Steady-State Optimal Power Flow in Integrated Electricity and Gas Transmission Systems with Hydrogen Injections

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***Abstract*—Hydrogen is a promising clean energy source for the future energy system. The power-to-gas facilities produce hydrogen from surplus renewable generations, and inject it into the natural gas transmission pipelines for transportation and further use. The operating condition of the Integrated Electricity and Gas Systems (IEGS) should be fully aware and optimized, for restraining the injection of hydrogen within a secure range. This paper proposes a steady-state optimal power flow technique for IEGS with distributed hydrogen injections. First, the IEGS is reformulated in an energy-balanced form considering the impact of hydrogen injection. Then, the steady-state optimal power flow problem is formulated, considering the security constraints of the Wobbe index, the composition of hydrogen, and the Gross Calorific Value at various gas buses. Finally, the proposed technique is validated using IEEE 24-bus RTS and Belgium gas transmission system.**

Keywords—optimal power flow, integrated electricity and gas power flow, hydrogen injection, Wobbe index

I. INTRODUCTION

Hydrogen, as a clean and efficient energy source, has become an alternative to traditional fossil fuels, such as natural gas in many countries. The UK government, as stated in its white paper, is working with the industry closely for achieving 5 GW of low-carbon hydrogen production capacity by 2030 [1]. Green hydrogen, which is usually produced by surplus renewable energy generations through power-to-gas (PTG) technologies, is also viewed as the most promising type of hydrogen to reduce carbon emission. The hydrogen can be transported by various means. Blending the hydrogen into the transmission pipelines of natural gas is one of the most attractive ways, for it can not only use the existing infrastructures and avoid further investment, but also can decarbonize the operation of the gas system.

However, blending the hydrogen into the gas pipelines can cause risks: 1) the hydrogen is more likely to cause fire hazards for its lower ignition point and higher burning rate compared with other fuels [2]. 2) gas appliances are designed and tested under certain gas pressure and composition. Otherwise, they will be working in an unidealized condition, which will lead to non-optimal combustions [3]. 3) at the network level, the components, such as pipelines, compressors, valves, etc., are usually designed for the given gas composition in this region. the variation of the gas mixture can cause damage to the materials [4]. 4) the injection of hydrogen at different locations can influence the pressures and gas flow pattern in the system. However, the safety issues can be minimized if the blended hydrogen is limited within a certain range. Therefore, it is important to be aware of the fraction of hydrogen at different locations of the network, and the optimize the operating status of the IEGS.

The impact of gas injection on the gas systems is extensively investigated in previous research. The dynamic behavior of non-isothermal compressible natural gases mixed with hydrogen in pipelines is studied in [5]. Steady-state simulation of gas networks with the distributed injection of alternative gas is studied in [6]. An efficient method for simulation of long-distance gas transport networks with large amounts of hydrogen injection is developed in [7]. In recent years, with the intensified interaction between the electricity and gas system, the impact of hydrogen injection on the operation of integrated electricity and gas systems (IEGS) gains attention. The IEGS coupled through hydrogen blending under increasing distributed photovoltaic generation is studied in [8]. The gas composition tracking is studied in [9], and an automatic gas flow direction identification method is developed. The probabilistic power flow calculation method is further developed in [10]. However, these studies focus on the simulation of electricity and gas flow with hydrogen injections, while the operating condition optimization is not conducted. By this means, the operating condition of the IEGS can be aware, but can not provide the suggestions for optimization if the specified safety constraints are violated.

In light of this background, this paper proposes a steady-state optimal power flow technique for IEGS with distributed hydrogen injections. Firstly, the IEGS with hydrogen injections is specified. Then, the IEGS is modeled. More specifically, the gas demand and gas supply, as well as the nodal gas flow balance are formulated in terms of energy. The mixture of hydrogen and natural gas is also modeled. Moreover, the steady-state optimal power flow problem is formulated, considering the security constraints of the Wobbe index, the composition of hydrogen, and Gross Calorific Value (GCV) at various gas buses. Finally, the proposed technique is validated using IEEE 24-bus RTS and Belgium gas transmission system.

