setpoints. Next, the input error signals for a current controller, obtained from current reference signals and D-STATCOM's output measures, determines the voltage to be applied by the stack to obtain the power setpoints. Moreover, NPC I-type converters suffer from unbalances between the DC-link capacitors (V_{c1} and V_{c2}) that must be compensated. Several modulation techniques with capacitor voltage balance capacity can be found in literature [44], [45]. In this case, the technique presented in [46] has been implemented due to reduce capacitor midpoint oscillation without increase power losses.

According to the Fortescue's theorem [47], any three-phase system can be represented by three symmetrical components. In practice, in a voltage-balanced electrical system, only the direct component of the current is capable of carrying effective power, whereas zero and negative components create pulsed power flows of zero mean value, adversely affecting the efficiency of the grid. Therefore, as Fig. 3 shows, the D-STATCOM is shunt connected to the utility grid to eliminate zero and negative sequence currents, so that upstream of the device the current is completely balanced. In this project, to allow balancing at a different point than the D-STATCOM installation point, grid values downstream are measured through a commercial grid analyzer, that sends average values of active and reactive power to the control DSP, limiting the line balancing to the fundamental frequency. Thus, given a generic electrical system with unbalanced currents, the power flow of each phase is given by the following expression:

$$\left.\begin{aligned} P_i^{down} &= Re\{\bar{V}_i^{down} \cdot \bar{I}_i^{down*}\} \\ Q_i^{down} &= Im\{\bar{V}_i^{down} \cdot \bar{I}_i^{down*}\} \end{aligned}\right\} \tag{4}$$

where active and reactive power (P_i^{down} and Q_i^{down}) are determined from the complex value of voltage ($\bar{V}_i^{down}$) and current ($\bar{I}_i^{down}$) downstream each phase of the line ($i = a, b, c$).

Of both power components, the active power is the only one that transmits energy, so that the reactive component could be eliminated to minimize the current in the network. In turn, the active power can be redistributed among the three phases as long as power conservation is satisfied ($\sum P_i^{STAT} = 0$). Thus, the desired power flow (P_i^{up} and Q_i^{up}) in each of the phases upstream of the D-STATCOM will be the average power downstream:

$$\left.\begin{aligned} P_i^{up} &= \bar{P} = \frac{\sum P_i^{down}}{3} \\ Q_i^{up} &= 0 \end{aligned}\right\} \tag{5}$$

where $\bar{P}$ is one third of the total power flowing through the line.

Thus, the power to be injected by the D-STATCOM (P_i^{STAT} and Q_i^{STAT}) can be calculated as the difference between the power downstream and upstream of the device:

$$\left.\begin{aligned} P_i^{STAT} &= P_i^{down} - P_i^{up} = P_i^{down} - \bar{P} \\ Q_i^{STAT} &= Q_i^{down} - Q_i^{up} = Q_i^{down} \end{aligned}\right\} \tag{6}$$

III. RESULTS

Fig. 4 shows the set up of the D-STATCOM installation in an urban environment. The power electronics cabinet can be seen on the right side of the picture, while the device is connected to the line inside the left enclosure. This enclosure has the protection components (fuses and disconnector) to allow safe handling of the prototype. In addition, a grid analyzer has been installed to measure the line parameters downstream the connection point which send this information, via Modbus communication, to the unit to perform the balancing algorithm. The D-STATCOM prototype has been installed in an intermediate point of a power line located in a residential area in the city of Malaga (Spain), in the living lab of e-distribución [48]. The prototype is framed in the scope of PASTORA Project (Preventive Analysis of Smart Grids with Real Time Operation and Renewable Assets Integration) [49], that aims at providing AI based solutions for maintenance and flexible operation purposes. Fig. 5 shows the one-line diagram of the network in which the prototype has been installed, where it can be seen that eight different lines depart from the DT, which is equipped with On-Load Tap Changing (OLTC)

