Practical Demonstration and Novel Optimization Control for a Smart Soft Open Point to Maximize the Synergy between the DC Metro Line and the LV Distribution Grid

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Abstract—The steady increment in electrical loads often requires expensive and disruptive upgrading of the electrical power supply infrastructure. This can be avoided by synergizing the DC railway networks with local AC grids using soft-open points to transfer the available regenerative braking energy of the trains to the nearby local grid. Besides, a battery energy storage system is integrated into the soft-open point to match the braking events with the grid load power. So that the new developed system effectively decouples both the rail and grid networks. This paper presents a practical study for such novel rail-grid energy management strategy. A 100kW smart soft open point is designed and implemented in this research to experimentally evaluate the new strategy in a lab environment using real rail data. Afterwards, the developed 100 kW prototype is accordingly validated in the real environment at Metro Madrid, Spain. Lastly, a multi-objectives optimization framework is designed for the developed management system to maximize the synergy between both networks. The multi-objectives framework aims to minimize the power losses in both networks, maximizing the profit of selling the harvested rail power to the grid and finally maximize the penetration level of the available renewables power in the grid.

Index Terms— DC Railway Network, Electricity Distribution Network, smart Soft Open Point (sSOP), Regenerative Braking Efficiency, Battery Energy Storage System (BESS).

NOMENCLATURE

Abbreviations

BESS Battery Energy Storage System
BMS Battery Management System
DCCB DC Circuit Breaker
DN Distribution Network
DoD Depth of Discharge
DSO Distribution System Operators
ESS Energy Storage Systems
EV Electric Vehicle
GUI Graphical User Interface
HIL Hardware-in-the-loop
LCOE Levelized Cost Of Energy
LCT Low Carbon Technologies
LV Low Voltage
MCCB Modular Case Circuit Breaker
MV Medium Voltage
MDM Metro de Madrid
PE Protective Earth
PV Photovoltaic
PSO Particle Swarm Optimization
R+G Railway + Grid
RES Renewable Energy Resources
SOC State of charge
SOP Soft Open Point
sSOP Smart Soft Open Point
TRL Technology Readiness Level
TCO Total Cost of Ownership

Parameters

\( E_{\text{Braking}} \) Braking energy captured during a testing profile
\( P_{\text{BESS-BMS}} \) Maximum allowable BESS power governed by BMS
\( P_{c} \) Cost of the power selling to LV AC grid from the SOP
\( P_{\text{define}} \) Optimized parameter for the \( P_{GR} \)
\( P_{\text{DN,loss}} \) Power loss in LV AC grid
\( P_{\text{ESS}} \) ESS converter power
\( P_{G} \) Grid converter power
\( P_{GR} \) Resultant power of the LV AC grid
\( P_{\text{Grid-U4}} \) set value for the grid active power
\( P_{L} \) Penetration level of the PV power in LV AC grid
\( P_{\text{load}} \) Load power for the LV AC grid
\( P_{\text{PV}} \) PV power for the LV AC grid
\( P_{\text{tot,loss}} \) Total power loss of the system
\( P_{\text{Rail-U4}} \) set value for the harvested rail power
\( P_{\text{RN,loss}} \) Unused regenerative braking power in metro line
\( P_{\text{SOP,loss}} \) Power losses of SOP converters
\( P_{\text{Rail}} \) Rail converter power
\( V_{\text{Rail}} \) Input voltage to the rail converter
\( V_{\text{sh}} \) Rail voltage setpoint to activate rail converter
\( \eta_{1} \) Efficiency of the sSOP at Rail + ESS operational mode
\( \eta_{2} \) Efficiency of the sSOP at ESS operational mode

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I. INTRODUCTION

Reducing the carbon dioxide emissions and ensuring the environmental sustainability of railway systems as the backbone of transport are becoming a leading global subject matter [1-2]. Recent trends have been developed to integrate the electrified railway networks with different approaches of the low carbon technologies (LCT). The superiorities of such railway networks present in the available regenerative energy produced by the network trains during their braking events. This regenerative braking energy could be utilized in several beneficial ways rather than be dissipated in the onboard or wayside dumping resistors that are employed to protect against the over-voltage in the rail during the braking events of the trains. The regenerative energy can be utilized by the neighboring trains that might be accelerating within the same section as the braking one. However, this involves a high level of uncertainty since there is no guarantee that a train will be accelerating at the same time and location when/where regenerative energy is available. As a result, more effective approaches have been developed by a broad scope of numerous research and industrial projects to reuse of these regenerative braking energies through different forms of synergies with the LCT applications, such as electrified railway networks incorporating reversible (bi-directional) traction substations connected to its medium voltage MV electrical network supplier. For an example, simulation environment has been presented in [3] for the reversible substations to recuperate the regenerative braking energy in rail transit systems. Besides, paper [4] provides comprehensive assessments and evaluations for the reversible substations as a means to return the surplus regenerated energy into the upstream MV AC distribution networks. Other approaches integrate the electrified railway with both energy storage systems (ESS) and reversible substations. A multi-application strategy based on the railway static power conditioner with the ESS is proposed in [5] to improve the economic benefits of the traction system. Research [6] investigates the optimal control of reversible substations and wayside storage for energy savings and voltage stabilization. Comprehensive overviews of the current strategies and technologies for recovery and management of braking energy in urban rail, covering timetable optimization, on-board and wayside ESS as well as the reversible substations, are demonstrated in [7-8]. Integration of the electrified railway with renewable energy resources (RES) and ESS is studied in [9]. Moreover, the inclusion of the electric vehicle (EV) charging stations within electric railway systems have also been investigated in the literature [10] for the DC metro lines and [11-12] for the AC high-speed railways. Nevertheless, in all the literatures, the synergy approaches between the electrified railway networks with the low voltage (LV) distribution grid are not explored yet.

Both LV distribution grids and light-railway networks present common issues: both have been developed as independent networks, relying on the resilience and robustness of existing power supplies. Furthermore, they both are looking at integrated solutions targeting: i) reduction of electricity losses, ii) accommodate the needs of new energy actors such as EVs, electrical storages and prosumers, and iii) increase the grid stability in a high local RES penetration scenario, especially RES progressive penetration introduced an increasing degree of uncertainty on the direction of power flows. As a result, electrified transport networks such as light railways could act to enhance distribution grid stability providing ancillary services inter-exchanging electricity. Nevertheless, such potential is still unexploited. The E-LOBSTER project [13] captures such potential through the development of an innovative transport-grid inter-connection system that is able to establish synergies between electrified transport, LV distribution networks, local RES and charging stations for EVs. The solution encompasses the integration of soft open point (SOP), back-to-back power electronic converters, with ESS to develop a smart soft open point (sSOP). The system is managed by an integrated railway + grid (R+G) management system to be able to promote the interexchange of electricity between both networks along with elevate the local RES self-consumption. This research paper presents the final stage of such innovative project to demonstrate and validate the software control algorithms along with the hardware prototype implementation at the technology readiness level (TRL) 6 in one of the substations of Metro de Madrid, Spain.

