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Signal and Thermodynamic Analysis for Evaluation of Thermal and Power of Gas Turbine-Solid Oxide Fuel Cell Hybrid System

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Abstract**—**In recent years, solid oxide fuel cells have been used as one of the main technologies for the production of electrical energy with high-efficiency ratio, which is used hydrogen and other hydrocarbons as fuels. The fuel cell technology can be used either alone or in hybrid gas turbines systems. In this study, thermodynamics analysis for GT-SOFC hybrid system is developed, and then mass balance and exergy equations have been applied not only on the process but also on the individual components of the hybrid system, which enable us to estimate the thermal efficiency of the hybrid systems. Furthermore, various sources of irreversibility in the solid oxide fuel cell system are discussed, and modeling and parametric analyses like heat and pressure are carried out. This study enables us to consider the irreversible effects of solid oxide fuel cells, and also it leads to the specification of efficiency of the system accurately. Next in the study, both methane and hydrogen as a fuel for SOFC are used and implemented, and finally, our results are compared with other references.

Keywords**—**Hybrid system, gas turbine, entropy and exergy analysis, irreversibility analysis.

I. INTRODUCTION

A SOLID oxide fuel cell system is one of the most important type of fuel cell. In variety of researches, fuel cell is used as a superiority kind of system for future power systems [1]. One of the advantages of this system can be related to generation of electrical power at the highest conversion rate with low emissions levels [2]. This electrochemical system works based on the electrochemical reactions of the elements such as oxygen and hydrogen which require high temperatures even up to 1000 degrees Celsius. This heat conditions applies technological restrictions on a variety of structural materials for the SOFC. On the other hand, this device has ability of synergies and coupling with the gas turbine.

Coupling of SOFC unit with gas turbine and other equipments such as compressors and heat exchangers coupling is one of the most common applications of this system. The SOFC-GT hybrid system can produce electrical energy, greenhouse gas emissions and the efficiency range between 75% to 85% [3]. The approach of dynamical system for the mechanical modelling is used by [4]. In recent years, many researchers are argued on SOFC and hybrid systems [5], [6]. Most of the resources investigated the efficiency of these systems under various operating conditions. Past researches that studied the hybrid systems were applied for the first time in 1970 by [7]. The method of signal processing in interdisciplinary approach is developed by [8]-[10]. One of the first studies in hybrid systems can be noted by [11]. In this research, the American company of Siemens Westinghouse launched the first power generation with 100 kW in 2000 in the Netherlands [12]. In January 2000, this company, with the support of the US government's National Center for fuel cell research at the University of California, combined a solid oxide fuel cell which was operated at a pressure of 3 atmospheres with a gas micro turbine with the power of 50 kW. That same year, tubular solid oxide fuel cell technology was investigated by Siemens Westinghouse [13]. Also, between the years 2000 and 2002, Paulson offered excellent research in the field of hybrid systems. They examined another hybrid system in other studies [14], with a power of 500 kilowatts. They used modeling software such as Aspen which indicated and used parameters like compression ratio, which has a vital role in the performance of the system. The results showed that in the low pressure ratios, the electrical efficiency of the system was over 65 percent.

In 2001, Massardo conducted research to examine the performance of the combined cycle [15]. The mathematical model that developed by them simulated the system in the transient and steady-state conditions. Yang tested and designed the operation of the gas microturbines with heat recovery parts and also SOFCs in high-temperature degrees [16]. In the [17], they evaluated two systems by improving the state of fuel systems in internal and external conditions, and also the effect of limiting the temperature difference between the fuel cell stack on their performance was measured by them. In the [18], they examined the design specifications and performance of a hybrid system with respect to the specific model of the gas turbine. In most of these studies, the performance of the fuel cell and hybrid gas turbine system are investigated according to the first law of thermodynamics. In addition, various researches have been done with regard to the second law of thermodynamics on this system. These modelings were investigated on the system and each of its components, and also irreversible rates in different parts of the system were modeled. By knowing the contribution of each component of the system in terms of the rate of the irreversibility of the whole system, edification can be implemented, and the role of each component in the system can be designed. In the [19], in two separate

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studies, they have examined the exergy and entropy production and also destruction in a hybrid system. They showed that by combining the fuel cell with a gas turbine, the first law efficiency increases to 27.8 percent.

