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Smart mobility integration in port microgrids with a Multi-Agent control system - POSEIDON

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Abstract —The European Commission's actions for a more sustainable future lead to a significant change in the power system, particularly in electricity production from renewables, energy efficiency, and polluting emission reduction in the transport sector. The distribution system has to host energy production from renewables, and new high consumption loads, e.g., battery charging for e-mobility and smarter solutions are necessary. The POSEIDON project aims at defining optimal control strategies of microgrids in the port areas, including the management of electric vehicles with public charging stations, energy storage systems installed on boats, flexible loads, and Renewable Energy Sources (RES). The paper presents the impact of the vehicle-to-grid (V2G) and boat-to-grid (B2G) on a port microgrid. A Multi-Agent control system developed for the optimal charging of batteries is also presented. Results derived by applying the methodology to a real case study demonstrate the methodology's effectiveness.

Keywords — *Port Microgrid, Energy Storage System, Smart mobility, Boat-to-Grid, Multi-Agent System*

I. INTRODUCTION

The European Commission (EC) outlined the European Green Deal (EGD), rooted in raising the emissions reduction target to 50%. The EU, through the EDG, defined investments and innovations focused on decarbonizing the energy sector, making buildings more energy-efficient, increasing cleaner forms of transport, and supporting greater sustainability in industry, among other objectives. Of course, such strategies must be fair (i.e., preventing inequalities in costs and benefits distribution) and involve all countries, regions, and individuals. At least € 1 trillion over a decade has been mobilized to reach these goals [1].

The UN defined the 17 Sustainable Development Goals (SDGs) to end extreme poverty, reduce inequality, and protect the planet by 2030. Such actions cover different aspects of social, economic, and industrial (energy efficiency, innovation) [2]. All these actions do not only aim at reducing polluting emissions but also water and soil contamination. For instance, port activities could cause many external economic costs associated with congestion, waste management, land degradation, light, and visual intrusion. At the same time, they connect maritime and land transport networks, playing a critical role in mitigating the effects of climate change.

In Italy, the interventions on sustainable infrastructures, mobility, and logistics contained in the *National Recovery and Resilience Plan* (NRRP), recently approved by the EC, amount to a total of 62 billion euros, including investments for green revolution and ecological transition, and the development of ports, logistics, and maritime transport, to pursue different objectives, including environmental sustainability, the energy efficiency of ports and land and sea accessibility [3].

Indeed, commercial and touristic ports have berths and widespread services on the quay, such as lifting systems (cranes), slides, and electricity supply. In addition, the massive presence of boats leads to considerable energy consumption, which could also be subjected to seasonality, especially for marinas. Such actions have not been seen as a limit but as a way to improve efficiency, create new economies (circular economy), and jobs (future-proof jobs and skills training for the transition) with an ad-hoc fund to support the change.

In this context, it arises the need for a change in the port power systems. Thanks to the new funds, several ports can adapt their system to reduce their footprint by increasing the electrification of the final consumption, increasing the energy efficiency, and producing energy from RES to satisfy the internal consumption and sell the energy surplus outside.

In addition, EGD and SDG give particular attention to sustainable cities and communities. Indeed, the cooperation between different entities belonging to the same environment (city, neighborhood, commercial activity) can increase the income of the Distribution Energy Resources (DERs) owner, through the participation to the flexibility market, selling their flexibility to the System Operator (Transmission or Distribution system). Of course, different DERs with different technologies and needs must be represented on the market through an Aggregator, a middleman that knows its portfolio of resources and can obtain the best price without compromising the quality of service of the network DERs are connected.

The POSEIDON project perfectly fits with these missions [4]. It deals with microgrids (MGs) in the port to favor a greater diffusion and integration of energy production from non-programmable RES (wind and photovoltaic power plants) with sustainable electric mobility due to the presence of recharging infrastructures for both electric vehicles and boats equipped with onboard energy storage systems and electric propulsion systems. In particular, the project is focused on the definition of optimal control strategies of MGs in port areas for the management of Electric Vehicles (EVs) with public charging stations, in coordination with energy storage systems on boats, flexible loads, and RES production. Moreover, the project will consider highly integrated hybrid energy storage systems for boats, providing multiple services to the port MG, according to the boat-to-grid (B2G) paradigm, thus determining economic benefits for the owner of the boats and the MG operator.