The benefits of SOP application in distribution power network have already been studied in the literature [14]. The applications of the SOP in the active distribution networks are employed to improve the system voltage regulation in [15-16] as well as to provide active management for the unbalanced distribution networks in [17]. On the other hand, the application of SOP between railway and grid has not been investigated yet in the recent research works. Accordingly, the developed sSOP in this project presents a new engineering solution to connect a DC railway network to an AC LV distribution grid through a battery energy storage system (BESS) and advanced power converters. The BESS operates as a shared asset to increase the power transfer compatibility between both networks in spite of their different dynamic characteristics.

In our previous work throughout the project, different architectures of sSOP to interface between the two networks have been investigated in [18] as well as the localization and sizing studies for the developed sSOP have been provided in [19]. Furthermore, simulation of two metro lines from Metro de Madrid have been demonstrated in [20] which shows that regenerative braking energy efficiency significantly increases by implementing sSOP in the metro lines and the recovered energy was able to support LV distribution grid to accommodate the EV integration. Afterwards, the proposed sSOP has been fully assessed through a simulation environment in paper [21].

In view of that, this new paper presents the practical validation phase of such innovative project. A 100kW sSOP is designed and implemented in this new paper. The sSOP comprises of three back-to-back power electronic converters to create the SOP between the two networks along with the BESS. Furthermore, novel optimization framework has been developed in this paper to maximize the synergies between the DC railway network and the local LV AC distribution grid.
Consequently, the research work in this paper targets to

1) Develop a 100kW sSOP and practically validate its capability to identify the braking events in the railway network by just monitoring the rail line voltage as well as validate its effectiveness in raising the local consumption of the RES in the local AC grid.

2) Design a multi-objectives optimization framework to maximize the synergies between the DC railway network and the local AC distribution grid.

The validation of the first target is passed through two successive stages in this paper as follow:

1.1 Hardware-in-the-loop lab environment. The developed sSOP is firstly validated in a lab environment at the Smart Energy Lab of Newcastle University, UK. A real local AC grid connection 400V/400A is utilized in the lab, which is supplied from Northern Power Grid, the distribution system operators (DSO) in northeast of UK. On the other hand, the rail network is modeled by a Rail Emulator which is “REGATRON” a bidirectional modular DC power supply with a total power of 128 kW.

1.2 DC metro line real environment. The developed sSOP is then validated in a real environment with an actual metro line of SACEDAL traction power substation in line 9 of Madrid Metro (MDM), Spain. While the 400 V grid connection is provided in this condition from the AC local power distribution grid of MDM which possesses a stable robust 15kV/400V AC network to feed the various facilities/services AC loads of the metro substations.

Regarding the optimization framework target, it has been validated through the following objective functions:

2.1 Minimization of the power losses in both the DC railway network and the local distribution AC grid.

2.2 Maximization of the profit of selling the harvested rail braking power to the AC grid.

2.3 Maximization of the penetration of the RES existing in the local AC grid by employing the BESS of the sSOP.

Accordingly, this paper is organized as follows: Section II thoroughly demonstrates the developed sSOP in this paper; its design, structure, control management system as well as its protection features. Then, the validation of the objectives of the developed sSOP at the lab environment is fully provided and discussed in section III. After that, section IV practically evaluates the developed sSOP objectives in the real metro line site. Next, the whole multi-objectives optimization framework has been represented and validated in section V. Lastly, the paper conclusions and final discussions are deliberated in section VI.

![Fig.1 Representation of the innovations of the paper along with its main objectives and their validations](image)

II. SMART SOFT OPEN POINT

The architecture of the proposed sSOP in this research is demonstrated in Fig.2. This novel 3-terminals power-electronic-based sSOP is used to interface the LV local distribution grid with the DC railway electrification network. This allows a unique management of the energy between traction substations and distribution network. The proposed sSOP comprises the following main systems:

A. Soft Open Point (SOP)

The SOP system includes three back-to-back power electronic converters as follows:

a) Rail converter: DC/DC converter with unidirectional isolated topology, so that the power flows only from the rail to BESS and LV grid not the vice versa. It also includes high frequency isolation transformer to limit the rail transients penetrating to the DC Link of the SOP and break the earth fault loop.

b) BESS converter: DC/DC converter with bidirectional non-isolated buck-boost interleaved topology, so the BESS is charging/discharging through this converter based on the rail and grid operating conditions.

c) Grid converter: DC/AC converter with bidirectional isolated topology, so the power flow is either from the SOP to the local grid (when the grid requires a support to supply its demands) OR from the grid to the SOP (when the grid has an excess of the generated electric energy from its RES). The converter has an isolation transformer (delta/star grounded) to galvanically isolate the DC system from the AC system and provide local protective earth (PE) point to the SOP.

The sSOP has been designed originally to undertake up to 200 kW. So, rail converter and ESS converter have been designed and developed with 200kW power rating.
However, the grid converter is designed to be limited only to 100kVA due to the restrictions set by the DSO on the amount of power injected to their LV AC grids from the local connected distributed generation systems. To design the SOP converters and analyze their operational and control behaviors, the PLECS power electronics simulation platform is employed for such purposes given that it comprises comprehensive modelling components cover electrical, magnetic, thermal, and mechanical aspects of power conversion systems and their controls. Moreover, real-time voltage measurements of the metro line under study at the SANCEDAL substation of MDM have been utilized as input to this simulation platform for the rail converter.

The nominal voltage of the DC traction at SANCEDAL substation is 600V and its operating values varies from 512V to 724V based on the running trains. Therefore, the rail converter is designed and controlled to have an output fixed voltage of 750 V for the SOP common DC bus with a current rating up to 266 A to fulfill the power rating requirements of the developed sSOP. Similar voltage and current ratings have also been assigned to the ESS converter as one of its two terminals is directly connected to the SOP common DC bus. Furthermore, this DC bus is also occupied with 1000V-2000uF capacitors banks to maintain the DC bus voltage constant and steady during the variations of the input rail voltage as well as at different power flows and demands of the system.

### B. Energy Storage system (ESS)

A battery system is designed for the ESS. The BESS comes with battery management system (BMS), which is responsible for battery cells temperature and voltage monitoring, cells balancing, charge/discharge management, cells diagnosis and data management. The BESS is also of 200 kW power rating as the SOP. As a result, to fulfill the power requirements, three Li-ion battery-racks are connected in parallel in the BESS of the developed sSOP. Each rack has a voltage level between 620 V - 750V with ampere-hour capacity of 87 A. That leads to having a total of 175 kWh BESS for the developed sSOP. For the selection of its storage technology, the manufacturer has performed comparisons between lead acid, Li-ion, NiMH and supercapacitors with respect to the application system rating as well as their parameters including: their capital and maintenance costs, charging and discharge efficiencies, cycle and calendar lifetimes, depth of discharge (DoD), and self-discharge. As a result, the Li-ion technology was designated for the developed sSOP since it offers the lowest total cost of ESS ownership (TCO) as well as the lowest levelized cost of energy (LCOE) among other types of storage technologies. The design specifications of the three converters along with the BESS are summarized in Table I.