In 2006 Calise and colleagues [20] were examined a solid oxide fuel cell power generation system with both hydrogen and methanol as fuel consumption, and influences of parameters such as resistance of the cell components on produced power were determined by them. In 2006, Calisea and colleagues [21] simulated the combined gas turbine cycle with a solid oxide fuel cell, hydrogen as a fuel, under different loads. Furthermore, the electrical efficiency of this cycle at the maximum load was obtained equal to 4/65%, respectively. They have investigated the effects of parameters such as mass flow rate of the air and fuel on the efficiency too.

Also, in 2004, the first and the second law of thermodynamics were studied for this cycle, and the irreversibility of the various components of the cycle with its efficiency was calculated [22]. Uechi and colleagues [23] examined the first and second law of thermodynamics for the combined gas turbine cycle with the solid oxide fuel cell with consideration of hydrogen as fuel. Also, the efficiency of this cycle and the impact of various factors on them were analyzed. Their analyses obtained an increase of 20% in the first efficiency and a 10% increase in the second law in comparison to the analysis of the simple-cycle systems. In this study, the energy efficiency and system exergy efficiency were evaluated at 7/55 and 49%, respectively. Motahar et al. [24], Haseli and colleagues [25], Komatsu and colleagues [26], Zhang and coworkers [27], Mazzucco and colleagues [28] have done very deep works in analyzing these systems under various conditions.

In this study, the first overall structure of the system is defined accurately, and then thermodynamic analysis on different parts of the system and as well as for the overall system is applied. Then, the simulation results for the system are examined, and finally, the comparison of the performance and efficiency in respect to the parameters are explained as well.

II. OVERALL STRUCTURE OF DESIGNED HYBRID CYCLES

The schematic diagram of the hybrid system is shown in Fig. 1. This system consists of six elements as follows:

- Air compressor
- Heater
- Fuel cell or SOFC
- Combustion chamber
- High turbine pressure (HTP)
- Low pressure turbine (LTP)

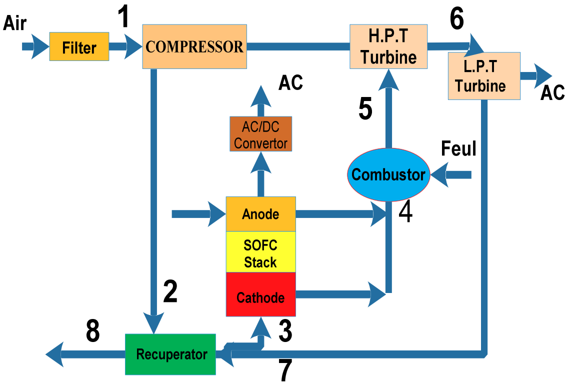

Fig. 1 Detail schematic diagram of the hybrid system

III. DESCRIPTION OF SEQUENCES ACTIVITIES IN THE CYCLE

In the proposed system, air enters to cycle through a compressor and after compression will be directed to the second part. In the power generation systems, preheating the air through the heat exchanger increases the overall efficiency of the system. So, in the second part, this activity is completed. After heating and passing the air in second part, air is transferred to the solid oxide fuel cell or the cathode section. In this field, the air is introduced to the cathode and then it will participate in the electrochemical reaction in the fuel cell. Since the electricity that is generated by this unit is DC power, a converter has been considered to convert it to AC power. Due to the irreversibility of the fuel cell, creation of heat increases and makes the temperature in the fourth part to go up. Almost, entirely mass flow rate by the SOFC fuel is not oxidized. Separately, the output products from the fourth part have warmed to the desired temperature and have burned in the combustion chamber completely.

Then, the working gas of the cycle that has a significant amount of heat energy was caused the high pressure gas turbine to rotate. As shown in the diagram, it is clear that more percent of the pressure of the working gas is used to turn the high pressure turbine. Then, the expanded gas has existed in the sixth part of the gas turbines. Here, it is noticeable that in this section, the working fluid still has a considerable amount of energy in the low pressure turbine section, which has the ability to turn turbines and create more power. So after leaving the low-pressure turbine, the combustion products are expanded to atmospheric pressure level (Part VII). Finally, the exhaust gas exits into the atmosphere in the eighth section.