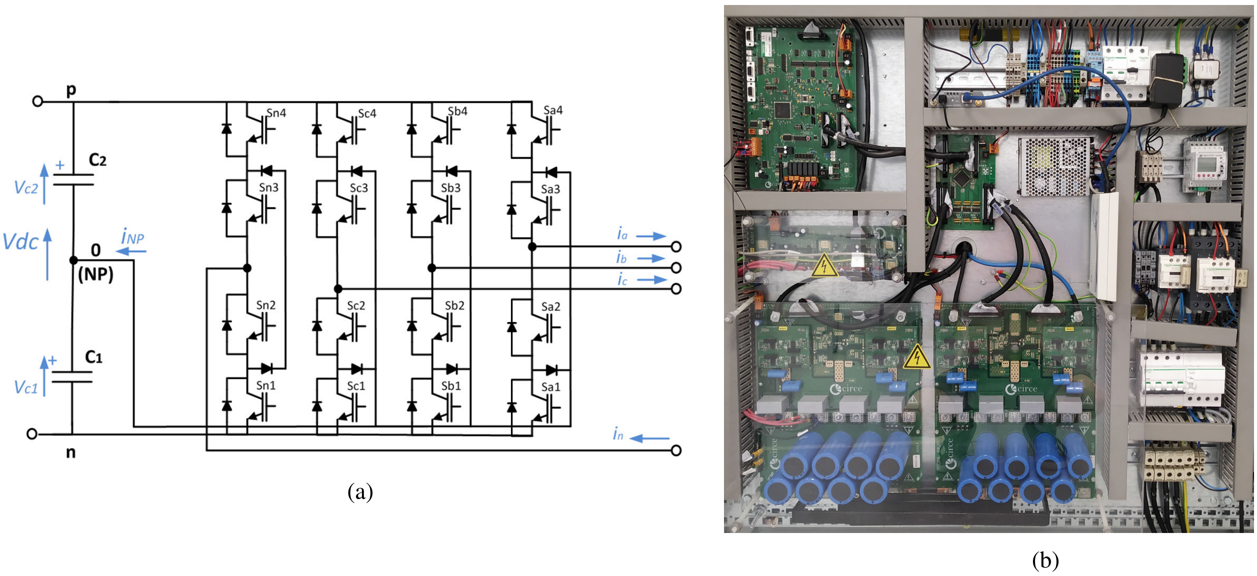

FIGURE 1. NPC I-type topology (a) and power electronics assembled inside the cabinet (b).

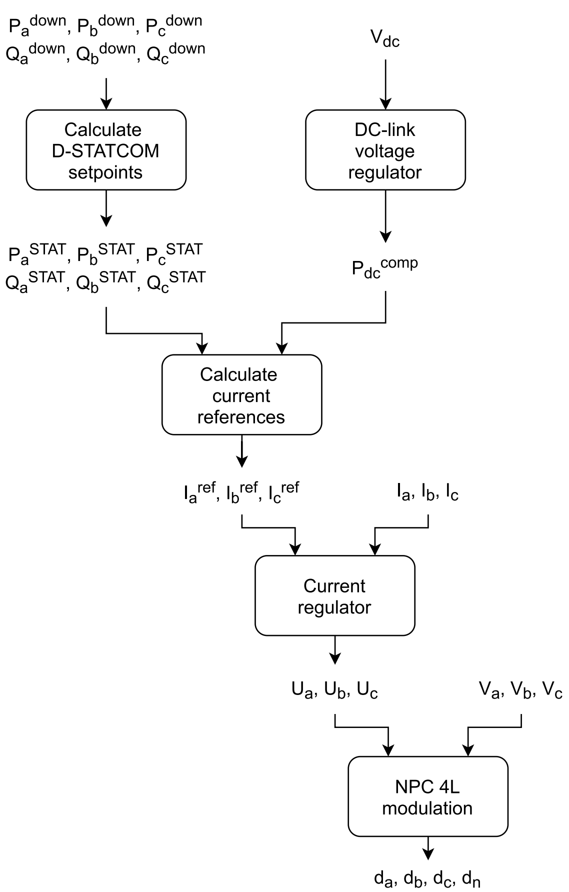

FIGURE 2. D-STATCOM control diagram.