### C. R+G management system

The R+G management system provides a unique framework for real-time energy flow management between rail and grid through the BESS. It is aiming at a multi-objectives task in both energy networks to lessen the braking losses in the railway network as well as elevate the self-consumption of RES in the distribution grid through smart charging / discharging management strategies of the BESS.

In this concept the R+G management strategy has been designed in this research to dispatch energy amongst the three SOP terminals: grid, railway, and BESS by switching intelligently between the following three operational modes:

**A. Rail + ESS mode:** Rail provides the available regenerative braking power to BESS and LV grid, if the LV grid requires power. However, if there is an excess of power in the LV grid from its local RES, both rail and grid charge the BESS.

**B. Grid mode:** Grid provides the available regenerative braking power to BESS and LV rail, if the rail grid requires power.

**C. Rail mode:** Rail provides the available regenerative braking power to LV rail, if the LV grid requires power.

### Table I – Design specifications for the developed sSOP

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Design Specifications</th>
</tr>
</thead>
</table>
| Rail converter | Power: 200 kW  
Output fixed DC voltage: 750 V  
Maximum output DC current: 266 A |
| ESS converter | Power: 200 kW  
Input fixed DC voltage: 750 V  
Maximum Input DC current: 266 A |
| Grid converter | Power: 100 kVA  
Output fixed line-to-line AC voltage: 400 V  
Maximum output AC current: 144 A at unity power factor |
| BESS | Technology: Li-ion  
Power: 200kW  
Energy: 175 kWh |
B. Rail only mode: BESS converter is disabled, and the available regenerative braking power is supplied to the LV grid only, if required, otherwise there is no power transfer through the SOP.

C. ESS only mode: Rail converter is disabled, and the power is exchanged between BESS and LV grid depending on the consumption and generation power levels in the grid side. In this condition, there is no braking power is harvested. Accordingly, at Rail and ESS mode, once rail voltage $V_{rail}$ is greater or equal to $V_{th}$ (set-point to activate rail converter), the set braking power from rail network ($P_{Rail-Ud}$) will be transferred to BESS and grid, if the grid needs. The ESS converter will aim then to balance the input/output powers of the SOP. However, if $V_{rail}$ is less than $V_{th}$, the power will be only exchanging between the BESS and grid to either charging/discharging the BESS from/to the grid. The latter condition is the same as ESS only mode when the power is only transferred between the grid and BESS terminals. Finally, for the Rail only mode, the regenerative braking power acquired from the railway network will be limited to the demanded grid power ($P_{Grid-Ud}$) and will be activated only when the $V_{rail}$ is greater than or equal to $V_{th}$. Otherwise, the powers of the rail and the grid converters are set to zero.

Regarding the chosen structure of the proposed sSOP, research [18] has compared the performance of the proposed sSOP of this project with and without the ESS converter. If the ESS converter is not included, the sSOP becomes two-terminal system where the BESS will be connected directly across the SOP common DC bus. The voltage of this DC bus won’t be then at a fixed value since it will be varied depending on the state of charge of the mounted BESS across the DC bus. It is demonstrated in [18] that the two-terminal SOP offers less power losses and lower cost with respect to the three-terminal SOP. However, the direct connection of the BESS across the common DC bus will allow the high frequency current components, generated by the SOP converters, to be taken up mainly by the BESS, which will contribute to increase its charging/discharging cycles and eventually reduce its lifetime. Moreover, as a variable voltage input to the inverter of the SOP, this will make its control more complicated to fulfill the desired charging/discharging cycles and eventually reduce its lifetime. Besides, The sSOP is galvanically isolated on the rail terminal and grid terminal to break the earth loop.

III. DEMONSTRATION OF PROTOTYPE IN SMART ENERGY LAB AT NEWCASTLE UNIVERSITY

The connection schematic of the sSOP demonstrator as well as its test bed in the smart energy lab at Newcastle University is illustrated in Fig.3, where the three-back-to-back converters of the SOP are supplied by Turbo Power Systems-UK, the three Lithium-ion modular batteries are supplied by Lithium Balance-Denmark, and the industrial PC for R+G management system is provided by RINA-Italy. The LV grid 400V/400A is a physical grid connection in the lab supplied from Northern Power Grid, while the rail network is emulated through a rail emulator supplied by Newcastle University, UK. In this test bed, a bidirectional high power DC supply REGATRON is used to emulate the rail behavior. Four single devices have been connected in matrix configuration to provide in total 128kW, 1000VDC and 160ADC.

The electrical energy consumption in DC electrified trains is very irregular because they can change rapidly their state from motoring/accelerating mode at one instant to braking mode at the following instant. Such behavior indicates the impact of the train motion on the common DC bus voltage in railway line. Accordingly, it is very crucial to study and investigate the $V_{th}$ value for the common DC bus voltage which identifies the initiation of braking events in nearby trains and consequently activates the rail converter of the sSOP.

Real-time voltage measurements of the metro line under study at the SACEDAL substation of MDM have been imported to the rail emulator to replicate the real metro environment in the smart energy lab at Newcastle University. These measurements are sampled every 100 msec for a 24-hour period. For the 24-hour measured data, it has been found that the voltage of the common DC bus of the MDM line under study (of nominal value of 600 V) reaches its maximum value at 724 V, and its minimum value at 515 V, with average of 650 V. The rail emulator replays the recorded data in 100 msec sampling time and three tests (15 minutes each) have been conducted at different $V_{th}$ (665V, 660V, and 655V) to activate the rail converter. Meanwhile, all the three tests have the same demanded rail power ($P_{Rail-Ud}$ =50 kW). Table II summarizes a comparison between the energy captured during the identified braking events ($E_{Braking}$) throughout the three tested cases. Certainly, with lower $V_{th}$, more energy will be captured for the same rail power limit $P_{Rail-Ud}$. This emphasizes the importance on selection of $V_{th}$ which is mainly dependent on the metro line’s nominal voltage, power demand, and time schedule.
TABLE II- Accumulated braking energy versus different $V_{th}$

<table>
<thead>
<tr>
<th>Threshold Voltage (V)</th>
<th>$E_{\text{Braking}}$ (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>665</td>
<td>0.148</td>
</tr>
<tr>
<td>660</td>
<td>0.187</td>
</tr>
<tr>
<td>655</td>
<td>0.271</td>
</tr>
</tbody>
</table>

