Multi-Agent System for Renewable Based Microgrid Restoration

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Abstract—**Power system restoration (PSR) is a very important procedure to ensure the consumer supply. In this paper, a decentralized multi-agent system (MAS) for dealing with the microgrid restoration procedure is proposed. In this method, each agent is associated with a consumer or microsource (MS) and these communicate with each other to reach a common decision. The agents solve a 0/1 knapsack problem to determine the best load connection sequence during the microgrid restoration procedure and then the proposed MAS is tested in one specific scenario where the microgrid is subjected to a blackout that occurred. This means that all the resources and loads are disconnected. This work is developed in Matlab/Simulink environment and the results show its feasibility and effectiveness in the microgrid restoration procedure.**

Keywords—black-start; distributed resources; microgrid; multi-agent system; restoration

I. INTRODUCTION

One of the most critical problems to be addressed is the power system restoration (PSR) issue. In a conventional way, restoration process begins in the transmission system by starting the power plants that provide the black start capability in the shortest possible time, such as hydroelectric generating units, gas and fuel turbine units and also incoming power from the interconnected systems in the vicinities [1].

This way, it is possible to energize transmission system and from there supply the consumers near the power plants first, thus the consumers at the distribution system will wait a long time to be supplied. In recent developments a new concept has emerged, the microgrid (MG). This changes the paradigm completely because the power flow becomes bi-directional and this type of grid can also work in islanded mode if necessary [2]. This new characteristic, when properly used, can be very beneficial in terms of PSR [3]. Besides, it will allow distribution system consumers to be supplied faster than using the conventional way.

There have been several studies and simulations in terms of taking advantage of the microgrid capabilities in terms of PSR [1]. In [4] the restoration of a smart grid system based on a distributed multi-agent system was performed on a six bus system using Tennessee Technological University Smart Grid Laboratory.

Ref. [5] addressed a stochastic model that can provide support to the decision making process of the power system restoration procedure in a pre-hurricane situation. It provided two strategies regarding a complete restoration and a partial restoration of the system. A stochastic mixed integer linear program was proposed in order to verify the potential of the microgrids black-start capabilities in [6].

Regarding spanning tree search methods, a graph-theoretic strategy for the power system restoration based on the incorporation of microgrids in the distribution system was presented in [7]. Here, the objective was to maximize the restoration of load by minimizing the number of actuation of the switching devices. The proposed algorithm is capable of determining an optimal solution in terms of network topologies.

In [8] the microgrid black-start capabilities were analyzed, supported by sectionalizing the existing microgrids in the power system. The unserved critical loads were then supplied by the microgrids with enough generation margins, through the application of a spanning tree search algorithm. In [3], the feasibility of microgrid restoration was examined using dynamic modeling of microgrid components. The microgrid central controller (MGCC) decided a proper sequence of restoration actions including setting-up the generation units with black start capability, energizing feeders, and reconnecting the loads and other generation units.

The sequence of actions was determined by the MGCC using the information received periodically from the microsource controllers (MCs) and load controllers (LCs), in terms of the level of generation and consumption in the MG. Ref. [9] investigated the restoration of distribution system with multi-microgrid in the presence of multi-MGCC. The sequence of actions is determined by the central autonomous management controller (CAMC).

In this paper a decentralized MAS for microgrid restoration was proposed. Each agent was assigned to a specific element (load or generation unit) and these communicated with each other to obtain the global information of the microgrid, regarding production and load values. After sharing the information, the agents solved a 0/1 knapsack problem by using the table-based dynamic programming algorithm. In this way it is possible to choose the loads that are more suitable to be connected in every step of the restoration process.

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The model was simulated considering that a blackout occurred in the MG and therefore, all the loads and generation units were disconnected from the latter.

The paper is organized as follows. In section II, the low voltage microgrid and its elements were modeled. Section III described the proposed decentralized MAS and the main assumptions considered during the restoration procedure. Section IV provided the obtained results and its discussion, thus assessing the feasibility of the proposed MAS. Finally, in section V the main conclusions were presented.

II. MICROGRID RESTORATION

One important aspect regarding the microgrid's control relies on its individual controllers. These controllers ensure the proper operation of the microgrid when in island mode, which is the case of the restoration procedure.