The POSEIDON project's reference context is the island of Sardinia – Italy: 53 ports, both commercial and tourist type, most accounting for more than 100 berths and a widespread presence of services (e.g., lifting systems, slides, and

electricity supply). Most of the ports are predisposed to adapt their electrical system to enable port MGs. The massive presence of boats leads to considerable energy consumption, which is subjected to seasonality, especially for marinas. The POSEIDON project investigates the operation of MGs and the bidirectional energy exchange with the onboard electrical energy storage systems installed on boats. In particular, the paper aims to show how highly integrated energy storage systems for boats could impact the port MG and proposes an optimal control strategy by using a Multi-Agent System (MAS). The examples refer to the port of "Marina di Capitana", which is the project pilot site in the South of Sardinia (Fig. 1).



Fig. 1. Port of Marina di Capitana – Sardinia (IT).

The paper is organized as follows: in Section II, the port microgrid and the available distributed energy resources are described; in Section III, the MAS exploitation for proper management of the available resources is presented. Then, in Section IV, a case study focused on a real port is shown. Final remarks close the paper.

II. DISTRIBUTED ENERGY SOURCES IN THE PORT MG

The exploitation of RES power plants could be possible with a natural evolution of the electrical systems into a power demand area as a microsystem. In addition to the direct use of RES, the port area's energy efficiency can be enhanced by coordinating flexible demand and the increase of electric transport within it. The operation of all the electrical systems as a unique advanced grid is fundamental for the port areas to achieve high quality and continuity of service, energy saves, and costs reduction [4].

The POSEIDON project aims at defining the optimal control strategies of different energy resources available in the MG port area [5]. Commonly, an MG is built to have enough power capacity to meet the local load demand. Therefore, MG can be operated as a self-sufficient energy system that interacts with the grid or in autonomous islanded mode if properly managed. Besides the generation sources, Energy Storage Systems (ESS) are also integrated into an MG for ensuring the load balance in real-time. The most common for MG applications are electrochemical batteries. More recently, the development of V2G systems promotes the adoption of electric vehicles as mobile energy storage systems. Similarly, the POSEIDON project aims at using boat chargers (BC) for exploiting B2G successfully, e.g., for frequency control of isolated port MGs.

The main components of the port MGs included in the POSEIDON project are:

- PV power plants and wind generators to obtain an adequate level of energy production and self-consumption.
- flexible loads, such as offices, shops, and industrial customers.
- Electric Vehicles Charging Infrastructures allows the unidirectional power flow in AC or DC mode, depending on the power rate (generally 22 kW and 50 kW, respectively).
- Boat Charging Infrastructure, to coordinate onboard energy storage systems according to the B2G paradigm.

III. MULTI-AGENT SYSTEM (MAS) CONTROL

The Literature proposes different techniques for DER management, with two main classes: centralized and decentralized approach [6]. The first approach is characterized by a central controller that decides the controlled resources' operating points to avoid network operation issues (e.g., overvoltage, undervoltage, overcurrent) at the minimum cost. On the contrary, the decentralized approach is up to the single resource its own strategy definition, considering internal and external limits. The choice between the two technologies depends on the time scale, type and number of resources involved, or resources' location. In the presence of many resources characterized by different technical limits and behavior, as in LV distribution networks, decentralized systems offer great scalability, reliability, and resiliency.

In the proposed model, the MG operation's core is the central controller (MGCC) able to coordinate the DERs: DG, controllable loads, EV/ESS, and BC charge and discharge. The MGCC has to consider different time scales depending on the element/component to be controlled [7]. For the mentioned advantages offered by the decentralized systems, as great scalability, reliability, and resiliency, in this paper, a distributed control system based on MAS is proposed for managing the resources in an MG. Among the distributed control techniques, MAS is one of the most common, thanks to the agent's characteristics (reactivity, proactiveness, and social ability) that make it capable of reacting to environmental changes, exhibit goal-oriented behavior, and interacting with other intelligent agents [8].