Another aspect to validate in this test bed, is to evaluate the capability of the proposed sSOP to support the local LV grid by raising its local consumption from its RES. Consequently, the developed sSOP of this project has been evaluated when the LV grid has an excess of power generated from its local RES. The parameters of this testing condition are chosen as $V_{th}$ equals 665 V, $P_{\text{Rail-Ud}}$ equals 50 kW, and $P_{\text{Grid-Ud}}$ equals (–30 kW). The negative sign indicates that the LV grid has an excess of 30 kW to inject to the sSOP. Fig. 4 shows the BESS power at this testing condition. So, during no braking in the rail side, the excess 30 kW from grid is used to charge the BESS. Once braking is identified, both rail and grid powers join to charge the BESS with approximately a total of 80 kW. The offsets between the expected power values for BESS and its measured values in Fig. 4 is due to the sSOP power losses consumptions. Given that there are various timetable schedules for trains running in the MDM metro line under study, eight 30-minutes rail voltage profiles have been extracted from the real-time measurements at various timetables to evaluate the sSOP prototype at the Newcastle University lab. The periods of the eight profiles are given in Table III. Throughout these eight testing profiles, the $V_{th}$ setpoint is selected to be 665V, while the $P_{\text{Rail-Ud}}$ demanded rail power is set to be at 50 kW.

The accumulated braking energy ($E_{\text{Braking}}$) captured during the 30-minutes profiles has been calculated and provided in Table II as well. The difference between the $E_{\text{Braking}}$ in the eight rail voltage profiles reveals the impact of trains timetable schedule on $E_{\text{Braking}}$ despite of the same harvested $P_{\text{Rail-Ud}}$ is set for the eight testing conditions. Fig.5 illustrates the boxplots of the real-time rail voltage measurements of the metro line under study for the eight testing profiles along with their associated $E_{\text{Braking}}$.

TABLE III- The eight testing profiles at the Newcastle University lab.

<table>
<thead>
<tr>
<th>Profile</th>
<th>Period</th>
<th>$E_{\text{Braking}}$ (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>06:05 to 06:35</td>
<td>0.316</td>
</tr>
<tr>
<td>Profile 2</td>
<td>06:35 to 07:05</td>
<td>0.425</td>
</tr>
<tr>
<td>Profile 3</td>
<td>07:00 to 07:30</td>
<td>0.344</td>
</tr>
<tr>
<td>Profile 4</td>
<td>07:30 to 08:00</td>
<td>0.293</td>
</tr>
<tr>
<td>Profile 5</td>
<td>14:30 to 15:00</td>
<td>0.623</td>
</tr>
<tr>
<td>Profile 6</td>
<td>21:00 to 21:30</td>
<td>0.445</td>
</tr>
<tr>
<td>Profile 7</td>
<td>23:00 to 24:00</td>
<td>0.462</td>
</tr>
<tr>
<td>Profile 8</td>
<td>01:30 to 02:00</td>
<td>0.562</td>
</tr>
</tbody>
</table>

Fig. 5 Boxplot of the real-time measurements of $V_{\text{Rail}}$ versus the harvested $E_{\text{Braking}}$ for the eight testing profiles at the Newcastle University lab.

Fig. 3. sSOP demonstrator at Newcastle University; (a) Connection schematic (b) Test bed
From Fig. 5 and Table III, it is shown that at the on-peak timetable periods, the rail voltage of the metro line is decreased since more trains are running on the line during these times. This is reflected on the morning profiles (i.e., 1 to 4) as they have shorter headways between their trains that lead to reduce their rail voltages. For an example of profile 4, the median of the rail voltage is at 645.4V with voltage range between [588.7V to 695.4V] excluding the outliers. This eventually leads to lower harvested $E_{Braking}$ of 0.293 kWh during such period. On the contrary, with longer headways at the off-peak periods in the afternoon and evening profiles, less trains are running on the line, which enables the rail voltage to increase beyond its morning values as shown in profiles 5 to 8. So, at profile 5 for an example, the median of the rail voltage is reached 655.7V with a voltage range between [605.9V to 702.8V] excluding the outliers. This accordingly results in higher $E_{Braking}$ of 0.623 kWh during profile 5 period.

Nevertheless, it is worth to mention that there were two main challenges been experienced during the sSOP evaluation at the Newcastle University hardware-in-the-loop (HIL) lab environment. These two challenges were considering 1) the malfunction of the initial communication architecture of the developed sSOP and 2) the frequent tripping of the rail emulator during harvesting the braking energy. Such challenges highlight the necessity of HIL testing stage for the proposed sSOP demonstrator in the Newcastle University lab prior to directly validating the sSOP at the real MDM testing field. Since, in the lab environment, the flexibility to modify and improve the functionality of the developed sSOP is much less problematic than performing that in the metro station. The details of these two challenges and the process to resolve them at the Newcastle University lab are provided as follows:

1. The first proposal of the Modbus TCP/IP communication architecture for the developed sSOP has been designed to set the control card of the battery management system (BMS) for the BESS to be as a slave to the control card of the SOP converters. At the same time, the SOP control card is operating as a slave to the main R+G management system of the whole sSOP. However, it has been found that the control card of the SOP was not able to process all data from the BMS and even some of transferred data between BMS and sSOP have been lost during the operation of the whole system. Accordingly, such communication architecture has been modified to overcome this challenge by assigning both the control cards of the BMS and SOP to be as slaves to the R+G management system which will be the master control as well as the main congregator of the measurements data of the whole system.

2. During the sSOP demonstrator testing at the Newcastle University lab, it was observed that the high current demand pulses of rail converter during the initiation of the braking events force the rail emulator to trip more frequently especially if the requested current goes beyond 100A. This is due to insufficient capacity of the rail emulator to cope with such rapid variations with high power demands. As a result, three capacitors have been added in parallel at the output of the rail emulator to compensate such limitation. The three paralleled capacitors with total capacitance of 2.1mF were providing 240 A to support the rail emulator during such high-power transient demands. On the other hand, such limitation would not be reflected in testing the sSOP demonstrator at the MDM field site, given that the DC traction substation is already designed with high power to cope with the high-power fast-transient traction demands.

IV. TESTING sSOP PROTOTYPE AT METRO DE MADRID

Single line diagram of sSOP connection in SACEDAL traction power substation of line 9 at MDM is demonstrated in Fig. 6-a. The substation is fed through two 15 kV AC lines from the DSO. A common 600V DC bus is generated at the output of the transformers-rectifiers units to supply the metro trains. Besides, a LV AC grid is existed within the metro substation to feed the substation AC loads including elevators, fans, air conditioning, etc. The input to the rail converter of the developed sSOP is directly attached to the common 600V DC bus through a DC traction cabinet in the substation. While the output of the sSOP grid converter is connected through the isolation transformer to the LV 400V grid of the MDM station. Such test bed is illustrated in Fig. 6-b.