A microgrid is centrally controlled by the MGCC. This device is responsible for managing the economic and technical constraints of the microgrid. It is located at the low voltage bus of the substation and also sends set-points to the LC and MC devices in order to maintain generation and load balance in the microgrid. The LC is located directly at the consumption points and enables the local load control and shedding schemes, in emergency situations. The MC allows the control of the MS's by adjusting their active and reactive power injection into the microgrid [2].

The main drawback of the centralized control schemes is when one or more communication channels between the local controllers and control center are lost then the entire control system may be compromised [10]. Moreover, these schemes are always exposed to the single-point failure and all the processes depend on the optimal performance of the control center.

To avoid these drawbacks, the decentralized control scheme is presented. In the case of decentralized control schemes, the objective is to enable a high degree of autonomy of the different loads and MSs and so every load and generation unit will possess an agent associated that will be able to communicate with their neighbors thus exchanging their information [11]. This way it is not necessary the existence of a central controller [12].

Contrary to the centralized control scheme, if one communication path is lost in the decentralized approach the system still works because the agents are all connected between each other through other communication links, which is its main advantage. However, the implementation of the local controllers and the implementation of control schemes that require high levels of coordination are harder [10], [13].

A. Dynamic Modeling

The low voltage benchmark microgrid modeled in this paper can be found in [14]. To be operated in island mode, the microgrid needs to possess an element that can provide power balance during transient periods. This device is a battery installed at the LV bus of the substation. Flywheels can also be used for this purpose, however in this microgrid the battery was used. The battery was modeled using a battery model, available at Matlab/Simulink libraries, connected to a linear DC/DC converter. The PV generators were modeled according to [15] and it was assumed that the system was being operated at the maximum power point during the simulation, for determined temperature and irradiance conditions.

The wind generator was modeled as an induction generator directly connected to the grid. The wind turbine model used is available at the Matlab/Simulink libraries and its main equations can be found in [16]. The microturbine was modeled as a single-shaft microturbine (SSMT) with a battery at its DC link, thus providing a fast response during transient behavior.

The battery at its DC link was modeled just like the main storage. The turbine was considered to be a GAST model, available in [17] and the generator model was modeled as a permanent magnet synchronous generator (PMSG), available at the Matlab/Simulink libraries. The fuel cell was considered to be a solid oxide fuel cell (SOFC). The model used is available in [17].

After modeling the microsources (MSs) the next step was to model the inverters that are responsible for the output power control. These inverters can be controlled in PQ mode or in V/f mode (also known as VSI mode). The first one injects a pre-defined active and reactive power output in the grid, while the second one will act just like a synchronous machine by controlling the voltage and frequency of the microgrid by using the following droop equations:

$$\omega = \omega_0 - k_P \times P, \tag{1}$$

$$V = V_0 - k_Q \times Q, \tag{2}$$

where ω_0 corresponds to the reference value of the angular velocity, V_0 represents the reference value of the voltage magnitude, P is the active power output and Q is the reactive power output. The constants k_P and k_Q represent the droop coefficients for the active and reactive power, respectively. The control diagrams of these two control modes can be found in Fig. 1 and in Fig. 2.

III. PROPOSED DECENTRALIZED MAS SCHEME

A multi-agent system is composed of different agents. According to [18], an agent is a software/hardware system that is inserted in a proper environment and has the capability to react to changes in the latter. Besides, the agent must be able to change and observe a part of the current environment.

In the case of a microgrid, or a general power system, the environment will be physical and consist in the power grid, that can be observable by the agent through sensor measurements, and the latter may also change this environment for example by opening/closing a circuit breaker thus reconfiguring the network. According to [19]-[18] in a microgrid environment an agent must have three key features:

- Reactivity: the agent needs to be able to be aware and react to changes that may occur its environment (which is the microgrid), this includes load changes, generation changes, network reconfiguration, among others;
- Pro-activeness: an agent needs to be pro-active, which means that in case the connection between two agents is lost for some reason, then both need to adapt and search for another connection with a different agent that ensures the same objectives. Besides, the agents must operate to achieve a common goal;
- Social ability: every agent must communicate with the others to obtain the information required to achieve the proposed goals. But the communication must be goal oriented, which requires the cooperation between agents.