II. STRUCTURE OF IEGS WITH HYDROGEN INJECTIONS

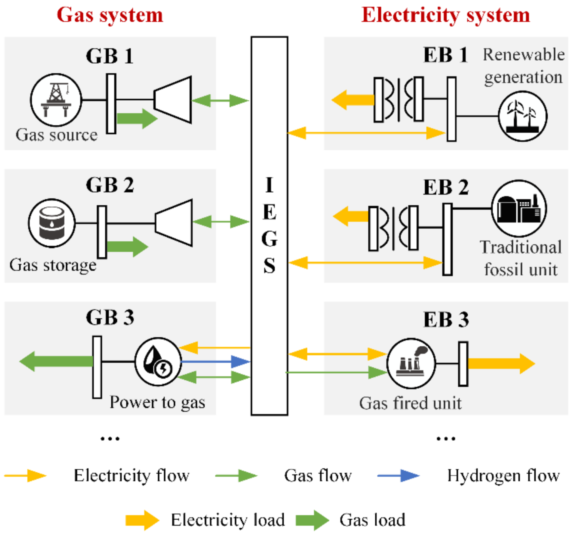

Fig 1. Structure of the IEGS with hydrogen injections

The structure of the IEGS with hydrogen injections is presented in Fig. 1. This paper focuses on the transmission level, where the pressure of the gas and voltage of electricity is high. The gas pipelines transport the gas from gas sources, including gas wells and gas storage at gas buses (GB) to various locations to satisfy the gas demand. The electricity and gas systems are coupled by gas-fired units (GFU) and PTGs. The GFU consumes the gas from the IEGS to generate electricity. PTG facilities consume electricity, usually from the surplus renewable generations, to produce hydrogen, or other synthetic gas, such as methane, which is injected into the gas pipeline for transportation and later use.

III. MODEL OF THE IEGS

A. Model of the Gas System With Hydrogen Injections

a) Gas demand

The nature of gas demand of consumers is to burn the gas to provide heat energy to appliances, for example, the cooking equipment. Therefore, the gas demand is the combustion energy demand essentially. In the traditional gas system, the gas demand is usually represented by the volume of gas at standard temperature and pressure (STP). This representation is suitable, and makes the calculation of gas flow easier when the gas composition across the gas network at various locations is the same. However, in the IEGS with distributed hydrogen injections, the gas composition may not be the same at different GBs. That is, the combustion of the same volume, mass, or mole of gas will not provide the same heat energy if the gas compositions are different. Therefore, the original gas demand represented by the volume in STP should be converted by:

$$e_i^d = q_i^d GCV^{gas} \tag{1}$$

where e_i^d is the gas demand measured by energy at GB i; q_i^d is the original gas demand measured by the volume of the original composition of gas in STP without the hydrogen injection; GCV^{gas} is the GCV of natural gas.

b) Gas source

The gas supplies of gas sources, including gas wells and gas storage, are usually measured by the gas flow rate in the traditional IEGS. For the same reason as the gas demand, it is converted into energy demand:

$$e_i^s = GCV_i^s q_i^s \tag{2}$$

where e_i^s is the energy supply at GB i; q_i^s is the gas supply at GB i measured in gas flow rate; GCV_i^s is the GCV of the gas supply of the gas source at GB i.

c) Steady-state gas flow in a pipeline

For the gas transmission system with high gas pressure (>7 bar), the Weymouth equation is used [11]:

$$\left(q_{i,j}\right)^2 = \frac{\pi^2 R^{air}}{64}\left(\frac{T^{STP}}{p^{STP}}\right)^2 \frac{\left(p_i^2 - p_j^2\right)D_{i,j}^5}{F_{i,j}S_{i,j}L_{i,j}TZ_{i,j}} \tag{3}$$

where $q_{i,j}$ is the gas flow rate in the pipeline between GB i and j in STP condition; R^{air} is the gas constant of air; T^{STP} and p^{STP} are the temperature and pressure of STP condition; p_i is the gas pressure at GB i; $D_{i,j}$ is the diameter of the pipeline; $F_{i,j}$ is the friction factor; $S_{i,j}$ is specific gravity; $L_{i,j}$ is the length of the pipeline; T is the temperature of the gas; $Z_{i,j}$ is the compressibility of the gas.

d) Nodal energy conservarion and mix

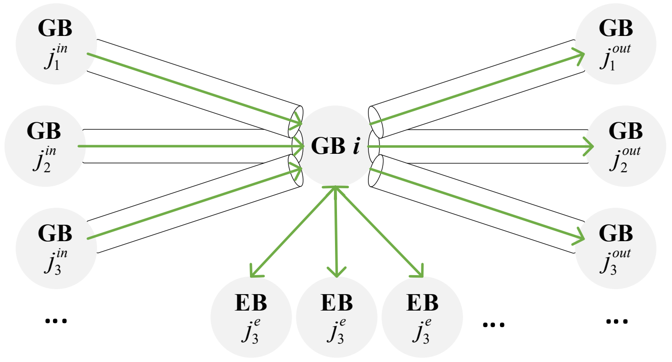

Fig. 2. The topological structure of GB and its connected pipelines

The topological structure of a generalized GB with connected pipelines is presented in Fig. 2. The nodal conservation is formed in the energy form, which indicates that the energy flows into GB i is equal to the energy flow out from GB i:

