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Interactions Between Gas Networks and Microgrids Through Microturbines

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***Abstract*—By supplying thermal and electric energies to host facilities, microgrids with combined heat and power can enhance the resilience of urban energy systems. However, the increasing use of gas-fired distributed generations is pushing gas distribution networks to their operating limits, which may cause significant adverse impacts on microgrids. This paper investigates the interactions between gas networks and microgrids from the viewpoint of integrated energy systems. Four operating modes of microgrids are discussed to describe their connections with external energy networks. A novel model for gas-fired distributed generations, particularly microturbines, is first proposed to capture the interactions between gas networks and microgrids. An integrated system model is then developed to characterize the behaviors of the interrelated gas network and microgrids under different scenarios. Numerical results demonstrate that the variation of microturbine outputs may cause a large pressure drop of the gas network, especially during the transient process of gas flow adjustments. The results also reveal that microgrids can alter the operations among themselves through the accessed gas network.**

Keywords*—*microgrids, gas network, interaction, modeling.

I. Introduction

As a lifeline of modern society, electrical grids play an integral role in supporting the operation of other infrastructures. Due to the increasing use of renewable generations, electric grids are becoming more vulnerable to varying and severe weather conditions. In extreme scenarios, the rising occurrence of natural disasters may cause physical damages to power grids, and further inflict adverse impacts on the society [1], [2]. To improve the flexibility and resilience of power grids, natural gas, as a low-cost and clean fuel, is widely used in the power generation. Such gas-fired generations could support the operation of the grids, i.e., smoothing renewable generations. However, the rising use of gas-fired generations also intensifies the risk of electrical grids due to the delivery of gas [3].

In urban areas, microgrids with combined heat and power (CHP) systems play a positive role in improving the resilience of local energy systems by providing thermal and power services to customers [4]. As a key component of the CHP, the effects of gas-fired distributed generations (DGs) on the energy networks have been recently discussed in terms of the generator sizing [5], interactions [6], and scheduling [7]. It has been demonstrated that fluctuations in one network can be propagated to the other through the coupling of gas-fired DGs. A large pressure drop as well as gas network faults, can cause the shutdown of gas-fired generators [8], which will significantly affect the energy supply to communities, and further increase the power demands to the electricity distribution network. When a CHP is set to track the thermal load and electric load variations, for example, to smooth the renewable output fluctuations, it couples all relevant systems [7]. In other words, all other systems, such as energy storage and solar panels, can affect the operations of power and gas grids. Therefore, the interactions between microgrids and the gas network need to be fully investigated.

At the transmission level, the interactions and interdependencies of gas and electricity infrastructures have received substantial interests in recent years. It has been shown that the physical characteristics and line-pack capability of pipelines can affect the security and operating cost of hybrid power and gas systems [9], [10]. In terms of dynamic gas systems, the penetration of wind generations can result in large utilisation swings for gas pipelines, when gas-fired generations are used to smooth the wind power fluctuation [11]. The slow transient process of gas flows can lead to infeasible or suboptimal schedules for the hybrid systems [12]. Furthermore, contingencies in gas systems can take months to repair, which will exert a long-term impact on the operation of power systems [13]. All the above issues need to be carefully addressed at the distribution level, particularly for the gas flow dynamics.

Some black-box or analytical models have been developed to reflect the energy conversion processes of microturbines (MTs) [14], [15] and the interactions between gas and electricity systems [6], [16]. The problem is that these models either focus on certain variables or are designed for MTs working around the rated operating point, which cannot capture various system dynamics in a wide range. To meet this need, this paper investigates the interplay between the gas network and microgrids through MTs. A novel MT model is developed to describe how the MT interacts with the gas system. Combined with electricity and gas network models, an integrated model is developed to describe the behaviors of urban energy systems. In case studies, two nearby microgrids are connected to the electricity and gas distribution network at different locations, in order to address the following aspects: 1) Dynamic impacts of MT output adjustment on the gas network; 2) Impact of gas network disturbance on the MT states; 3) Interactions between nearby microgrids through the gas network.