Different Agents, acting at local and global levels, are considered. All contribute to the network voltage regulation, modifying the expected active power profile (i.e., consumption, production, charging/discharging) of the DERs. The local Agents (i.e., Active Demand - AD, Distributed generation - DG, EV, and DES Agent) perform a local optimization based on local and global information to maximize their own benefit without degrading power quality and stability [9]. The AD Agent acts at a local level and can manage the behavior of one or a group of active customers that give their availability to modify their consumption according to the Agent's request. The DG Agent is the local Agent that regulates the active and reactive power injected by the generators in the MG. It is worth noticing that one local Agent can behave contemporarily as an AD or DG Agent by optimizing both DG and controllable loads that belong to his portfolio. This feature is typical for the DES Agents (as well as EV agents and BC Agents) that regulate the charging and discharging profile of the controlled storage systems, taking into account both battery characteristics (e.g.,

charging/discharging efficiency, energy capacity) and users' needs. The DG and ESS Agents can also control the reactive power exchange [10], for contributing to the Volt/Var regulation, according to the Italian technical rules for DG connection in LV networks [11]. Moreover, to consider the possibility that active customers do not satisfy the AD Agent request and recover part of the curtailed demand at a later time, causing unforeseen imbalances in the system, the payback effect is taken into account, according to the model proposed in [12] -[13].

Only one Agent acts at a global level, the Master Agent, and its role matches the role of MGCC. The local Agents communicate directly with the Master Agent through vertical communication without exchanging information between the agents (horizontal communication). The Master Agent supervises the activities of the local Agents. It broadcasts the data necessary to perform the local optimizations (i.e., electrical quantities, the energy price, etc.), gathers the results, and requires new optimizations until an optimal stable solution is reached, without imposing any setpoint.

A. Proposed procedure

More in detail, the flow chart of the proposed MAS control is shown in Fig. 2. At each k th iteration, every N local Agent receives the voltage threshold from the Master Agent (i.e., the MGCC) and a limited number of other global information (e.g., the energy price). Each i -th Agent optimizes its strategy for the whole day by solving a constrained quadratic minimization and sends the results to the MGCC [8]. The Agent strategy aims at minimizing the Objective Function (OF), subject to technical constraints and DER owner needs (more details are provided in section B). Once the Master Agent has received the locally optimum patterns from all Agents, if the convergence criterium is not met, it sends again to the Agents the relevant voltage and the necessary data to start a new local optimization. The result of this iterative optimization process is the coordination of DERs to obtain a global optimum. The convergence of the procedure is assured if (i) the maximum number of iterations reached or (ii) the difference between the results of one iteration and the next one is smaller than a pre-defined threshold.

It is worth to notice that the proposed methodology is a day-ahead optimization, based on predictive models and suitable for studying the potential development strategies of the port network.

B. Local Agents' strategy

1) OF

The Agent aims at minimizing the OF described in (1):

$$\min J_i(P_i, P_{-i}) = \sum_{t=0}^{T-1} \{p(t, P_t) \cdot P_i(t) + \delta \cdot [P_i(t) - \text{avg}(P_t)]^2\} \quad (1)$$

where $p(t, P_t) = f\left(\frac{D(t) + \sum_{i=1}^N P_i(t)}{P_{tr}}\right)$ is a virtual cost function; $P_t(t) = \sum_{i=1}^N P_i(t)$ is the sum of the power contributions $P_i(t)$ of the i -th ($i=1, \dots, N$) Agent; N is the number of the local Agents; $D(t)$ is the contribution to the forecasted demand at the MV/LV transformer of the not controlled customers (i.e., the ones that not participate in the network operation), at time t ; P_{tr} is the nominal power of the MV/LV transformer; $\text{avg}(P_t)$ is the average of the power controlled by the Agents, and δ is a tracking parameter with non-negative constant value crucial for Nash's equilibrium,

which links the individual behavior of the agent to the social behavior.