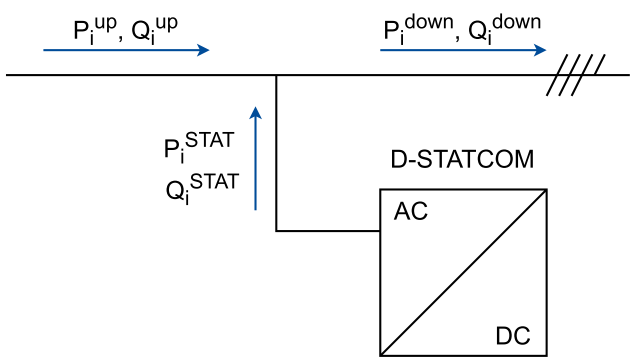

FIGURE 3. The D-STATCOM is shunt connected to the grid, allowing a disconnection without power supply interruptions. The sign convention used for power flows is shown.

capabilities and belongs to a MV/LV Secondary Substation with advanced sensorization in the DT and the low-voltage switchboard. At the end of line F8, section highlighted in red in the image, there is a high concentration of single-phase loads connected to the same phase, which causes frequent unbalances on that line. Thus, this location has been chosen for the D-STATCOM deployment to compensate imbalances as close as possible to the point where they are originated. In order to analyze the operation of the D-STATCOM in the grid, the measurements of the currents supplied by the device and downstream the unit have been recorded for one month (February 2021). From both measures the current upstream has been calculated to quantify the impact of the device in the line. With these parameters, the upstream current will be considered as the current corrected by the D-STATCOM and the downstream current as the current flow if the D-STATCOM had never been there, which will be used as a basis for comparison. Fig. 6 shows an oscilloscope snapshot where the prototype is consuming 7 kW from the *c* phase to supply them into the *a* phase whereas I_b current is zero. In addition, DC capacitor voltage oscillations are shown to prove that, although modulation does not completely eliminate the midpoint oscillations, they are reduced and allowing to reach a stable steady state.

FIGURE 4. D-STATCOM prototype installed in a residential neighborhood in the city of Malaga. The power converter is installed in the cabinet on the right side, while the enclosure on the left side contains the shunt connection of the prototype to the grid, protection elements and measurements of the line downstream of the device.

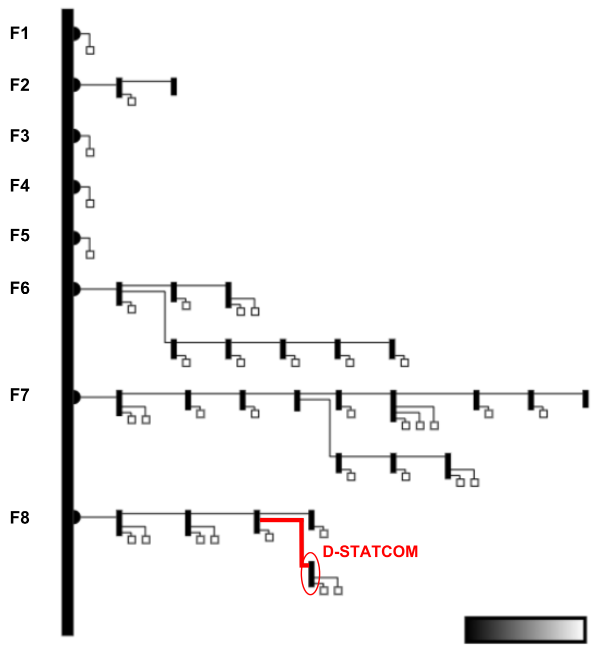

FIGURE 5. Location where the D-STATCOM prototype has been installed within an urban network in the city of Malaga.