$$e_i^s - e_i^d + \sum_{j^e \in \vartheta_i^e} \left(e_{j^e}^{ptg} - \sum_{j^e \in \Gamma_{j^e}^{gfu}} e_{j^e, j^{gfu}}^{gfu} \right) + \sum_{j^{in} \in \vartheta_i^{in}} e_{j^{in},i} - \sum_{j^{out} \in \vartheta_i^{out}} e_{i,j^{out}} = 0 \quad (4)$$

$$e_{j^{in},i} = q_{j^{in},i} GCV_{j^{in}} \quad (5)$$

$$e_{i,j^{out}} = q_{i,j^{out}} GCV_i \quad (6)$$

where ϑ_i^e is the set of electricity bus (EB) that is connected to the bus i; $e_{j^e}^{ptg}$ is the energy of gas that is consumed by the PTG at EB j^e; $\Gamma_{j^e}^{gfu}$ is the set of GFU at EB j^e; $e_{j^e, j^{gfu}}^{gfu}$ is the energy of gas consumption of GFU j^{gfu} at EB j^e; ϑ_i^{in} is the set of the GB where the gas flows from j^{in} to i; ϑ_i^{out} is the set of the GB where the gas flows from i to j^{out}; $e_{j^{in},i}$ and $e_{i,j^{out}}$ are the energy of gas flows from j^{in} to i and from i to j^{out}, respectively; $q_{j^{in},i}$ and $q_{i,j^{out}}$ are the gases flow from j^{in} to i and from i to j^{out}, respectively; GCV_i is the GCV of the gas at bus i.

It should be noted that the compositions of the gases from upstream pipelines (e.g., pipeline $j_1^{in}i$, $j_2^{in}i$, etc.) may be different. Then, the gases are mixed at GB i, and the mixture is further transported through different downstream pipelines (e.g., pipeline ij_1^{out}, ij_2^{out}, etc.). Therefore, the direction of the gas flow should be prespecified before the optimization. We assume the flow direction is always from i to j. Then, the constraints which describe the specific gravity and GCV of the mixture at GB i can be calculated by [12]:

$$S_{i,j} = \left(M^{hy} x_i^{hy} + M^{gas} x_i^{gas} \right) / M^{air} \quad (7)$$

$$GCV_i = GCV^{hy} x_i^{hy} + GCV^{gas} x_i^{gas} \quad (8)$$

where M^{gas}, M^{hy}, and M^{air} is the molecular weights of natural gas, hydrogen, and air, respectively; GCV^{hy} is the GCV of hydrogen; x_i^{hy} and x_i^{gas} are the molar fraction of hydrogen and natural gas, respectively, which can be calculated by:

$$x_i^{hy} = \frac{\sum_{j^e \in \vartheta_i^e} q_{j^e}^{ptg} + \sum_{j^{in} \in \vartheta_i^{in}} x_{j^{in}}^{hy} q_{j^{in}i}}{\sum_{j^e \in \vartheta_i^e} q_{j^e}^{ptg} + q_i^s + \sum_{j^{in} \in \vartheta_i^{in}} q_{j^{in}i}} \quad (9)$$

$$x_i^{gas} = \frac{q_i^s + \sum_{j^{in} \in \vartheta_i^{in}} x_{j^{in}}^{gas} q_{j^{in}i}}{\sum_{j^e \in \vartheta_i^e} q_{j^e}^{ptg} + q_i^s + \sum_{j^{in} \in \vartheta_i^{in}} q_{j^{in}i}} \quad (10)$$

where $q_{j^e}^{ptg}$ is the volume of hydrogen production of the PTG at bus j^e.

B. Model of the Coupling Components

a) PTG facilities

PTG facilities consume electricity to produce hydrogen. The energy conversion relationship is represented by:

$$e_i^{ptg} = \eta_i^{ptg} g_i^{ptg} \quad (11)$$

$$e_i^{ptg} = GCV^{hy} q_i^{ptg} \quad (12)$$

where η_i^{ptg} and g_i^{ptg} are the efficiency and electricity consumption of PTG at bus i, respectively.

b) GFU

GFU consumes gas to produce electricity. It should be noted that the composition of gas may be different in different EBs:

$$g_{i,j}^{gfu} = \eta_{i,j}^{gfu} e_{i,j}^{gfu} = \eta_{i,j}^{gfu} q_{i,j}^{gfu} GCV_i \quad (13)$$

where $g_{i,j}^{gfu}$, $q_{i,j}^{gfu}$, and $\eta_{i,j}^{gfu}$ are the electricity generation, gas production, and efficiency of GFU j at bus i, respectively.