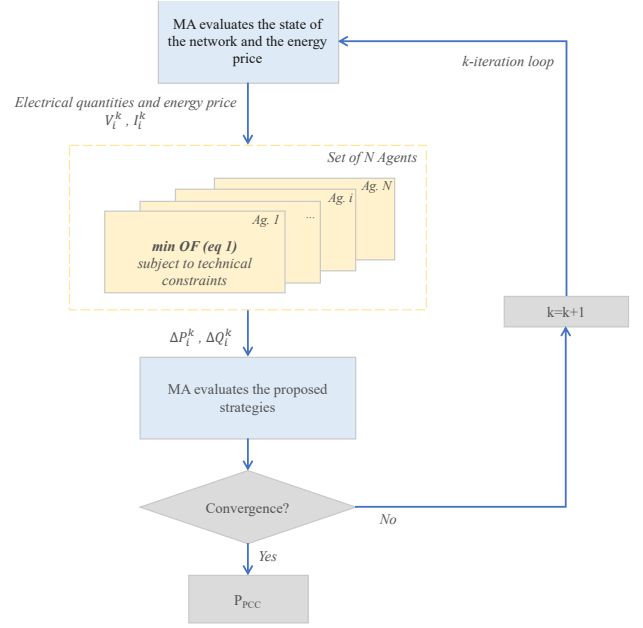


Fig. 2. Flow chart of the MAS control.

The first term of the OF (1) is the virtual cost of purchasing energy from the system that increases in the peak hours; the second term of (1) avoids the risk that all Agents moving far from the peak will create a new undesired peak in another hour. Indeed, each Agent tries to maximize its own benefit, but the deviation from the mean behavior is a cost that guides the global optimization to the global (system) optimum.

2) Constraints

The local minimization is subject to network technical constraints on nodal voltage, cable thermal limit, and DERs technical limits (e.g., battery capacity, PV size, inverter capability curve). DER owners' needs (e.g., amount of curtailable power, willingness to participate in the AD program, final SoC of the battery, end of charging session) are also problem constraints.

The voltage constraint is described by equation (2):

$$\begin{cases} V_{\min F\varphi}^{(k-1)} + [s_{Vp,i} \cdot (P_i^{(k)} - P_i^{(k-1)}) + s_{Vq,i} \cdot (Q_i^{(k)} - Q_i^{(k-1)})] \geq \frac{(V_n - V_{TH})}{KC} \\ V_{\max F\varphi}^{(k-1)} + [s_{Vp,i} \cdot (P_i^{(k)} - P_i^{(k-1)}) + s_{Vq,i} \cdot (Q_i^{(k)} - Q_i^{(k-1)})] \leq \frac{(V_n + V_{TH})}{KC} \end{cases} \quad (2)$$

Where:

- $V_{\min F\varphi}^{(k-1)}$ and $V_{\max F\varphi}^{(k-1)}$ are the minimum and maximum voltage in the phase of the feeder in which the agent is located,
- $s_{Vp,i}$ and $s_{Vq,i}$ are the coefficient of sensitivity of nodal voltage with respect to the $P_i^{(k)}$ and $Q_i^{(k)}$ exchanged power. The sensitivity coefficients – the elements of the Jacobian matrix of the load flow equations – are used in the paper to linearize the relationship between the nodal voltages and the nodal power injections so that constraints remain linear [13];
- $P_i^{(k)}$ and $Q_i^{(k)}$ are the active and reactive power exchanged by the i -th agent at the k iteration
- V_n is the network nominal voltage

- V_{TH} is the voltage threshold
- KC is a coefficient that allows considering the "pro quota" participation of each Agent to improve the voltage by assuming that each Agent can be responsible for its rated power capacity. The role of KC is fundamental since all loads in the network cause voltage variations. But, when a single Agent performs the local mono-dimensional optimization, the unique control variable is represented by the Agent's controlled power, which might not be enough to improve voltage regulation.

IV. CASE STUDY

The proposed methodology has been applied to the POSEIDON project pilot, the touristic port Marina di Caputana (Fig. 3). The port is constituted of 15 piers with 460 boat berths (boat lengths 4÷27 m), 85 charging services in piers, one gas station, maintenance and storage yard, and some service structures (bar/restaurant/offices).