Regarding the nominated location of the proposed sSOP in the MDM network, research [19] provides a detailed optimization study for the localization of the proposed sSOP within the MDM metro line in order to maximize the recuperation of the regenerative braking energy from the line under study at different headways through the day. The selection of the optimal location is mainly dependent on the specifications and architecture connection of the metro line under study as well as the selected trains’ timetables. It is demonstrated in [19] that there is no need to install several sSOP substations at the traction power substation of the line, but a suitable choice of the location is sufficient to maximize the aggregated braking energy efficiency for the line.

Several testing scenarios have been carried out at the SACEDAL substation to verify the sSOP performance at different operational and power conditions. The sSOP have been evaluated at $P_{Rail-UD}$ (ranges from 20 kW to 100 kW), $P_{Grid-UD}$ (10 kW and -10 kW), and $V_{th}$ (652V, 655V, and 675V). An example of these tests is provided in Table IV. The $P_{Rail-UD}$ are set to be 50 kW at these three tests. For test A, the $P_{Grid-UD}$ is +10kW which indicates the LV grid will receive 10 kW from the sSOP (resembling the LV grid demands more power to its loads). While for the tests B and C, the $P_{Grid-UD}$ is –10 kW which refers to transfer 10 kW from the LV grid into the sSOP to be stored in its BESS (resembling the LV grid have excess of power from its RES).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Values</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test A</td>
<td>Test B</td>
<td>Test C</td>
</tr>
<tr>
<td>$V_{th}$</td>
<td>655 V</td>
<td>652 V</td>
<td>657 V</td>
</tr>
<tr>
<td>$P_{Rail-UD}$</td>
<td>50 kW</td>
<td>50 kW</td>
<td>50 kW</td>
</tr>
<tr>
<td>$P_{Grid-UD}$</td>
<td>+10 kW</td>
<td>-10 kW</td>
<td>-10 kW</td>
</tr>
<tr>
<td>$E_{Braking}$</td>
<td>0.16 kWh</td>
<td>0.19 kWh</td>
<td>0.06 kWh</td>
</tr>
</tbody>
</table>

TABLE IV- Testing parameters at three testing scenarios at SACEDAL substation
Fig. 6 sSOP connection in SACEDAL substation of MDM (a) Single line diagram (b) Test bed

Fig. 7 Example of the testing results for the sSOP at SACEDAL substation when (a) $V_{th} = 655V$, (b) $V_{th} = 652V$, and (c) $V_{th} = 657V$
A maximum of 10 kW for grid power is restricted in these testing due to the regulations of the DSO MV distribution network supplying the MDM substations.

Figure 7 (a to c) shows the resultant $P_{\text{Rail}}, P_{\text{ESS}}$ and $P_{\text{G}}$ through the sSOP versus the variation of the common DC bus voltage $V_{\text{Rail}}$ input to the rail converter of the sSOP. As shown in Table IV along with Fig. 7, the $V_{\text{th}}$ in the MDM field tests have been chosen to be between 652V-657V which is at lower values than those selected for the demonstrator testing at Newcastle University. This is essentially dependent on the rail DC bus voltage behaviors with respect to the traction loads for the metro line under study. Additionally, with the studies that carried out in previous work [19-21], it is shown that the braking events in such metro line last for 15-30 seconds. According to that, with $V_{\text{th}}$ equals to 657 V as in Fig.7(c), small number of braking events have been identified at which the rail converter is activated ($P_{\text{Rail}} > 0$). Therefore, choosing $V_{\text{th}}$ more than 657 V for this MDM line would lead to nearly deactivate the rail converter for the whole operational time and lose all the regenerative braking power within the rail network. On the other hand, with $V_{\text{th}}$ equal to 652V, a lot of short periods (2-5 seconds) have been identified as braking events ($P_{\text{Rail}} > 0$), but there was no braking at such short times. As a result, $V_{\text{th}}$ at 655V as shown in Fig. 7-a becomes more relevant to represent the initiation of braking event at such line. Nevertheless, Table III also presents the accumulated rail energy through sSOP during these three 15-minutes testing scenarios, which are within the same range of those acquired during the demonstrator testing at Newcastle university given in Table II.

A continuous testing has also implemented for the sSOP demonstrator at MDM site, in which seven 15-minutes testing profiles have been carried out in sequence starting from 9:10 am to 11:55 am. The seven profiles are listed in Table-V, where all profiles have the same set-point $V_{\text{th}}$ at 655V, but the $P_{\text{Rail,UD}}$ is increased throughout the seven profiles from 20 kW to 80 kW in step of 10 kW. Fig. 8 demonstrates the boxplot of the $V_{\text{Rail}}$ real-time measurements of the seven testing profiles as well as its harvested $E_{\text{Braking}}$. Accordingly, Fig. 8 along with Table V illustrate the impact of the $P_{\text{Rail,UD}}$ on the harvested $E_{\text{Braking}}$. As expected, more $P_{\text{Rail,UD}}$ is resulting in more harvested $E_{\text{Braking}}$ as a general trend from the seven testing profiles. However, another factor is also influencing on the $E_{\text{Braking}}$ values which is the timing of the testing.

![Fig. 8 Boxplot of the real-time measurements of $V_{\text{Rail}}$ versus the harvested $E_{\text{Braking}}$ for the seven profiles at the MDM site](image)

For an example, profile 5 has the highest $E_{\text{Braking}}$ even though its $P_{\text{Rail,UD}}$ is at 60 kW lower than those of profile 6 and 7, but it has the higher $V_{\text{Rail}}$ values with a median 651 V and voltage range [634-666] excluding the outliers. This leads to initiate more braking events to harvest the $E_{\text{Braking}}$ than those in profiles 6 and 7. Similarly, profile 2 ($P_{\text{Rail,UD}}=30kW$) comparing to profile 3 ($P_{\text{Rail,UD}}=40kW$), profile 2 has higher $E_{\text{Braking}}$ since its $V_{\text{th}}$ has the higher values than those in profile 3. $V_{\text{th}}$ has the median of 651 at profile 2 with voltage range between [634V to 666V] excluding the outliers, while $V_{\text{th}}$ has the median of 649 at profile 3 with a voltage range between [630V to 666V] excluding the outliers. Moreover, the performance of the developed sSOP demonstrator is also evaluated during these seven testing profiles. During these testing profiles, $P_{\text{Grid,UD}}$ has set to be 10 kW. Consequently, during the braking events $P_{\text{Rail}}$ supports the grid side with 10 kW and the remainder of the power is utilized to charge the BESS (i.e. the Rail + ESS operational mode). While at no braking, the BESS is then discharged in the grid side with the requested 10 kW (i.e. the ESS operational mode). In view of that, the performance of the sSOP demonstrator is evaluated during these seven testing profiles by measuring the average of its power efficiencies at these two operational modes. Fig. 9 illustrates the average power efficiencies of the sSOP at (Rail + ESS operational mode) in blue line and (the ESS operational mode) in orange line.