II. Microgrid with Electricity and Gas Systems

A. The Microgrid Framework

In microgrids, different energy systems, i.e. electricity, gas, thermal and hydrogen systems, are coupled and integrated through various energy conversion units, such as MTs, gas boilers, air-conditioners, electrolyzers and fuel cells. These systems, combined with other DGs and energy storage facilities, can provide energy services to the host facility separately or as a whole. Although the mutual support among various systems can largely enhance the resilience of the overall energy system, the resultant interactions among these systems can also cause problems to the safe operation of all related local systems as well as external energy networks. In this paper, microgrids with CHP are investigated, where the CHP is connected not only to the electricity network, but also to the gas network. In this section below, the possible operating modes of the microgrid are discussed, considering its connection with the two energy distribution networks.

B. Operating Modes

Through various coordination strategies, a microgrid can operate either independently or in conjunction with other microgrids, gas and electricity networks, as shown in Fig. 1. The operation of microgrids can have four different modes.

1) Dual-Grid-Connected Mode: In this mode, the microgrid is accessed to both gas and electricity networks, and takes in energy from the two networks. When DGs and gas producers exist, the microgrid can also feed gas and power back to the energy networks.

2) Power-Grid-Disconnected Mode: When a contingency occurs to the power grid, the microgrid can be isolated from the main grid and operate independently. If connected to the gas network, the microgrid can still keep facilities running for a long period by using CHP and renewable generations.

3) Gas-Grid-Disconnected Mode: When there is no gas-fired equipment or gas leakage occurs, microgrids are considered to operate in the gas-grid-disconnected mode. In this mode, microgrids only exchange power with the external energy networks. Gas demands are met by local gas producers.

4) Islanded Mode: In an extreme weather event where both gas and electricity networks are not able to supply the required energy, the microgrid is operated in the islanded mode by coordinating the DGs, energy storage, and demand response.

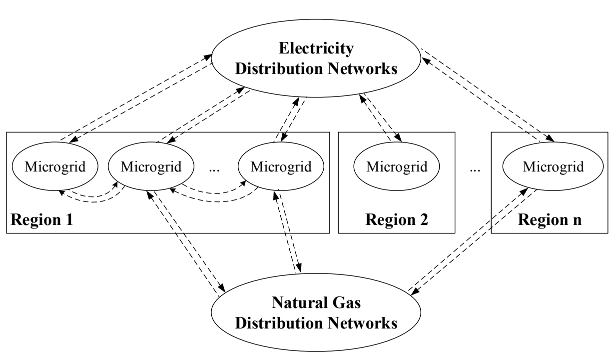


Fig. 1. Energy change between microgrids and the energy networks

C. Interaction and Disturbance Analysis

When MTs are used to support the operation of microgrids, any change in the load demand or in the renewable generations can lead to variations in the MT outputs, which will then be propagated to the gas network. When multiple microgrids exist, a large pressure drop can occur to the gas network during the MT output adjustment processes. On the other hand, disturbances introduced to the gas network, such as pressure variations, can also affect the operation of MTs. For example, the MT output will be limited when the pressure level of the gas network is low, which indicates that the disturbances are propagated to heat and power systems in microgrids. Furthermore, interactions between different microgrids can arise through the pressure variation of the accessed gas network.

III. System Modelling

A. Microgrid

1) Coupling Unit: As mentioned earlier, this paper focuses on the coupling function of the single-shaft MT which is commonly used in practice. It usually includes a gas turbine, a permanent magnet synchronous generator, and electronic converters. Inspired by the Wiener-Hammerstein model [14], this paper proposes an extended model for MTs based on the mechanism analysis and system identification. The model consists of a nonlinear part and a linear part with delays, as shown in Fig. 2.

For the nonlinear part, a radial basis function network model trained by the two-stage fast recursive algorithm [17] is employed to reflect the relationship between the load signal and the rotational speed. The parameters of the model (1) are identified by physical experiments. With this model, the load signal u of the MT is converted to the reference of the engine speed ω_{ref}, and then passed to the linear part as an input.

$$\omega_{ref} = \sum\nolimits_{i=1}^{m} \lambda_i \phi_i(u, \sigma_i, c_i) = \mathbf{\Phi}\mathbf{\Lambda} \tag{1}$$

where $\mathbf{\Phi} = [\phi_1, \phi_2, ..., \phi_m]$, $\mathbf{\Lambda} = [\lambda_1, \lambda_2, ..., \lambda_m]$, λ_i is the linear output weight of node i, and $\phi_i(u, \sigma_i, c_i)$ denotes the RBF of the ith hidden node. $\mathbf{c} = [c_1, c_2, ..., c_m]$ and $\sigma = [\sigma_1, \sigma_2, ..., \sigma_m]$ represent the center and width vectors of the Gaussian function.