IV. THERMODYNAMIC ANALYSIS OF COMPONENTS OF SOFC-GT HYBRID SYSTEM

At first, all the assumptions that were applied in the modeling are mentioned.

1. All the components of the gas turbine, are assumed to be adiabatic.
2. Fluid flow components is stable.
3. Changes in potential and kinetic energy are assumed to be zero.
4. The behavior of all gases is ideal gas.

5. Gas spillage of the system was ignored.
6. The distribution of the temperature, pressure and chemical components of the cell are ignored.
7. The anode and cathode exhaust gas temperature are assumed equal to the operating temperature of the fuel cell.

Thermodynamic performance of each component in the system are analyzed here. Energy and mass balance under the premise of a steady flow in the main system are written for components. Working fluid in the system is considered as an ideal gas.

A. Compressor

Isotropic compressor efficiency is defined as in (1).

$$\eta_c = \frac{Wcs}{W_{ca}} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{1}$$

The ideal temperature of the working fluid in the output of the compressor can be characterized in (2).

$$\frac{T_{2s}}{T1} = \left(\frac{P_2}{P_1}\right) \wedge \left(\frac{\gamma - 1}{\gamma}\right) \tag{2}$$

By applying the energy balance for the system, the required work for compressor can be written as (3).

$$\dot{W}_C = \dot{m}_1 \left(h_2 - h_1\right) \tag{3}$$

B. Heater Section

The efficiency of this unit can be modeled as in (4).

$$\varepsilon_{recup} = \frac{T_3 - T_2}{T_7 - T_2} \tag{4}$$

C. Solid Oxide Fuel Cell

Methane fuel is used for system, which has a low heat value of 50050 kJ/ kg. In (5), the anode and cathode sections are formulated as follows.

$$\dot{m}_2 \left(h_3 - h_2\right) = \dot{m}_7 \left(h_7 - h_8\right) \tag{5}$$

The methane and hydrogen used as the fuel in SOFC. In the anode section, the subsequent chemical reactions occurs which can be formulated as in (6).

$$\begin{gathered} H_2 + O = H_2O + 2e^- \\ CO + O = CO_2 + 2e^- \\ CH_4 + 4O = 2H_2O + CO + 8e^- \end{gathered} \tag{6}$$

The net reaction cell can be written as in (7) and (8).

$$\frac{1}{2} O_2 + 2e^- = O \tag{7}$$

$$CH_4 + 2O_2 = 2H_2O + CO_2 \tag{8}$$

Voltage sustainability of the system by the Nernst equation can be expressed as (9).

$$H_2 + \frac{1}{2} O_2 = H_2O \tag{9}$$

In this regard E0 is the ideal cell voltage in the normal working conditions, T = 298.15K and P = 1bar and R are the global gas constant and T is the temperature. Faraday's constant, F, is equal to 96.485 C /mol. The Nernst equation established a link between the potential and ideal standard cell reaction and also other parameters such as temperature and the pressure. With determining of current density J as an electron transfer rate per unit area of the fuel cell, electric power which generated by the fuel cell can be articulated as in (10).

$$E = E^0 + \left(\frac{RT}{8F}\right) \ln \left(\frac{P_{CH_4} P_{O_2}^2}{P_{CO_2} P_{H_2O}^2}\right) \tag{10}$$

Differences between the voltage that obtained by the Nernst voltage are shown as in (11).

$$\dot{W}_{FC,DC} = V_C \times J \times Ac \tag{11}$$

in which VC is the fuel cell voltage and ΔV_{loss} are the total losses due to the irreversibility in the fuel cell. Also, some heat which is generated in fuel cell, is modeled by the (12).

$$V_C = E - \Delta V_{loss} \tag{12}$$

Oxygen that is used in the reaction equation is supplied by the normal air that is imported to the system. If stoichiometric rate is equal to one, the (13) is used for the mass air flow.

$$Q_{gen,FC=} I \Delta V_{loss} = JAc\left(E - V_C\right) \times 10^{-6} \left[kw\right] \tag{13}$$

Mass balance is obtained as in (14) and (15).