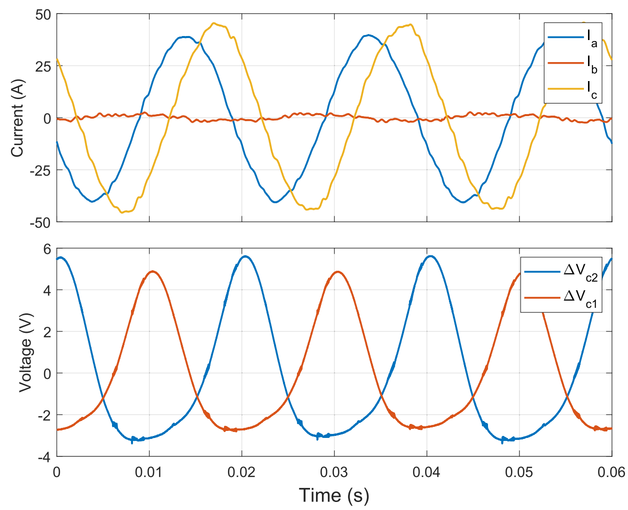

FIGURE 6. Three-phase currents (top) and capacitor voltage oscillating component ΔV_{c1} and ΔV_{c2} (bottom) at $P_i^{STAT} = \{7, 0, -7\}$ kW and $Q_i^{STAT} = \{0, 0, 0\}$ kVAr.

Furthermore, the efficiency of the D-STATCOM has been calculated. Table 1 shows the power losses as a function of the D-STATCOM output power. These measurements have been taken with the prototype injecting reactive power at balanced setpoints. In addition, according to California Energy Commission (CEC) [50], the prototype achieves a CEC efficiency of 97.7 %.

In order to show the operation of the D-STATCOM in the grid, Fig. 7 represents the current in the three phases and the neutral wire downstream and upstream of the connection

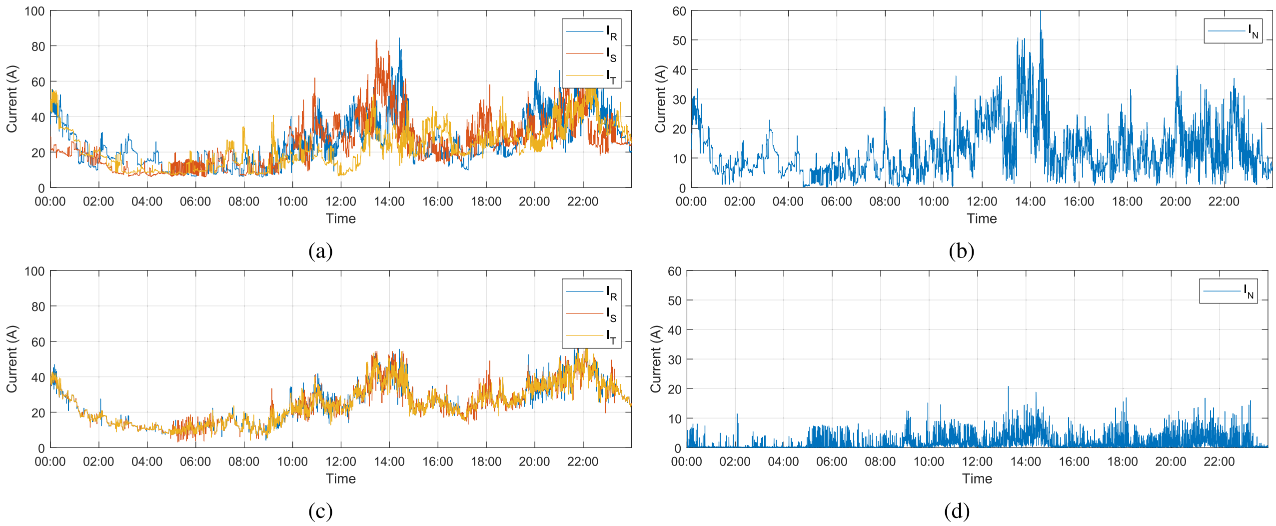

FIGURE 7. Comparison of the current through the wires with and without D-STATCOM: phase currents downstream (a), neutral current downstream (b), phase currents upstream (c), and neutral current upstream (d).