The linear part of the MT model is obtained from [6] to describe the interactions between the two networks. The reference value for the engine speed is combined with the obtained model to describe the behavior of the MT over a large operating range. MT fuel consumption F_{mt} is also taken as an input of the model. The MT power output P_{out} and the fuel inlet pressure p_{mt} are chosen as outputs of the model.

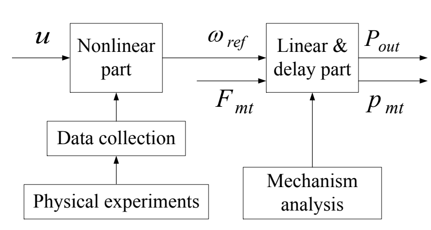


Fig. 2. Extended MT model

2) Microgrid Model: Combining the MT model with other DGs and load models, the dynamic model of microgrid i can be expressed as

$$\begin{cases} \dot{\boldsymbol{x_i}} = \boldsymbol{f_i}(\boldsymbol{x_i}, \boldsymbol{y_i}) \\ \boldsymbol{0} = \boldsymbol{g_i}(\boldsymbol{x_i}, \boldsymbol{y_i}, \boldsymbol{u_m^i}) + \boldsymbol{h_i}(c_e^i u_e^i, c_g^i u_g^i) \end{cases} \tag{2}$$

where $\boldsymbol{x_i}$ and $\boldsymbol{y_i}$ are state variables (rotor angles, rotor speeds, gas node pressure, etc.) and algebraic variables (bus voltages, bus angles, gas flows, etc.), $i = 1, 2, ..., l$; l is the number of microgrids; $\boldsymbol{f_i}$ and $\boldsymbol{g_i}$ are hybrid continuous and discrete functions, representing dynamic and algebraic relationships between different energy subsystems in microgrid i; $\boldsymbol{u_m^i} = [u_i^{Ren}\ u_i^{Load}]^T$ represents the amount of loads u_i^{Load} and renewable generations u_i^{Ren}; u_e^i and c_e^i are the power exchange and connection state between microgrid i and the electricity network; u_g^i and c_g^i denote the gas exchange and connection state between microgrid i and the gas network.

B. Energy Networks

1) Gas Network: The whole gas network model consists of the pipeline model and the network topology. Based on the mass and momentum conservation laws, the gas flow in a pipeline can be expressed as [18]

$$\begin{cases} 0 = \dfrac{B^2}{A}\dfrac{\partial M}{\partial x} + \dfrac{\partial p}{\partial t} \\ 0 = \dfrac{\partial p}{\partial x} + \dfrac{1}{A}\dfrac{\partial M}{\partial t} + \dfrac{pg}{B^2} sin\theta + \dfrac{fB^2M^2}{2DA^2p} \end{cases} \tag{3}$$

where $B^2 = (\frac{\partial p}{\partial \rho})_s$ is the sound speed, s stands for the isentropic process, A is the cross-sectional area of the pipe, D is the diameter of the pipeline, M is the mass flow, f is the friction coefficient, g is the acceleration of gravity, and θ is the angle between the horizon and the pipeline.

The network topology can be embedded in the formulation of initial conditions and boundary conditions. Initial conditions, including the node pressure and the pipeline flow, can be obtained by calculating the steady state gas flow. Boundary conditions include the conservation of mass at each node, as well as pressure or mass flow of gas sources and loads. Thus, the gas network model can be expressed as

$$\begin{cases} \partial_t \boldsymbol{x_g} = \boldsymbol{f_g}(t, \boldsymbol{x_g}, \partial_p \boldsymbol{x_g}) \\ \boldsymbol{x_g}(0, p) = \boldsymbol{x_g^0} \\ \boldsymbol{x_g}(t, 0) = \boldsymbol{g_g}(\boldsymbol{u_g}, \boldsymbol{x_g}) \\ \boldsymbol{x_g}(t, \boldsymbol{D}) = \boldsymbol{h_g}(\boldsymbol{u_g}, \boldsymbol{x_g}) \end{cases} \tag{4}$$