![Fig. 9 Efficiencies $\eta_1$ and $\eta_2$ through the 7 testing profiles of the sSOP at MDM site](image)

**TABLE V- The seven testing profiles at the MDM site.**

<table>
<thead>
<tr>
<th>Profile</th>
<th>Period</th>
<th>$P_{\text{Rail,UD}}$ (kW)</th>
<th>$E_{\text{Braking}}$ (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile 1</td>
<td>09:10 to 09:25</td>
<td>20</td>
<td>0.07</td>
</tr>
<tr>
<td>Profile 2</td>
<td>09:25 to 09:40</td>
<td>30</td>
<td>0.14</td>
</tr>
<tr>
<td>Profile 3</td>
<td>09:40 to 09:55</td>
<td>40</td>
<td>0.12</td>
</tr>
<tr>
<td>Profile 4</td>
<td>09:55 to 10:10</td>
<td>50</td>
<td>0.17</td>
</tr>
<tr>
<td>Profile 5</td>
<td>10:10 to 10:25</td>
<td>60</td>
<td>0.33</td>
</tr>
<tr>
<td>Profile 6</td>
<td>10:25 to 10:40</td>
<td>70</td>
<td>0.29</td>
</tr>
<tr>
<td>Profile 7</td>
<td>10:40 to 11:55</td>
<td>80</td>
<td>0.31</td>
</tr>
</tbody>
</table>
Efficiency (\(\eta_1\)) at Rail + ESS operational mode is evaluated as follows:

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_{\text{ESS}} + P_G}{P_{\text{Rail}}} \tag{1}
\]

while, at ESS operational mode, the efficiency (\(\eta_2\)) is calculated as:

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_G}{P_{\text{ESS}}} \tag{2}
\]

Although more power losses are involved in Rail+ESS operational mode since the three converters are running, \(\eta_1\) is always greater than \(\eta_2\). This is due to the following:

Given that, as the set-point for the power increases, the output power increases and also with higher ratio than the slight increase in the converters’ power losses. This is because the switching losses in converters are mainly fixed independently of the increase in the output power. Provided that the SOP converters are operating at 20 kHz switching frequency, their switching losses become dominant over the conduction losses particularly for these SI IGBT converter types operating at switching frequencies > 5 kHz [22]. As a result, the ratio of the power losses to the output power will decrease with the increase of the output power. This leads eventually to raise the efficiency with the increase of the output power \(P_{\text{out}}\). Such correlation can be represented as follows:

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{losses}}} = \frac{1}{1 + R} = \frac{1}{1 + \frac{P_{\text{losses}}}{P_{\text{out}}}} \tag{3}
\]

So, as \(P_{\text{out}}\) increases, \(R\) decreases, which leads to increase the whole efficiency \(\eta\). Accordingly, since the desired set-point powers in Rail+ESS operational mode is \(P_{\text{rail, UD}}\) (varies from 20 kW to 80 kW in steps of 10 kW), and it is always higher than set-powers in ESS mode, \(P_{\text{ESS}} = 10\ kW\). As a result, \(\eta_1\) is always greater than \(\eta_2\). For the same reason, \(\eta_1\) is also mostly increasing through the seven profiles with the increase of the \(P_{\text{rail, UD}}\). However, other factors are still impacting the efficiency and the harvested \(E_{\text{Braking}}\) such as the testing timing and \(V_{\text{rail}}\) values as discussed previously for Fig. 7.

On the other hand, the general trend of \(\eta_1\) is also increasing through the seven profiles despite it has almost the same set-point power \(P_{\text{ESS}}\). This is fundamentally due to the SOC of the BESS which is increasing through the seven testing profiles. The raise in the SOC of the BESS is leading to the decrease of the BESS power losses during the discharging of the BESS into the grid side [23]. The SOC profile is illustrated through the testing profiles along with the \(P_{\text{rail}}\) in Fig. 10. There are also slight divergences in the \(\eta_1\) and \(\eta_2\) from their expected trends due to the influences form the outliers’ measurements.

Another validating test set is demonstrated in Fig. 11 for the sSOP at SACHEDAL substation. Table VI shows the parameters of such test, where \(P_{\text{rail}}\) is set to be up to 100kW. Besides, a constrain is applied on the \(P_{\text{ESS}}\) to be not greater than 80 kW. Such power limit represents the \(P_{\text{BSS-BMS}}\) to derate the BESS charging/discharging power if overtemperature or overvoltage faults could occur within the battery cells beyond such power value.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Parameters & Values \\
\hline
\(V_{\text{th}}\) & 655 V \\
\(P_{\text{rail, UD}}\) & 100 kW \\
\(P_{\text{grid, UD}}\) & \(+10\ kW\) \\
\(P_{\text{BSS-BMS}}\) & 80 kW \\
\hline
\end{tabular}
\caption{Testing parameters at 100kW rail power}
\end{table}

Fig. 10 SOC of the BESS through the seven testing profiles along with the harvested \(P_{\text{rail}}\)

As demonstrated in Fig. 11, once there is a braking event on the metro line, \(V_{\text{rail}}\) becomes equal or greater than \(V_{\text{th}}\). So, the rail converter is activated and the \(P_{\text{rail}}\) is transferred from rail side into the sSOP. Portion of this power is injected into the grid side as \(P_G\) and the remaining power is used to charge the BESS through the \(P_{\text{ESS}}\) (negative \(P_{\text{ESS}}\) means the BESS is charging).

Fig. 11 Testing the sSOP at SACHEDAL substation when \(P_{\text{rail, UD}} = 100\ kW\)
However, since $P_{ESS}$ is limited only to 80 kW the $P_G$ then has to be increased over $P_{Grid-Ud}$ to cover the remaining of $P_{Rail}$ as illustrated within the dotted red circles. The MDM LV grid will be able to consume locally such rises in $P_G$ within these short intervals without transferring them to the DSO MV distribution network. On the other hand, if there is no braking event, the $V_{Rail}$ becomes less than $V_{th}$, and the rail converter is deactivated. As a result, the sSOP becomes operating in the ESS only mode, where the ESS converter is discharging the BESS into the grid with $P_G$ (where; $P_{ESS} \approx P_G \approx 10$ kW). Similarly, a positive $P_{ESS}$ means the BESS is discharging. The input rail energy along with SOC of the BESS during such 15-minutes test are plotted in Fig 12. It is shown that a total energy of 0.52 kWh is accumulated during such test with an increase of 3.5% in the BESS SOC.