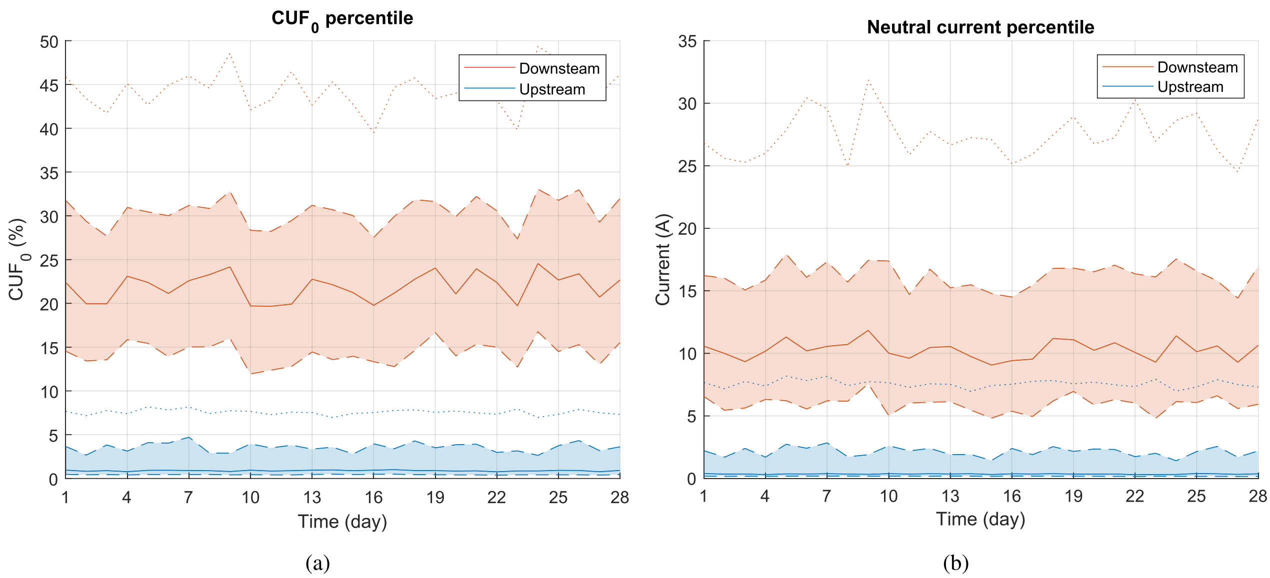

FIGURE 8. Effect of the D-STATCOM on the grid comparing 25th, 50th, 75th and 95th percentiles of CUF_0 (a), and neutral current (b) downstream (orange) and upstream (blue) the D-STATCOM.

TABLE 1. D-STATCOM power losses and efficiency in function of the three-phase output apparent power.

Load (%)	Output power (kVA)	Power losses (W)	Efficiency (%)
5	174	1.96	91.1
10	170	3.56	95.2
20	187	7.03	97.3
30	250	10.54	97.6
50	370	17.54	97.8
60	450	21.03	97.8
75	580	26.28	97.7
90	730	31.53	97.6
100	810	34.68	97.6

point was first analyzed for 24 hours. On the one hand, it can be noted that the imbalances present downstream, mainly in the period 12:00-15:00 and 20:00-1:00 (Fig. 7a), have been eliminated upstream where it can be seen that the currents in the three phases are similar (Fig. 7b). As a result, the RMS current in the period between 13:00 and 15:00 present in the most load cable has been reduced from more than 80 A to less than 60 A. On the other hand, the neutral current has been significantly reduced from conducting tens of amperes most of the day (Fig. 7d) to being virtually unload for the whole day (Fig. 7c). However, total balancing has not been achieved due to three factors: the approximation to the fundamental frequency in the calculation of the references, the delay produced in the communications between the grid analyzer and the D-STATCOM, and the sporadic presence of unbalances higher than the rated power of the prototype.