where $\boldsymbol{u_g} = [\boldsymbol{u_g^m}, \boldsymbol{u_g^g}]^T$, $\boldsymbol{u_g^m} = [c_g^1 u_g^1, c_g^2 u_g^2, ..., c_g^l u_g^l]^T$ and $\boldsymbol{u_g^g}$ represent the gas demand of microgrids and other gas loads. $\boldsymbol{x_g}$ represents the node pressure and pipeline flow of the gas network, p is the position variable, $\boldsymbol{D} = [D_1, D_2, ..., D_k]$ is the length of the pipelines in the gas network, k is the pipeline number. $\boldsymbol{g_g}$ and $\boldsymbol{h_g}$ are the boundary conditions of the gas network. Initial conditions for the gas network $\boldsymbol{x_g}(0, p) = \boldsymbol{x_g^0}$.

2) Electricity Network: Power systems are usually described by differential algebraic equations [19], including models of loads, generators, and networks. The electricity network in the UES can thus be expressed as

$$\begin{cases} \dot{\boldsymbol{x_e}} = \boldsymbol{f_e}(\boldsymbol{x_e}, \boldsymbol{y_e}) \\ \boldsymbol{0} = \boldsymbol{g_e}(\boldsymbol{x_e}, \boldsymbol{y_e}, \boldsymbol{u_e}) \end{cases} \tag{5}$$

where $\boldsymbol{x_e}$ are the state variables of the system at each phase, including generators, control systems, and loads. $\boldsymbol{y_e}$ are the algebraic variables of the system at each phase, including magnitudes and phase angles of the node voltage and current. $\boldsymbol{u_e} = [c_e^1 u_e^1, c_e^2 u_e^2, ..., c_e^l u_e^l]^T$ are power grid disturbances, such as load variations, generation adjustments, microgrid tieline power variations, etc. $\boldsymbol{f_e}$ and $\boldsymbol{g_e}$ are dynamic and steady states of each phase and their relations with other phases.

C. Numerical Implementation

It can be seen from Fig. 1 that microgrids and the two energy networks are interconnected systems. To characterize the behaviors of these systems, an interactive methodology is used to simulate the whole system. The proposed method is presented as follows.

1) Estimate the gas and power exchange ($\boldsymbol{u_g^0}$ and $\boldsymbol{u_e^0}$) between microgrids and energy networks based on DG outputs and loads of microgrids.
2) Set microgrids as PQ buses in the electricity network, and then solve the electric power flow according to the power exchange $\boldsymbol{u_e^0}$. Calculate the gas demand of the electricity network if gas-fired generations exist.
3) Solve the gas flow according to the microgrid gas demand $\boldsymbol{u_g^0}$ and calculate the gas pressure of each node as initial conditions of (4).
4) Set $t_s = 0$, $t_f = 0$, and then initialize state variables of microgrids and energy networks.
5) Solve (2) to obtain microgrid variables including the variations of power exchange $\boldsymbol{u_e}$ and the gas inlet pressure $\boldsymbol{u_g}$.
6) Substitute $\boldsymbol{u_e}$ into (5), and then calculate the power grid dynamics and its demand from the gas network.
7) Set $t_f = t_f + \Delta t_f$, if $t_f > t_s + \Delta t_s$, continue; otherwise go to Step 5).
8) Substitute $\boldsymbol{u_g^m}$ and variations of other gas loads $\boldsymbol{u_g^g}$ into (4), and then calculate the states of the gas network.
9) Set $t_s = t_s + \Delta t_s$, and exchange the data of the gas network with microgrids and the electricity network. If $t_s < t_{end}$, go to Step 5), otherwise terminate.

IV. CASE STUDIES

Fig. 3 shows the topology of two microgrids connected by gas and electricity networks. In this section, we apply the proposed MT model to investigate the interactions between the gas network and microgrids. In microgrid I, MT I combined with the solar panel, supplies both heat and power to customers. In microgrid II, MT II is used to smooth the output of the solar panel and to provide electricity service to customers. The pressure of the gas source at node 1 is assumed to be 5 kPa. For simplicity, the two MTs are assumed to be the same. The rated power is 30 kW. Detailed parameters of the MT and the gas network can be found in [6]. An integrated simulation platform is implemented in MATLAB/Simulink to investigate the behaviors of the microgrids and the gas network.