$$\sum_{IN} M = \sum_{OUT} M \tag{14}$$

$$Air_{usage} = 3.75 \times 10^{-7} \times \frac{\dot{W}_{FC,DC}}{V_C} \times \lambda \left[kg / s\right] \tag{15}$$

U_f is the factor for fuel. By applying the first law of thermodynamics for the single SOFC and by assuming the adiabatic process, the (16) can be obtained:

$$\begin{aligned} &\dot{m}_3 \dot{m}_{fuel,FC} = \dot{m}_4 = \dot{m}_3 \\ &+ m_{fuel,FC} \times U_f + \dot{m}_{fuel,FC} \times \left(1 - U_f\right) \end{aligned} \tag{16}$$

where LHV is the low heat rate value.

D. Combustion Chamber

By considering the mass of the SOFC unreacted in the combustion chamber to burned mass in the combustion chamber, the subsequent mass balance can be determined. In addition, the fuel products in the fuel cell heats up again in the combustion chamber.

$$\dot{m}_3 h_3 + m_{fuel,FC} \times U_f \times LHV + \dot{m}_{fuel,FC} \times \left(1 - U_f\right) h_{fuel,in} - \dot{W}_{FC,DC} - \dot{m}_4 h_4 = 0 \qquad (17)$$

The first law of thermodynamic for the combustion chamber can be determined as in (18).

$$\left(\dot{m}_3 h_3 + \dot{m}_{fuel,FC} \times U_f\right) + \dot{m}_{fuel,FC}\left(1 - U_f\right) + \dot{m}_{fuel,comb} = \dot{m}_4 + \dot{m}_{fuel,comb} = \dot{m}_5 \qquad (18)$$

E. Gas Turbine

As shown in schematic of the system, the required work for compressor is defined as in (19).

$$\left(\dot{m}_3 + \dot{m}_{fuel,FC} \times U_f\right) h_4 + \dot{Q}_{comb} - \dot{m}_5 h_5 - \dot{Q}_{loss} = 0 \qquad (19)$$

By having the inlet turbine temperature, the output temperature can be obtained and by applying the isotropic efficiency of turbine, this temperature is obtained as in (20).

$$\dot{Q}_{comb} = \left[\dot{m}_{fuel,FC} \times \left(1 - U_f\right) + \dot{m}_{fuel,comb}\right] \times LHV \qquad (20)$$

Also, pressure at the bottom of the flow can be estimated as in (21).

$$\dot{Q}_{loss} = \left[\dot{m}_{fuel,FC} \times \left(1 - U_f\right) + \dot{m}_{fuel,comb}\right] \times \left(1 - \eta_{comb}\right) \times LHV \qquad (21)$$

F. Power Turbine

The principal equations for the power turbine are similar as before. By considering the isotropic efficiency, the temperature of T7 can be obtained as in (22) and (23).

$$\dot{W}_{GT} = \dot{W}_C \qquad (22)$$

$$\eta_{GT} = \frac{W_{GTa}}{W_{GTs}} = \frac{h_5 - h_6}{h_5 - h_{6s}} \qquad (23)$$

The transformed work by generator is obtained as in (24).

$$P_6 = P_5 \left(\frac{T_{6s}}{T_5}\right) \wedge \left(\frac{\gamma}{\gamma - 1}\right) \qquad (24)$$

V. VERALL BALANCE EQUATION FOR HYBRID SYSTEM

Integrated power generation system, which can be shown in schematic diagram, can be modeled as a volume system. In the following, mass balance with applying the first law of thermodynamics can be written as in (25).

$$\eta_{PT} = \frac{W_{PTa}}{W_{PTs}} = \frac{h_6 - h_7}{h_6 - h_{7s}} \qquad (25)$$

VI. ENERGY BALANCE FOR WHOLE SYSTEM

The overall energy balance for the system can be computed as in (26) to (30).