In order to obtain more significant results, the data analyzed in Fig. 7 has been obtained for a 4-weeks period, from

February 1st to February 28th, 2021. As explained before, the operation of the D-STATCOM proposed in this paper directly acts over current imbalances so that, its results are directly related with CUF. With the information obtained during the 28 days analyzed, the instantaneous values of CUF_0 were calculated and analyzed, obtaining the median of these values and the 25th, 75th and 95th percentiles on a daily basis. The evolution of these results throughout the entire month is shown in Fig. 8a downstream the D-STATCOM in orange, and upstream in blue. The median value is represented by the solid line within the shaded area between 25th and 75th percentiles, whereas the 95th percentile has been represented by the upper dotted lines.

Moreover, as explained above, one of the main consequences and most important benefits of the line balancing is the neutral current reduction. As in the previous case, Fig. 8b shows the 25th, 50th, 75th and 95th percentiles for neutral current upstream and downstream for the 28 days analyzed.

Fig. 8a shows a clear reduction of the CUF_0, where it can be seen that the shaded area has been reduced from the range 15 % – 30 % downstream to 0 % – 2.5 % upstream. Similarly, the maximum values have been reduced from around 45 % to less than 10 %, and the median value of the whole month has dropped from 21.9 % to 0.9 %.

In the same way, the shaded area of the neutral current has been reduced from the range of 5 A – 15 A to 0 A – 2.5 A (see Fig. 8b). In addition, current peaks through the neutral wire have been minimized from more than 25 A to less than 10 A. Thus, the current in the neutral wire has been practically suppressed, decreasing its average value from 10.3 A to 0.4 A.

The power factor (PF) shows the relationship between active power (P) and apparent power (S) in an electric line. It provides information on how optimal the power transmission is, giving a maximum line utilization when $P = S$ and $PF = P/S = 1$; hence, the lower PF the lower line efficiency. However, although the calculation of the PF is trivial in balanced three-phase networks, this does not happen in unbalanced grids. [51] shows, how the different ways of calculating S affect PF and proposes the effective apparent power (S_e). S_e assumes a virtual balanced circuit that has exactly the same line power losses as the actual balanced circuit. This equivalence leads to the definition of an effective current I_e

$$3\, rI_e^2 = r(I_a^2 + I_b^2 + I_c^2 + \rho I_n^2) \tag{7}$$

where r is the line resistance and ρ is the ratio of neutral and line wire resistances. In addition, [51] defines the effective voltage (V_e) so that S_e can be calculated in the same way as in a balanced line

$$S_e = 3V_e I_e \tag{8}$$

leading to the definition of the effective power factor

$$PF_e = \frac{P}{S_e} \tag{9}$$

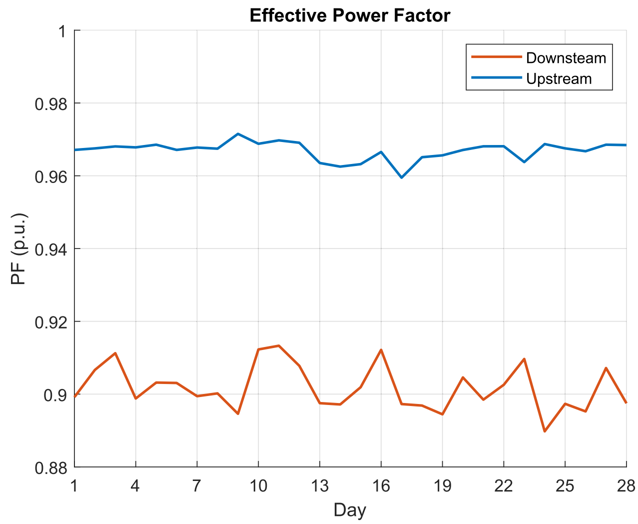

FIGURE 9. Daily average effective power factor downstream (orange) and upstream (blue).