![Accumulated rail energy and BESS SOC](image)

Fig. 12 Accumulated rail energy and BESS SOC when $P_{Rail-Ud} = 100$kW

Accordingly, upscaling the rating power of the developed sSOP to the metro train power of 2.4 MW and operating it for the 20-hours service of such line per day, the sSOP will be able to harvest up to 998.4 kWh daily. Even though such estimated values are reliant on trains different time-schedules, but it still validates the effectiveness and significance of such innovative solution.

V. MULTI-OBJECTIVES OPTIMIZED SYNERGY FRAMEWORK BETWEEN THE DC RAILWAY NETWORK WITH THE LV AC LOCAL GRID

Eventually, a novel optimized control strategy is demonstrated in this section for the proposed sSOP of this paper. The new optimization strategy aims to minimize the total energy losses in both networks, maximize the penetration of the RES in the AC grid as well as the profit to sell the harvested rail power to the grid.

A. Basic system structure with its control strategy

The novel optimization framework has been developed and evaluated for a typical DC metro line and a LV AC grid as illustrated in Fig. 13. The DC metro line has three train stations with two traction power substations. While the LV AC grid contains several feeders equipped with 11/0.4 kV 500 kVA distribution transformer to connect with the MV AC grid [24]. The domestic households in the LV AC grid are equipped with a rooftop solar photovoltaic distributed generation (PVDG) of 5.75 kW each [24-25].

The implemented control process used for the optimization strategy is shown in Fig. 14. Firstly, the system data (power profile of PV and household load, metro operational information) is loaded into the control process. The resultant power of the LV AC grid ($P_{GR}$) is set as the controlled parameter, which is the difference between its total generated PV power ($P_{PV}$) and its demanded household power ($P_{load}$). If $P_{GR}$ is larger than a pre-defined value ($P_{define}$), both the sSOP along with the MV AC grid will support the LV grid. The sSOP will support the LV grid with the power difference between the $P_{GR}$ and the $P_{define}$. This supporting power ($P_G$) will be feeding from both the BESS through the ESS converter ($P_{ESS}$) as well as the regenerative braking power ($P_{RBE}$) through the rail converter ($P_{Rail}$). On the other hand, if the $P_{GR}$ is lower than zero (i.e. $P_{PV}$ is greater than $P_{load}$), The ESS will be then charged by the excess of the PV powers along with the $P_{RBE}$ from the metro line. Finally, when $P_{GR}$ is larger than zero but lower than the $P_{define}$, there will be no power exchange between SOP and LV grid. The ESS will be only charged by the $P_{RBE}$. While the LV grid will be only supported by the MV grid.

![Basic system structure](image)

Fig. 13 Basic system structure
Accordingly, The value of $P_{\text{define}}$ is crucial to determine the system work state. Thus, this value will be then the optimized parameter in the developed optimization framework of this paper.

**B. Multi-objectives optimization framework**

The multi-objectives function is set as minimizing $f$, where $f$ is defined as follows:

$$f = W_1 \sum P_{\text{tot loss}} + W_2 / P_L + W_3 / PC$$

(1)

$$PL = \frac{\sum_{k=1}^{n} P_{\text{RES_used},k}}{\sum_{k=1}^{n} P_{\text{RES_total},k}}$$

(11)

where $P_{\text{RES_used}}$ is the power of PV which has been consumed in the system, $P_{\text{RES_total}}$ is the total rated power of PV.

The PC is calculated by (12), where $C$ is the price of power sold from SOP to the LV AC grid.

$$PC = CP_{\text{RN, C}}$$

(12)

The variable which needs to be optimized is $P_{\text{define}}$, and it has various optimal results for different periods according to the load demand of LV grid.

The Particle Swarm Optimization (PSO) algorithm is applied in this paper to solve the multi-objective function. The PSO has been widely used in parameter optimization problem [26-27], and it can meet the speed and accuracy requirement. In PSO, a particle swarm with $M$ particles is randomly generated in an $N$-dimensional space. Each vector particle position of $k$-th iteration $X_k^i = [X_1^k, \ldots]$ represents a potential solution of the problem. The process of each particle moving is consisted of updating velocity and position based on local optimal position $P_k^i$ and global optimal position $G_k^i$, formulated by:

$$V_k^i = \chi [V_k^{i-1} + c_1 r_1 (P_k^i - X_k^i) + c_2 r_2 (G_k^i - X_k^i)]$$

(13)

$$X_k^i = X_k^{i-1} + V_k^i$$

(14)

where $c_1$, $c_2$ are learning constants; $r_1$, $r_2$ are the vector of random numbers in the range of [0, 1]. $\chi$ is the constriction factor to limit the velocity oscillation:

$$\chi = \frac{2}{2 - c - \sqrt{c^2 - 4c}}$$

(15)

**C. Case study**

1) Parameter setting

The case study is conducted based on the system structure shown in Fig.13. The LV AC grid model considered in this study has three feeders (F1, F2, and F3) supplying different numbers of households. It includes one 400 V substation with an 11/0.4 kV transformer. This network serves 275 single-phase domestic households, and 160 households are equipped with a single-phase PVDG with the maximum power of 5.75 kW. The operation time of trains in metro line is set from 6:00 to 23:00. The price of electricity from SOP sold to AC LV grid is 0.2 GBP/kWh. Detailed parameters of the metro line, the ESS, and AC LV grid are shown in tables VII, VIII, and IX respectively.

**TABLE VII- Metro line parameters**

<table>
<thead>
<tr>
<th>Length</th>
<th>1750 m</th>
<th>Headway</th>
<th>5 mins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail line resistance</td>
<td>0.016</td>
<td>Substation resistance</td>
<td>0.0161</td>
</tr>
</tbody>
</table>

**TABLE VIII- ESS parameters**

<table>
<thead>
<tr>
<th>ESS power</th>
<th>0.8 MW</th>
<th>ESS Capacity</th>
<th>3 MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC max</td>
<td>0.9</td>
<td>SOC min</td>
<td>0.2</td>
</tr>
</tbody>
</table>
TABLE IX- AC LV grid parameters

<table>
<thead>
<tr>
<th>Line resistance (R_{line})</th>
<th>0.016 Ω/km</th>
<th>Transformer resistance (R_{Trans})</th>
<th>0.0161 Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1 household percentage of total consumption</td>
<td>40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2 household percentage of total consumption</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3 household percentage of total consumption</td>
<td>30%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The result of single train operation is illustrated in Fig. 15. The load demand and PV power of LV AC grid under study are shown in Fig. 16. The total power demand of house is around 400 kW from 0:00 to 15:00. Then, it increases from 0:00 to 15:00, with a peak value of 1.1 MW. The PV power is rising from 6:00 to 11:00, and then it decreases to zero gradually at 20:00.

During 8:00 to 17:00, the PV power becomes larger than the LV grid load power. Thus, the household load is now fully supported by PV power, and ESS is charged by extra PV power and P_{R_{Rail}}.