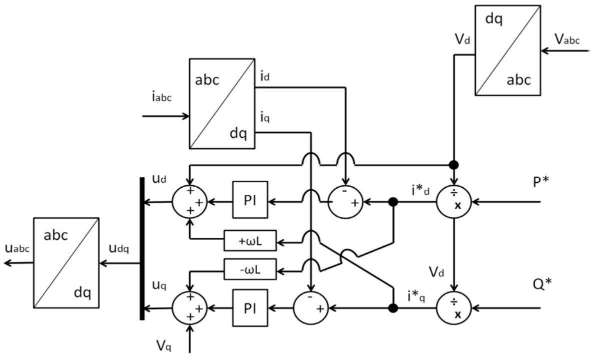

Fig. 1. PQ control diagram.

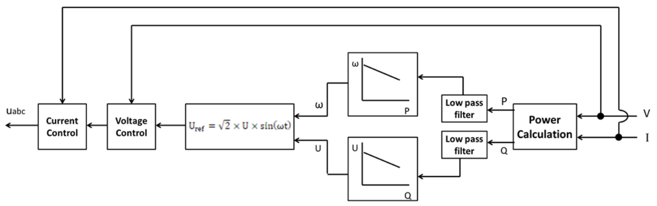

Fig. 2. V/f control diagram.

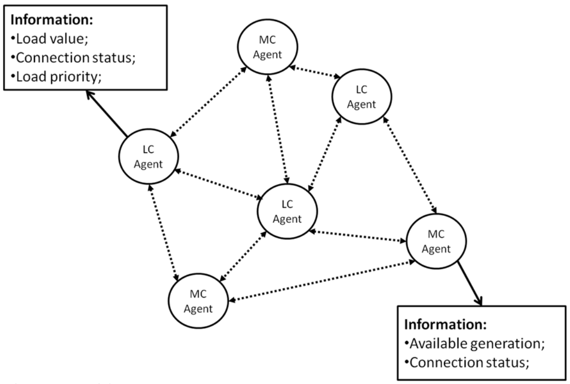

Fig. 3. Multi-agent system structure.

A. MAS characterization

For the studied microgrid with the goal of its own restoration, the multi-agent system had the structure depicted in Fig. 3. Here the load controllers (LCs) and the microcontrollers (MCs) were assigned to different agents with different information. For example, in the case of the LC agent, the important information would be the load value while in the case of the MC agent would be the available production. For the case of the SSMT, the available generation would correspond to its active power reserve while in the PQ controlled MSs, the available generation would correspond to the maximum active power that these units may provide.

The communication time between agents was verified in [20] by using a consensus algorithm. It concluded that this communication time was so small (less than 0.01 seconds) that for the time periods considered in this microgrid (around 5 seconds between the connection of loads and MSs), this communication time can be neglected. It was assumed that the communication between agents follows the above-mentioned consensus algorithm.

B. Knapsack problem formulation

The knapsack problem consists of a combinatorial optimization problem very common to find in the decision making situations encountered every day [21], [22].

Considering N items, the objective is to place a subset of these items in a knapsack with a defined capacity of W, knowing that each item has a determined weight (w_i) and value (v_i), by maximizing the total value in the knapsack such that the sum of the weights is less than or equal to its capacity. This problem can be easily adapted to the conditions of the MG restoration problem.

By considering that v_{ij} corresponds to the priority of the load j of the consumer i, x_{ij} corresponds to the same binary variable which indicates if the load is connected or not, L is the sum of the weights and w_{ij} corresponds to the active power load value, the following problem can be formulated:

Objective function: $$\max f(x) = \sum_{i\in N}\sum_{j\in L} v_{ij} \cdot x_{ij} \tag{3}$$

Subject to: $$\sum_{i\in N}\sum_{j\in L} w_{ij} \cdot x_{ij} < W \tag{4}$$

The proposed strategy consists in solving the knapsack problem every time a new load is connected. This problem would be solved by every agent. The agents would possess the structure presented in Fig. 4. If the SSMT and storage are already synchronized together, the algorithm followed by the agents will be:

1. Update W with the available active power production, in the first step will be the SSMT reserve;
2. Solve the 0/1 knapsack problem and determine the loads to connect based on their priority;
3. Remove the loads that were connected from the inputs of the algorithm to consider only the ones that are not connected already;
4. Then, connect the MS with the most available capacity; if there are more than one with the same capacity, choose randomly between those units.
5. Update W. This value will always be the SSMT reserve since this MS is operated in V/f control. This means that after an MS is connected, the SSMT will decrease its output to maintain a frequency of 50Hz, thus increasing its reserve. The contrary situation happens when a load is connected.
6. Repeat step 2 to 5 until there are no more MS to connect and the SSMT reserve is not enough to connect more loads.