The LV network consists of 112 nodes supplied by one 400 kVA 20/0.4 kV transformer and disposed of nine feeders of different lengths (mostly small cross-section ABC cable for a total extension of about 5.2 km). The first feeder (F_1) is committed to the port services structures. The second and the third feeder (F_2 and F_3) are dedicated to the lighting system. The BCs are located from feeder F_4 to feeder F_9. Two PV generators (16.5 and 14.8 kWp) are connected to the network at the end of feeder F_1.

Different scenarios have been analyzed to evaluate the impact of the penetration of the energy storage systems for boat integration in the port microgrid, particularly the effect of the charging pattern. In the project, three scenarios of BCs spread have been considered (see Table I): the base scenario, with 11 BCs, the medium scenario with 32 BCs, the high scenario with 49 BCs. Six different types of BCs are considered, with different maximum power (from 3 kW to 12 kW), capacity (from 3 kWh to 150 kWh), and connection type: single-phase (SF) or three-phase (TF). Their location in the three scenarios is shown in Fig. 3. It is supposed that each boat charger BC is controlled by an Agent capable of exploiting B2G service. In addition, in all the scenarios, it is also supposed to have two V2G chargers (10kW-25kWh) controlled by one Agent each. In order to stress the methodology in the worst cases, the scenarios are compared considering a critical summer day in which all the boats arrive and leave the port at the same time with the same state of charge, while the two EV chargers (10kW-25kWh) are used from 10 pm to 7 am, and from 10 am to 6 pm.

A. Base scenario

An uncontrolled charge at boat arrival in the port (dumb charging) determines voltage drops that last more than 3 hours, mostly in feeders F_6 and F_7. On the contrary, smart charging through the MAS control avoids any contingency. Fig. 4 shows the MAS global strategy (power exchanged between the agents controlling the BC and the V2G and the network): with the dumb charge (orange bars), the power absorbed is high immediately after the boats' berthing, while with the smart control (yellow bars), the charging is spread during berthing time to avoid voltage violation and cable overloading. Finally, the grey bars represent the MAS strategy without considering the network's technical constraints (on nodal voltage and cable thermal limits). Fig. 5 shows the

voltage profile of one of the most critical nodes under different charging strategies (a dumb strategy with the orange line, without control with the grey line, and considering the technical limits with the orange one). Load demand without considering the network technical limits causes voltage drops in some network nodes.

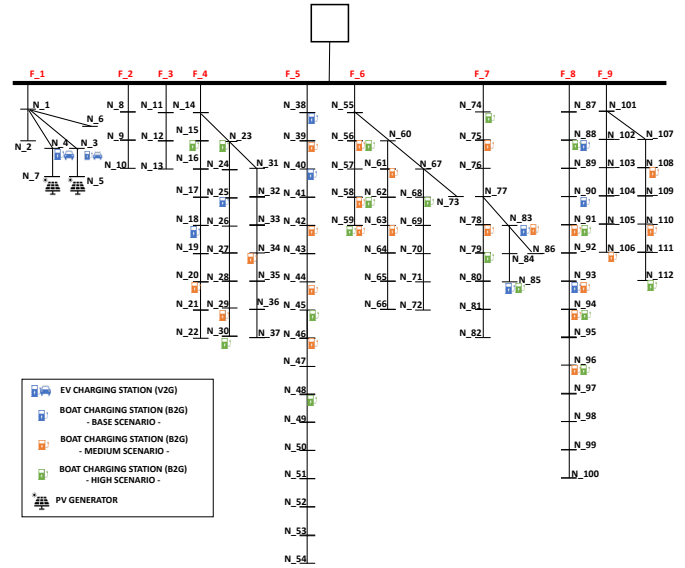


Fig. 3. Representation of the network.