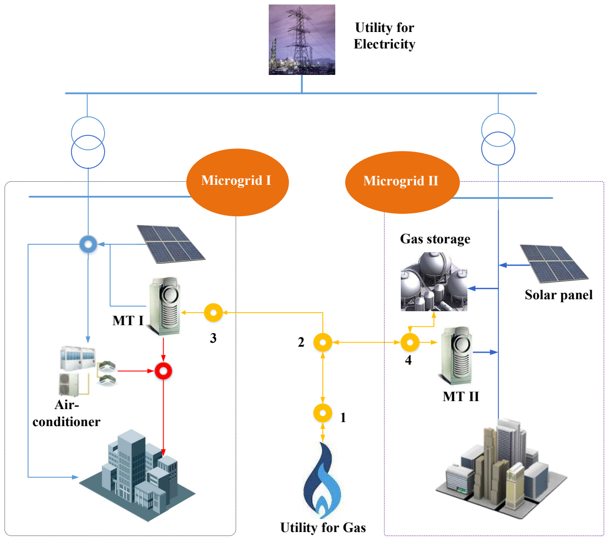


Fig. 3. Configuration of the two microgrids and energy networks

A. Interactions of Microgrid with Gas Network

Without loss of generality, MT I at node 3 is adjusted to analyze its impact on the gas network. MT II with a gas storage at node 4 is used to mimic a gas prosumer with controllable pressure, which allows the analysis of the influence of the pressure variation of the gas network on the microgrid. This influence is reflected by the variation of the MT output which is determined by the energy management system of the microgrid. For simplicity, the load signal of the MT is set to be equal to the mismatch of the solar panel output variations and load variations The obtained load signal of the MT and the relevant engine speed are shown in Fig. 4.

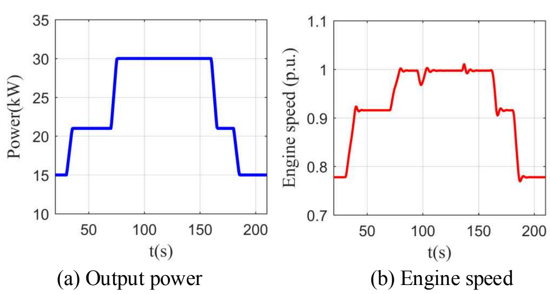


Fig. 4. Variation of the MT during the output adjustment process.

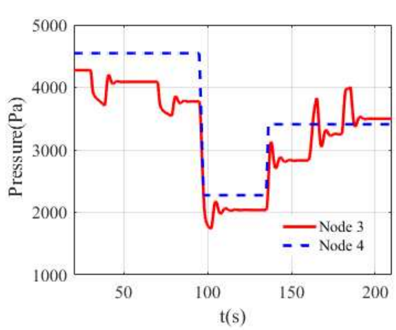


Fig. 5. Pressure variations during the MT output adjustment process.

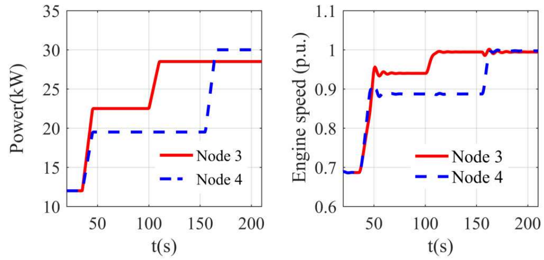
It can be found that the MT output adjustment results in pressure variations of the gas network. As shown in Fig. 5, the minimum value of the inlet pressure transient process is lower than the final pressure at steady state, as the MT output increases. This is due to the fact that more energy is used for MT acceleration. Similar observations can be found during the MT output decreasing process at 160s and 180s, but with less energy consumption. These pressure differences reveal that the gas network pressure can be lower than its expected steady state value, and this will affect the operation of other gas-fueled devices in the neighbouring area. Therefore, dynamic impacts of the MT should be considered in the design and operation control of microgrids.