Furthermore, [51] defines PF_e taking into account harmonics generated by non-linear loads. This approximation has been used to calculate the PF_e during the operation of the D-STATCOM. Thus, Fig. 9 shows the daily average PF_e downstream and upstream the power converter, that has been improved from a mean value of 0.901 to 0.967.

As eq. (7) shows, power losses are proportional to the equivalent squared current, so that the reduction in power losses achieved with the D-STATCOM can be calculated as

$$\Delta P(\%) = \frac{3r(I_e^{down})^2 - 3r(I_e^{up})^2}{3r(I_e^{down})^2} \cdot 100 = (1 - \left(\frac{I_e^{up}}{I_e^{down}}\right)^2) \cdot 100 \tag{10}$$

By substituting eq. (8) and (9) in (10), and simplifying V_e and P that must be equal downstream and upstream, the following relationship between power loss reduction and PF_e is reached

$$\Delta P(\%) = (1 - \left(\frac{PF_e^{down}}{PF_e^{up}}\right)^2) \cdot 100 \tag{11}$$

where substituting the PF_e mean values calculated previously a loss reduction of 13 % is obtained.

As discussed above, the VUF is a key parameter regulated by current legislation. Since, unlike current, the function relating voltage and position on the line is continuous, thus, it is impossible to analyze the VUF in the same way as was done for current indicators. For this reason, the DSO has provided phase voltage measurements from a close-located smart meter and the transformer substation, at the line header. The data analyzed correspond to the months of February 2020 (when the D-STATCOM had not yet been installed) and February 2021.

Thus, the measures from both locations and dates have been analyzed to compare the VUF values without and