$$T_{7s} = T_6 \left(\frac{P_7}{T_7}\right) \wedge \left(\frac{\gamma - 1}{\gamma}\right) \qquad (26)$$

$$\dot{W}_{PT} = \dot{m}_6\left(h_6 - h_7\right) \qquad (27)$$

$$\begin{aligned} &\dot{m}_1 + \dot{m}_{fuel} - \dot{m}_8 = 0 \\ &\dot{m}_1 = \dot{m}_2 = \dot{m}_3 \\ &\dot{m}_{fuel} = \dot{m}_{fuel,FC} + \dot{m}_{fuel,comb} \\ &\dot{m}_5 = \dot{m}_6 = \dot{m}_7 = \dot{m}_8 \end{aligned} \qquad (28)$$

$$\dot{m}_1 h_1 + \dot{m}_{fuel,FC} \times U_f \times LHV_{CH_4} + \dot{Q}_{comb} - \dot{m}_8 h_8 - \dot{Q}_{loss} - \dot{W}_{FC,DC} - \dot{W}_{PT} = 0 \qquad (29)$$

$$\begin{aligned} &\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{tot}} \\ &\dot{W}_{net} = \dot{W}_{FC,AC} = \dot{W}_{Gen} \\ &\dot{W}_{FC,AC} = \eta_{invert} \dot{W}_{FC,AC} \\ &\dot{W}_{Gen} = \dot{W}_{Gen} \dot{W}_{PT} \\ &\dot{Q}_{tot} = \dot{m}_{fuel,FC} \times U_f \times LHV_{CH_4} + \dot{Q}_{comb} \end{aligned} \qquad (30)$$

The operational parameters of this simulation are shown in Table I.

TABLE I
OPERATIONAL PARAMETERS FOR FUEL CELL

Gas turbine	
Compressor efficiency	0.81
Turbine efficiency	0.84
Power turbine efficiency	0.89
Heat exchanger efficiency	0.8
Combustion efficiency	0.98
AC convertor efficiency	0.95
Solid oxide fuel cell	
Factor of air use	0.25
Factor of fuel use	0.85
Temperature of fuel cell	1273
Current density	0.3
Efficiency of AC/DC convertor	0.89
Area of fuel cell	834
Pressure losses	
Heat exchanger	4
Fuel cell	4
Combustion chamber	5
Environment conditions	
temperature	288
pressure	1

In Fig.2, the power rate of the fuel cell in respect to the mass flow rate of methane is plotted. As shown in the figure, it can be determined that, there is an optimal point for the flow rate that above that, it has adverse effect for the generated power.

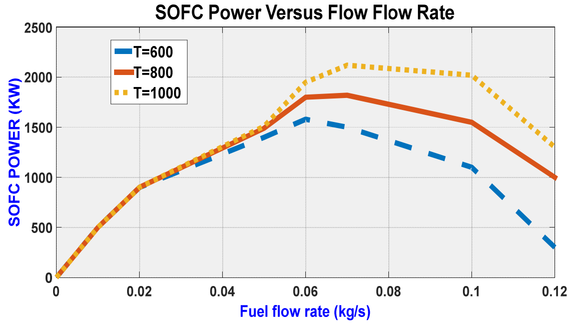

Fig. 2 Comparison of power of fuel cell according to the mass flow

On the other hand, for having comparison result in respect to the type of the fuel on power generation of the fuel cell, two kinds of fuel like methane and hydrogen are used for the simulation. This result is shown in Fig. 3 and it is understandable that hydrogen makes more power. Also, it can be concluded if the fuel ratio is increased above an optimal point, it causes to the decrease of the power.

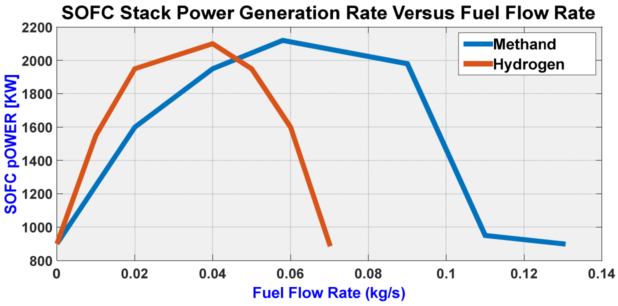

Fig. 3 Comparison of fuel cell power according two different type of fuel

In Fig. 4, it is obvious that efficiency of the hybrid system is more than the gas turbine independently. Also it is noticeable that there is an optimal point for the pressure ratio that above it, the efficiency would be decreased.