TABLE I - B2G TYPES DISTRIBUTION IN THE FEEDER

Scenario	P [kW]	3	3	7	7	12	12	TOT
	E [kWh]	3	22	10	100	15	150	
	type	SF	SF	TF	TF	TF	TF	
Base	F 4	0	1	1	0	0	0	2
	F 5	0	0	0	2	0	0	2
	F 6	0	2	0	0	0	0	2
	F 7	0	2	0	0	0	0	2
	F 8	0	0	0	2	1	0	3
Medium	F 4	1	2	3	0	0	0	6
	F 5	0	0	0	6	0	0	6
	F 6	0	2	0	3	0	0	5
	F 7	0	3	1	1	0	0	5
	F 8	0	0	0	5	1	1	7
High	F 4	1	4	3	0	0	0	8
	F 5	0	0	0	9	0	0	9
	F 6	0	3	0	6	0	0	6
	F 7	0	4	2	2	0	0	8
	F 8	0	0	0	8	1	2	11
	F 9	0	4	0	0	0	0	4

SF: single-phase TF: three-phase

B. Medium scenario

In the case of a dumb charging strategy, the increased number of boats to be charged determines a voltage decrease in all the nodes of feeder F_5 and F_6 during the berthing time and for more than 2 hours in F_7. The voltage is below the threshold also in the last two nodes of feeder F_8. The unconstrained smart charge (i.e., considering only the virtual energy price and the customers' needs) would allow the complete charging of the boats without satisfying the voltage threshold in most of the nodes of feeder F_5 and F_6. On the contrary, if the networks' limits are considered, some boats berthed in feeder F_5 and F_6 cannot be charged. At the same time, the support provided by the B2G exploitation allows the

full recharge of all the berthed boats in feeder F₇, while without B2G, only one of them is charged.

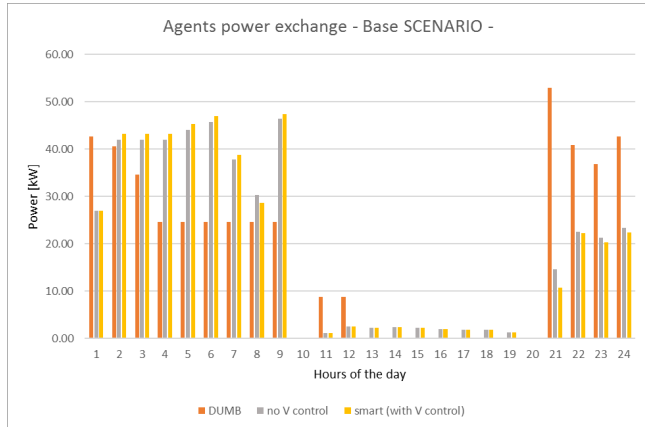


Fig. 4. The power exchange between the network and BC, VC in the base scenario considering the dumb charging, the smart charging (without voltage control), and the constrained smart charging.

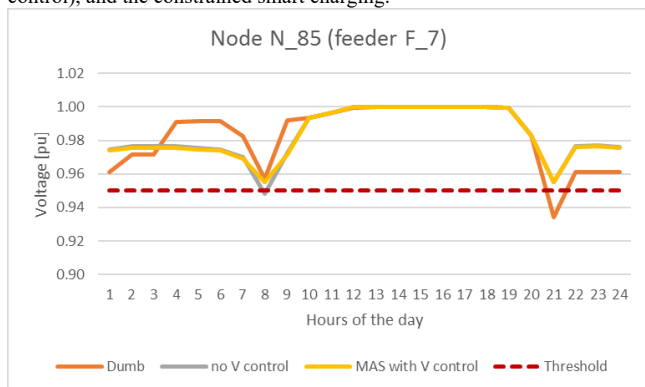


Fig. 5. Voltage profile in one of the nodes of the network, considering different charging strategies.

Fig. 6 shows the exchanged power by the Agents on Feeder F₇. The blue and the orange bars represent the exchanged power by the BC on node N₇₅ exploiting the B2G functionalities and without using it, respectively. It is worth to notice that the exploitation of the B2G functionalities (blue bar) allows the total recharging of the other BCs located in the same feeder (grey line), that is not possible without B2G operation; the yellow line represents the total load demand in the feeder.