It should be noted that the storage is not considered as an MS with reserve since it is supposed to act only during transient periods, thus returning its active power production to zero.

C. Dynamic programming

To solve the 0/1 knapsack problem, the table-based dynamic programming algorithm was used. The table based dynamic programming algorithm is based on the principle of Bellman equation [21]:

$$f_j(i) = \max(p_j + f_{j-1}(i - w_j), f_{j-1}(i)) \tag{5}$$

where, considering the knapsack problem, $f_j(i)$ corresponds to the maximum value that results from the objective function of the knapsack problem. This method requires that all the coefficients are integers and that the items are sorted in an ascending order by the weights. More information and examples regarding this method can be found in [21].

D. Load priority

The first step is to make a description of every type of residential loads existent in the microgrid. In [23] it was possible to find the most common groups of home appliances in residential loads. Besides, each group had a maximum off time, which consists of the maximum time that these devices can be turned off without causing discomfort to the consumers.

So, to minimize the consumers' discomfort, it was assumed that the loads with smaller maximum time off would have higher priorities than the ones with higher maximum time off. These considerations were adopted and can be found in [24]. From here on, load *i.j* corresponds to the group of loads j of the consumer *i*.

Since the SSMT would be supplying a local load, and this MS is in the same bus as the consumer 5, the loads 5.2, 5.3, 5.4 and 5.5 would be supplied due to their higher priority, so these won't be considered by the algorithm since they are already connected.

The load 5.1 would not be supplied as well since the SSMT as a limited capacity of 30kW and so it is not possible to supply this load. It was assumed that the storage unit would be responsible for supplying the lighting loads due to its maximum time off which is the lowest, thus having the highest priority. Since the lighting loads were not too high the storage would stabilize the frequency in a value below 50Hz but close to the latter. In the other island the SSMT would have the secondary control activated.

IV. RESULTS AND DISCUSSION

In this section the dynamic simulations were carried out to validate the proposed MAS restoration scheme. The low voltage benchmark microgrid implemented in Matlab/Simulink environment is presented in Fig. 5 and its electrical characteristics can be found in [14].

It is supposed that all the microgrid is subjected to a blackout and all the loads and generation units are disconnected. The first steps in the microgrid restoration procedure are the following: the storage unit should energize the feeders of the microgrid and supply only the critical loads (loads with the least maximum off time) and the SSMT should be black-started and supply a local load, thus creating two different islands. Then the two islands should be synchronized. It is assumed that the MGCC is responsible for these steps. For the synchronization procedure, some conditions need to be assessed to choose the most appropriate moment to synchronize both islands.

TABLE I. INDIVIDUAL DOMESTIC LOAD GROUPS CHARACTERIZATION.

Group	Description	Maximum off time	Priority
1	Electric space and water heaters, refrigerators, freezers	5 minutes	1
2	Washing machines, tumble dryers	3.5 minutes	2
3	Cooking appliances	2 minutes	3
4	In line heaters	15 seconds	4
5	Lighting loads	4 seconds	5

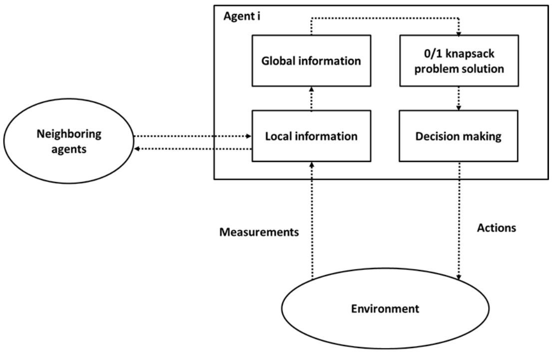

Fig. 4. Structure of an agent for the MG restoration problem.

TABLE II. DISTRIBUTION OF LOAD FOR EACH CONSUMER.