After 17:00, the LV grid load power is rising significantly with a peak value of 1.1 MW, and the P_{define} has been optimized to P_{define 2} (i.e. 590 kW). The P_{ESS} and P_{R_{Rail}} are injected to P_{G} through SOP till around 23:00.

Finally, intervals from 16:00 to 17:00 and from 23:00 to 24:00 the LV AC grid becomes supported only by the MV AC grid since P_{GR} is less than P_{define 2}.

### Table X- Optimized result

<table>
<thead>
<tr>
<th>Variable Period</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{define 1} 00:00-15:00</td>
<td>60 kW</td>
</tr>
<tr>
<td>P_{define 2} 15:00-24:00</td>
<td>590 kW</td>
</tr>
</tbody>
</table>

2) Results and analysis

Based on the optimal results for the system under study, the outcomes of the developed optimized control strategy are demonstrated in this subsection. Fig. 17 illustrates the power of SOP converters. From 00:00 to 6:00, the rail converter is not operating, the ESS is discharging to LV grid through SOP given that P_{GR} is greater than P_{define 1} (i.e 60 kW). From 6:00 to 8:00, the metro line operates and P_{R_{Rail}} collaborates with the ESS discharge power (P_{ESS}) to support the P_{G}.

The power and SOC of ESS is shown in Fig 18. From 00:00 to 8:00, the ESS is discharging, and its SOC is decreasing. Then, the ESS is charged to the maximum value. When load demand is increasing, the ESS discharge power is rising at the same time till its SOC is close to the minimal value.

The LV grid power from the upstream MV grid is illustrated in Fig. 19 with and without the SOP implementation. Before the implementation of the SOP, the LV grid power has the peak power of 427 kW during 0:00 to 15:00, and 1.1MW during 15:00 to 24:00. Besides, during 8:00 to 14:00, the extra PV power which cannot be consumed in LV grid, is injected to the MV upstream grid. After applying the SOP, the peak power of two periods is limited to 60 kW and 590 kW respectively. When PV power is larger than load demand, this grid power is kept as zero, as this extra PV power is stored in the ESS of the SOP.
The detailed comparison between system with and without SOP is shown in Table XI. Before applying SOP, the total grid energy consumption is up to 8696.2 kWh, which has been reduced to 4898.5 kWh when SOP is equipped. Besides, the peak power of grid has been reduced by SOP. In metro line, the power losses are decreased significantly from 1816.5 kWh to 1173.8 kWh. In LV grid, the energy loss has been reduced by SOP as well, from 854.3 kWh to 300.2 kWh. The PV power can be fully consumed in the whole system, without feeding back to the MV grid. Accordingly, the proposed SOP system along with its novel optimized control strategy can efficiently reduce the demanded peak power from the MV grid to the LV grid, as well as maximize the utilization rate of RES in LV grid and minimize the power losses in both LV grid and metro line networks. Lastly, SOP can gain a benefit of 759.5 GBP per day.

**TABLE XI - Comparison of system with and without SOP**

<table>
<thead>
<tr>
<th></th>
<th>Without SOP</th>
<th>With SOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation 2 energy(kWh)</td>
<td>6477.1</td>
<td>6477.1</td>
</tr>
<tr>
<td>Grid energy(kWh)</td>
<td>8696.2</td>
<td>4898.5</td>
</tr>
<tr>
<td>Total PV energy(kWh)</td>
<td>6135.3</td>
<td>6135.3</td>
</tr>
<tr>
<td>Total RBE(kWh)</td>
<td>3752.2</td>
<td>3752.2</td>
</tr>
<tr>
<td>Actual use of RBE(kWh)</td>
<td>1935.7</td>
<td>2578.4</td>
</tr>
<tr>
<td>Efficiency of RBE</td>
<td>51.6%</td>
<td>68.7%</td>
</tr>
<tr>
<td>RBE loss(kWh)</td>
<td>1816.5</td>
<td>1173.8</td>
</tr>
<tr>
<td>Energy loss in SOP(kWh)</td>
<td>\</td>
<td>1100.1</td>
</tr>
<tr>
<td>Energy loss in LV grid (kWh)</td>
<td>854.3</td>
<td>300.2</td>
</tr>
<tr>
<td>Total energy loss(kWh)</td>
<td>2670.8</td>
<td>2574.1</td>
</tr>
<tr>
<td>*PL*</td>
<td>78.5%</td>
<td>100%</td>
</tr>
<tr>
<td>*PC*(GBP)</td>
<td>\</td>
<td>759.5</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

A novel sSOP has been presented in this paper to resolve the challenges of two distinct networks of different dynamics; the DC metro lines and the LV AC grids. Recently, with the high progression of the EV charging stations and the installed RES systems within LV grids, many of such grids become unable to cope with these new LCT approaches since they disturb the LV grid’s stability and resilience. In view of that, the new proposed sSOP provides resolutions for such issues.

The proposed sSOP succeeds to diminish the power losses in the DC metro lines by harvesting their braking regenerative power to store it into the BESS as well as inject it to the interconnected LV AC grid. At the same time, such injected power is used to support the LV grid to cope with its increasing loads demand. Additionally, if there is an excess of power in such LV grid from its local installed RES, the BESS of the sSOP can also be used to store such power in order to utilize it again within the LV grid when need, rather than transferring this power to the upper stream MV distribution networks. This results in elevating the local consumption of the RES in this LV grid. The 100 kW sSOP in this research has been evaluated and validated at two different test beds: i) through a hardware-in-the-loop lab environment at Newcastle University, UK, and ii) through a real DC metro line environment at MDM, Spain. In both test beds, different $F_{\text{in}}$ voltage levels have been investigated to properly indicate the initiation of the braking events on the metro line. Furthermore, the sSOP have been tested at different grid power flow directions to resemble the grid conditions when it requires power or has an excess of power. Furthermore, the developed R+G management system for the sSOP has been validated to control the whole system along with fulfilling any power constraints such as $P_{\text{ESS-RBE}}$ limit. Eventually, by upscaling the proposed sSOP to the metro train power, around 1 MWh can be acquired daily form the metro line. This will be greatly significant to support the interconnected LV AC grid and highly reduce its power consumption from its upper stream MV distribution network. Furthermore, a novel optimization control strategy has also been developed for the proposed sSOP in this paper. The optimization strategy aims to minimize the power losses in both the LV grid and DC metro networks, maximize the local utilization of the RES in the LV grid and eventually maximize the profit to sell the harvested RBE to the LV AC grid. It has been demonstrated that by implementing the sSOP in a typical DC metro line with LV local AC grid, the total daily energy losses in whole system have been decreased from 2671 kWh to 2574 kWh, the local utilization of the RES in the LV grid increased from 78.5% to 100%, and the demanded daily energy from the MV grid to the LV grid decreases from 8696 kWh to 4898 kWh. Finally, a daily profit of 759.5 GBP has been attained due to sell the RBE from metro line to the LV grid.

REFERENCES