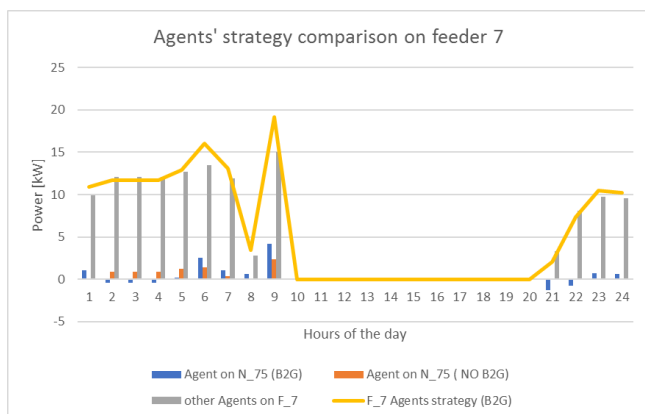


Fig. 6. Comparison of the power exchange in feeder F₇.

However, since even the exploitation of the B2G does not allow for recharging the ESS completely, a possible solution could be the adoption of flexible contracts in which boats' owners agree on a lower final SoC or on a delayed end of

charging, in exchange for a lower price or rewards. For instance, if the owners decide on a lower final SoC (acceptable in case of more days of stay in the port), all the five boats located in feeder F₆ can be charged with a final SoC equal to 50%, without compromising the feeder's voltage profile.

Fig. 7 shows the voltage profile of node N₆₃ (feeder F₆), considering the dumb charging (orange line), the smart charging without voltage control (grey line), the smart charge with voltage control (but without all the B2G fully charged) with the yellow line, and the smart charge with voltage control (but without all the B2G fully charged) with the green line.

C. High scenario

Finally, with the high penetration scenario, the voltage profile worsens in all the feeders from F₅ to F₉. The voltage profile is below the voltage threshold during the whole boats' charging (from 8 pm to 8 am) in feeders F₅ and F₈, and for more than 3 hours in feeders F₆, F₇, and F₉. Even exploiting the flexible charging contracts, the MAS smart management does not allow fully charging the boat batteries due to the high load demand required by the boats. In this case, it would be necessary a network reinforcement for the most stressed network branches.

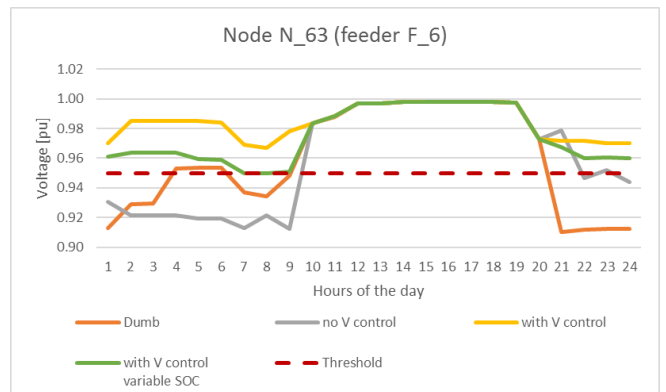


Fig. 7. Comparison of the voltage profile in one of the most critical nodes of feeder F₆.

V. CONCLUSION AND FUTURE WORKS

The proposed case studies show the importance of using a smart system for the management of the DER located on a microgrid, capable of taking into account both users' needs and network constraints to avoid excessive voltage variations. The network management could be supported by special tariffs and rewards that entice the users to accept a lower SOC for lower prices or cheaper additional days of stay. In addition, the results underline the fact that an increased presence of B2Gs could require the reinforcement of those assets with a lower capacity. As highlighted by the recent Literature, such reinforcements have not to be made considering the worst day scenario that could lead to expensive solutions but considering the real behavior of the network (i.e., considering most probable conditions), supported by real measurements and smart management tools like the one proposed in the paper.

Even if the described procedure is a day-ahead optimization based on predictive strategies, future works will integrate the procedure with the intra-day operation for real-time corrections to compensate forecast errors and to properly manage related risks. Improved boats' traffic models will be considered, by including uncertainty management. Also, the possibility of selling flexibility services outside the MG port,

showing the interaction between the MG and the main grid, will be investigated.

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