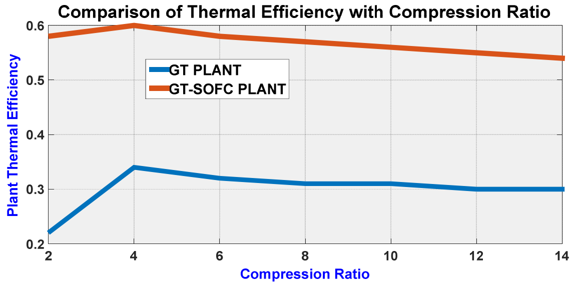

Fig. 4 comparison of thermal efficiency in different pressure ratio

By increasing the pressure and simultaneously fixing the cell operating temperature, cell voltage is expected to drop. But the important thing is that by increasing the pressure, which are shown in Figs. 5 and 6, temperature of the fuel cell stack and also gas output would be declined.

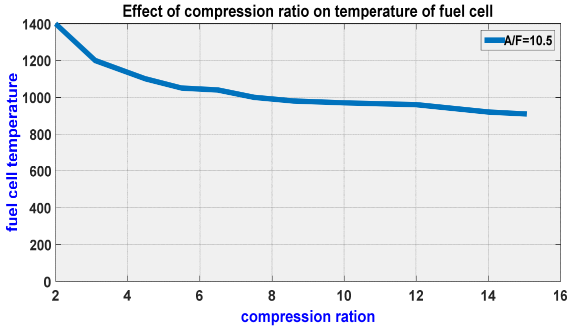

Fig. 5 Influence of compressor pressure ration on operational temperature of fuel cell

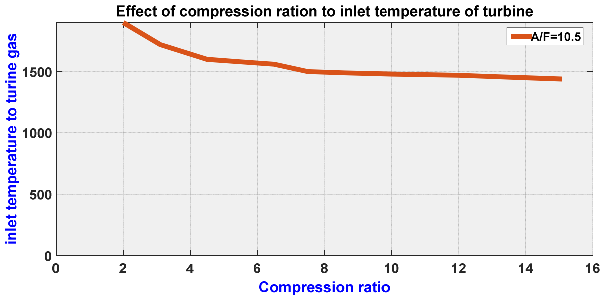

Fig. 6 Influence of compressor pressure ration on output temperature of turbine

Since the output heat of the turbine is used for pre heating of air and also inlet fuel in the system, the result of decreasing the temperature in inlet section of the fuel makes the operational temperature and inlet temperature of the turbine to decrease. Also, by increasing the fuel to air ratio value, the cooling effect on the fuel cell is increased and the output power is decreased. On the other hand, for deprivation of raising of the temperature to limit of the 1000 degree and also avoiding to the hazardous status for the fuel cell, the minimum operational pressure at different ratio of the fuel to air ratio should be calculated accurately.

In Fig. 7, the electrical efficiency of the hybrid system at different pressure is shown and simulated. As obvious in the figure, the efficiency variation is dependent to the fuel to air ratio and also compression ratio as well.

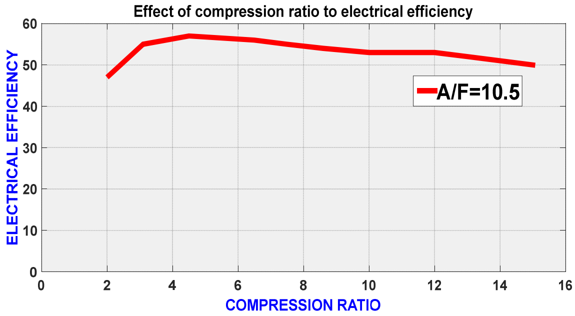

Fig. 7 the influence of compression ratio on electrical efficiency

In summary, limitation of the temperature in the fuel cell, lead to the restriction conditions in choosing the operational pressure for the system. So, compression ratio and inlet temperature of turbine are the two key parameters that we should consider and simulate it accurately.

VII. CONCLUSION

In this study, energy analysis for the hybrid system with two different types of the fuel cell are developed and then the parameter analysis on the performance and output power of the fuel cell are simulated. In summary, it can be concluded based on the simulation results that, the compressor ratio and inlet temperature of the turbine are the two significant parameters for design of the system and also for defining the optimal operational range for the system. So, these two parameters should be defined accurately in the different ranges of the operational conditions of the system.

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