Consumer	Group 1	Group 2	Group 3	Group 4	Group 5
1	60%	11%	12%	9%	8%
2	59%	12%	11%	9%	9%
3	62%	10%	9%	10%	9%
4	63%	9%	10%	8%	10%
5	65%	9%	8%	8%	10%

TABLE III. AMOUNT OF LOAD FOR EVERY GROUP.

Consumer	Total (kW)	Group 1 (kW)	Group 2 (kW)	Group 3 (kW)	Group 4 (kW)	Group 5 (kW)
1	4.845	2.907	0.53295	0.5814	0.43605	0.3876
2	19.55	11.5345	2.346	2.1505	1.7595	1.7595
3	21.25	13.175	2.125	1.9125	2.125	1.9125
4	4.845	3.05235	0.43605	0.4845	0.3876	0.4845
5	48.45	31.4925	4.3605	3.876	3.876	4.845

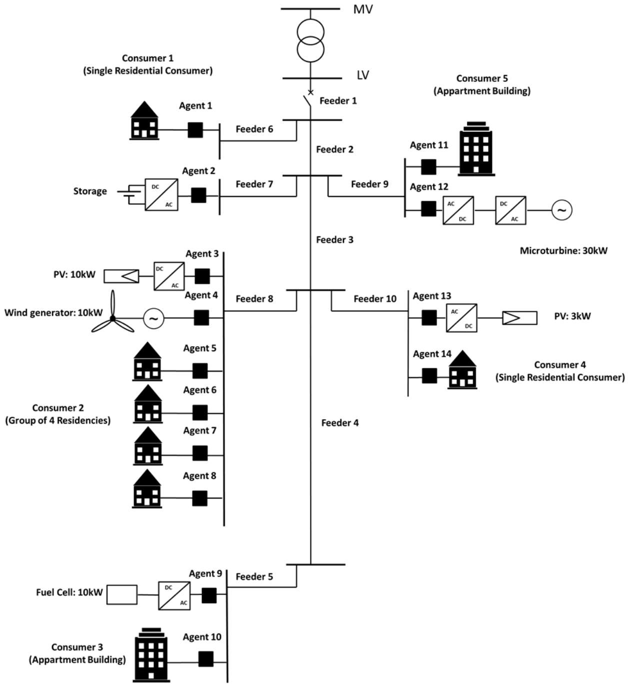

Fig. 5. Benchmark low voltage microgrid.

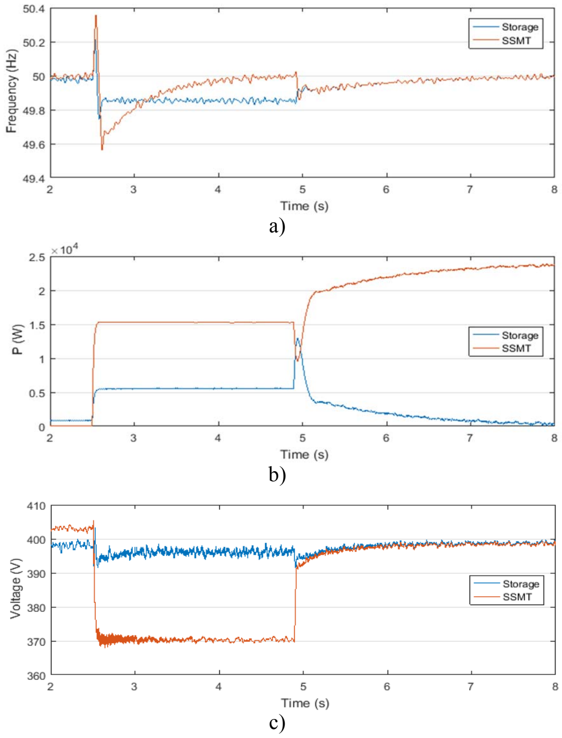

Fig. 6. Synchronization time span: a) Frequency b) Storage and SSMT active power output c) Storage and SSMT voltages.

These conditions include checking the voltage magnitude difference and phase difference. By checking the synchronization conditions, it is expected that the resulting transient from the connection between the two islands is very small.