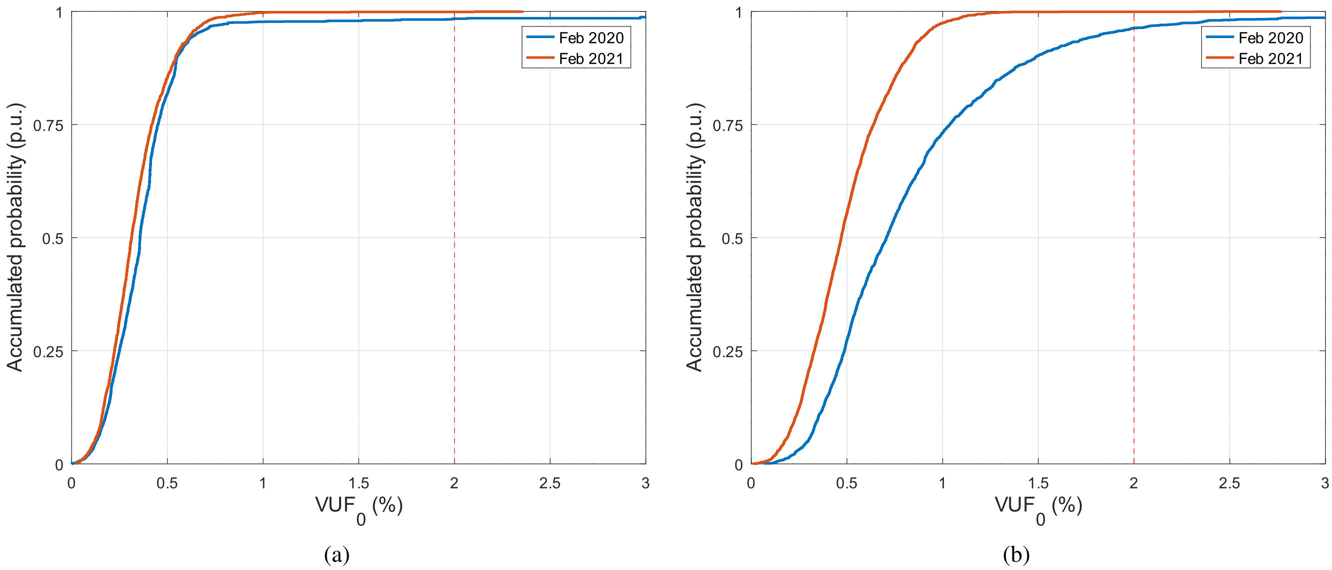

FIGURE 10. Comparison of VUF_0 values with D-STATCOM (February 2021) and without D-STATCOM (February 2020), at the transformer substation (a) and at a consumption point close to the location of the prototype (b).

with D-STATCOM, respectively. Fig. 10a shows the VUF_0 cumulative probability diagram at the transformer substation whereas Fig. 10b shows the same results at near to the D-STATCOM. On the one hand, it can be seen that there are no significant differences between the two years analyzed near to the line header. However, in the influence area of the device, a change in trend between the two years can be seen. The results shown a clear decrease in the time that the network is unbalanced, especially noticeable for unbalance values above 0.5 %. Thus, whereas during February 2020, the VUF value was below 1 % for approximately 75 % of the time, in February 2021, with the D-STATCOM in operation, this value increased to 97 %.

IV. DISCUSSION

The legislation establishes the VUF as a normative parameter to ensure the quality of supply to consumers of the electricity grid. However, this parameter do not represent the totality of the problems caused by imbalances in the network. Therefore, other parameters highlighted in the literature have also been analyzed. First, how the D-STATCOM has contributed to the reduction of CUF_0 on the line has been analyzed. The mean value of the current imbalances has dropped from 21.9 % to 0.9 % during the month under analysis. This reduction will mainly impact in a more balanced voltage drop along the line, and therefore in less unbalance in the supply voltage. Another direct consequence of the reduction of current imbalances has been seen in the reduction of neutral current. This conductor must be sized in its design to withstand the maximum current flowing through it. In this case, the maximum current detected during the period analyzed has been reduced by 77 %, from 30 A to 7 A, which would make it possible to use conductors of smaller cross-section and therefore more economical.

Then, an approximation has been established to determinate the power losses in the line, since these are proportional to the square of the current flowing through the network. This has resulted in a reduction of 13 % in conduction losses. This reduction only occurs on the line where the prototype has been installed and, since a 13 % reduction in losses in a single line are low compared to those of a complete network, these will not result in significant savings. However, this parameter clearly represents how imbalances affect the efficiency of the grid and how the efficiency could be improved if imbalances are faced.

Finally, the VUF_0 has been calculated in the DT and a smart meter near to the D-STATCOM prototype. Although no improvements were observed at the network header, there was a notable reduction in voltage imbalances at the supply points furthest from the DT. Thus, despite the limited data available for this analysis, there is evidence that the D-STATCOM has also contributed to improving the power quality parameters established by legislation.

V. CONCLUSION

The rapid electrification of the power sector is revealing a number of problems that compromise grid stability. This paper has proposed a D-STATCOM for current balancing in low voltage distribution grids. The designed converter has a 4W-4L topology with a switching frequency of 20 kHz, making its operation completely soundless. This prototype achieves a rated power of 35 kVA, which allows a maximum current balancing capacity of 70 A.

The D-STATCOM prototype has been commissioned successfully in a residential area of the city of Malaga (Spain) in order to test its operation in a real environment. The data acquired over a period of one month demonstrates the ability of the unit to decrease neutral current from 30 A to 8 A in the worst case, reduce technical losses by 13 % and improve power quality in the line. The paper has shown how technical losses have been reduced and quantified them, as well as has pointed out at which level the neutral current has been reduced at the installation site.

Furthermore, the proposed solution can be implemented in a wide range of possible three-phase equipment applications such as EV chargers, PV facilities and energy storage systems, adding an interesting extra-functionality to these devices.

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