With respect to the impact of the gas network on the MT, the pressure at node 4 starts to drop at 95s and stays at a low value for 40s. Then the pressure starts to increase and stops at a new level. It can be seen from Fig. 5 that the pressure of the MT at node 3 is affected significantly as the pressure drops or increases at node 4. As shown in Fig. 4(b), this pressure variation results in the fluctuation of the engine speed at both 95s and 135s. At 95s, the MT fuel control system increases the valve opening in order to maintain the MT output at the set-point. Similarly, rapid pressure rise can be observed at 135s, when the MT output decreases. These variations indicate that the pressure change of the gas network can significantly impact the operation of the MT, which needs to be taken into account in the microgrid control and dispatch.

B. Interactions of Two Microgrids Through Gas Network

When the MTs are used to compensate for the variation of solar panel outputs, the fluctuation of the solar irradiance will be passed to the gas network, particularly, when the microgrids are operated in the gas-grid-connected mode. Considering the spatial distribution of solar panels, their output variations caused by clouds drifting usually occur in sequence. The time delay of the solar panel output changes between different areas can be different, according to the distance between panels and the speed of the cloud drafting. In the worst scenario, the two solar panel outputs change at the same moment, which leads to simultaneous adjustments of MTs in the two microgrids.

Suppose a sudden decrease of the solar irradiance occurs at 35s, the two MTs will be adjusted to compensate for the losses of solar panel outputs. The load signal of the two MTs is shown in Fig. 6(a). The gas storage is not considered. The outputs of the two MTs are adjusted simultaneously to show the adverse effects of microgrids on the gas network. Then the two MTs are adjusted separately to investigate their interactions through the gas network. It is shown from Fig. 7 that simultaneous adjustments on the MTs will cause a significant impact on the pressure level of the gas network. Although the inlet pressure of the two MTs converges to values which are higher than 3000 Pa, the minimum value of the pressure during the adjustment process is below 2000 Pa, due to the increasing use of gas for the acceleration of the two MTs. The minimum value is merely close to the pressure at 160s, where much more gas is consumed by the MTs. If the output increase is higher, one or both MTs may be shut down by the protection system. Therefore, when multiple MTs exist in one gas network, dynamic analysis is required for the design of the management and control system.



(a) Output power (b) Engine speed

Fig. 6. Variation of the MTs in the two microgrids.

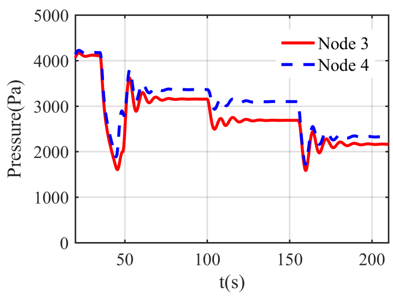


Fig. 7. Pressure variations caused by the output adjustment of the MTs.

As shown in Fig. 7, the output increase of MT I results in the gas pressure drop at node 3. Then this pressure variation is propagated to node 4. It can be seen from Fig. 6(b) that speed swings are observed in MT II, as the output of MT I changes at 100 s. Similar observation can be found at 155s when the output of MT II is adjusted. Although no obvious output variation of the two MTs occurs, the impacts on the speed of the MTs should be taken into account from the prospect of security operations, since the engine speed plays a key role in the MT operation. In addition, it can be seen from Fig. 7 that the gas pressure only varies slightly when the two MTs are adjusted separately, compared with the evident pressure change caused by simultaneous adjustments of the two MTs. This study indicates that the dynamic coordination of the MTs can reduce their influences on the gas network.

V. Conclusion

This paper investigates the interactions between the gas network and microgrids through MTs. Considering the energy services provided by the gas network, four operating modes of microgrids are discussed, namely dual-grid connected mode, gas-grid-disconnected mode, power-grid-disconnected mode, and islanded mode. A novel MT model is proposed to capture the interactions between the gas network and microgrids. Then an integrated model is introduced to simulate the behavior of the urban energy system. Numerical results reveal that although MTs can increase the resilience of the local energy systems, the gas delivery of MTs can lead to a vulnerable energy supply systems in microgrids if they are not well coordinated. This study clearly indicates that dynamic characteristics of gas flows should be considered in the planning and scheduling of microgrids. Future work will focus on the coordination of microgrids, in order to mitigate dynamic impacts of the gas network and avoid the relevant failure in control and dispatch.

Acknowledgment

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