In Fig. 6 the synchronization results are presented. Before 2.5 seconds, the storage unit and SSMT were disconnected from the MG. At 2.5 seconds the MGCC sent a signal to the circuit breakers to connect the storage unit to the loads with the highest priority and to connect the SSMT to the local load, thus creating two different islands.

The SSMT has a secondary frequency control which corrected the frequency deviation in its island. The storage unit maintained a frequency of 49.85Hz because it does not have a secondary frequency control. At 4.5 seconds, the frequency in the SSMT island was restored to 50Hz and so the MGCC sent a signal to check the synchronization conditions.

At 5 seconds, the synchronization conditions were met therefore the MGCC sends a signal to the circuit breaker to connect both islands, After the synchronization procedure, the next step is to connect the loads according to the proposed MAS.

For every step of the algorithm, the knapsack problem was solved, and the selected loads were connected. The results can be found in Fig. 7 where the effects of the losses can be observed at 14 seconds and 24 seconds, where the SSMT's active output is over 30kW, which is its capacity.

For example, in the first step the SSMT's reserve is 6kW and 6kW of loads are connected but the SSMT produces more than 6kW, exceeding its capacity. However, the SSMT can produce over its maximum capacity for short periods of time so this effect is not important in this simulation.

TABLE IV. SSMT'S RESERVE, SELECTED LOADS AND ITS SUM.

Step	Reserve (KW)	Loads	Sum of loads (kW)
Step 1	6	4.4/1.4/4.2/4.3/1.3/2.4/3.3	6
Step 2	10	1.2/2.3/3.4/3.2/2.2	9.28
Step 3	10	1.1/4.1	5.96
Step 4	18	3.1	13.18

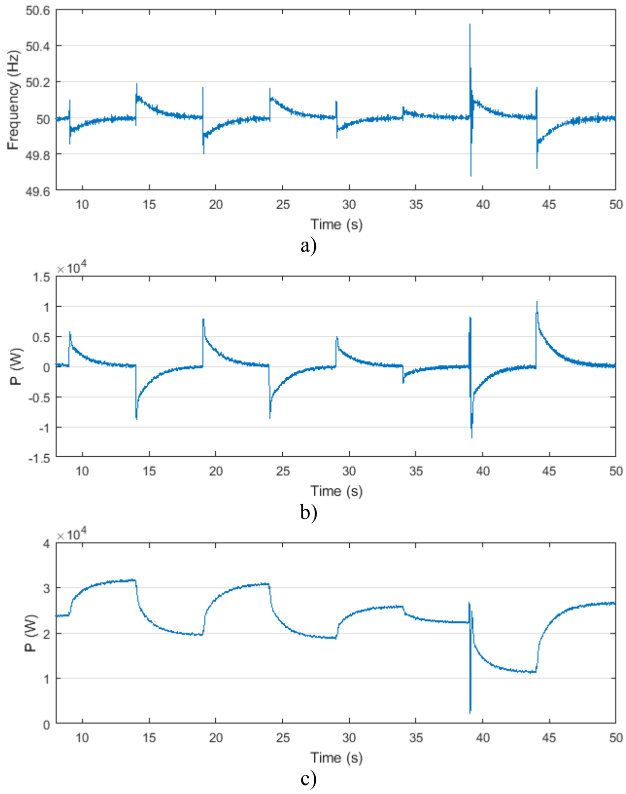

Fig. 7. Load connection time span: a) Frequency b) Storage active power output c) SSMT active power output.

After 50 seconds, the MG is supplying the maximum amount of load according to the available local production. So, the next step would be to wait until the medium voltage (MV) grid is available and then connected the MG to the latter, thus supplying the remaining loads. Since this work is based on MG restoration, its connection to the MV grid is not simulated, however it would be necessary to check the exact same conditions verified previously.

V. CONCLUSION

In this paper, a decentralized MAS for microgrid restoration was proposed. Each agent was associated with a specific load or generation unit, thus enabling connection or disconnection from the microgrid. A low voltage microgrid was modeled and then tested to assess the feasibility of the proposed decentralized control scheme, where the agents solve a 0/1 knapsack problem to reach a common decision, using the table based on dynamic programming algorithm. The sequence of actions to follow during the restoration procedure was based on the online information of every load and MS that was shared by the corresponding agents. The results showed that this scheme was feasible, thus enabling the correct MG restoration procedure considering a blackout in the MG.

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