C. Model of the Electricity System

The electricity system is modeled using the DC model:

$$\sum_{j \in \Gamma_i^{tfu}} g_{i,j}^{tfu} + \sum_{j \in \Gamma_i^{gfu}} g_i^{gfu} - g_i^{ptg} - g_i^d - \sum_{j \in \vartheta_i} g_{i,j} = 0 \quad (14)$$

$$g_{i,j} = (\theta_i - \theta_j) / X_{i,j} \quad (15)$$

where Γ_i^{tfu} is the set of traditional fossil units at bus i; $g_{i,j}^{tfu}$ is the electricity generation of traditional fossil unit j at bus i; g_i^d is the electricity demand at bus i; $g_{i,j}$ is the electricity flow from bus i to j; θ_i is the phase angle of the voltage at bus i; $X_{i,j}$ is the reactance of the electricity branch i,j.

IV. FORMULATION OF STEADY-STATE OPTIMAL POWER FLOW OF IEGS WITH HYDROGEN INJECTIONS

The steady-state optimal power flow of IEGS with hydrogen injections is formulated based on the network model in the last Section. Similar to the electricity optimal power flow, the optimal power flow of IEGS with hydrogen injections can be used as the theoretical foundation for economic dispatch, contingency management, unit commitment, system planning in representative scenarios, etc.

It should be noted that different from the electricity system, the dynamics of the gas system are slower. To apply the steady-state model, some assumptions are made: 1) the dispatch interval should be long enough, or the scale of the gas system is relatively small, so that the time constant of the gas flow dynamics in the corresponding physical system is shorter than the dispatch interval. The gas flow can then be regarded as stabilized during the dispatch. 2) The gas is regarded as an ideal gas, so that the compressibility factor can be regarded as a constant; 3) the injection of the hydrogen, and the transportation of the gas mixture are isothermal processes. No extra work is done to the gas in the pipeline during the hydrogen injection process.

The optimal power flow in the IEGS with hydrogen injections is to determine the operating condition of the system with a certain objective, such as minimum operating cost C^T. The optimization variables include: 1) gas supply of gas sources q_i^s; 2) nodal gas pressure p_i; 3) electricity generation of traditional fossil unit g_i^s; 4) phase angle of voltage θ_i; 5) electricity generation of GFU g_i^{gfu}; 6) hydrogen production of PTG q_i^{ptg}; 7) compositions of hydrogen and natural gas x_i^{hy} and x_i^{gas}. The optimization problem is formulated as:

$$Min\ \ C^T = \sum_{i\in EB}\sum_{j\in\Gamma_i^{tfu}} cst_{i,j}\left(g_{i,j}^{tfu}\right) + \sum_{i\in GB}\rho_i q_i^s + \mu\sum_{i\in EB} q_i^{ptg} \tag{16}$$

where EB and GB are the set of EBs and GBs, respectively; $cst_{i,j}(\cdot)$ is the cost function of traditional fossil unit j at bus i; ρ_i is the nodal gas production price at GB i; μ is the subsidy price for green hydrogen production.

The objective is subject to the constraints of IEGS in the last Section (1)-(15), and the following constraints:

1) Wobbe index. The gas composition will affect its combustion characteristic, and further affect the performance, lifespan, and even operating security of the appliances. Wobbe index, WI, is commonly used in Europe to measure the feasibility and interchangeability of the alternative gas [13]. It should be limited within the threshold in each GB:

$$WI_i = GCV_i \ / \sqrt{S_{i,j}} \tag{17}$$

$$\left|\frac{WI_i}{GCV^{gas} / \sqrt{M^{gas} / M^{air}}} - 1\right| \le \xi_i \tag{18}$$

where ξ_i is the threshold usually set to 5%-10%.

2) upper limit for gas composition and GCV:

$$0 \le x_i^{hy} \le \alpha_i \tag{19}$$

$$\beta^{\min} \le GCV_i \le \beta^{\max} \tag{20}$$

where α_i is the upper limit for the molar fraction for hydrogen; It should be noted that the requirement for gas composition can vary. Generally, the upper tolerance for hydrogen can be up to 10% in the gas pipeline, while up to 2% for the natural gas vehicles refueling system [4]. $\beta^{\max}$ and $\beta^{\min}$ are the upper and lower limits for GCV, respectively.

3) upper and lower boundaries for other variables:

$$q_i^{s,\min} \le q_i^s \le q_i^{s,\max} \tag{21}$$

$$0 \le q_i^{ptg} \le q_i^{ptg,\max} \tag{22}$$

$$0 \le q_{i,j} \le q_{i,j}^{\max} \tag{23}$$

$$\left|g_{i,j}\right| \le g_{i,j}^{\max} \tag{24}$$

$$x_i^{hy} + x_i^{gas} = 1 \tag{25}$$

$$0 \le x_i^{gas} \le 1 \tag{26}$$

$$g_{i,j}^{gfu,\min} \le g_{i,j}^{gfu} \le g_{i,j}^{gfu,\max} \tag{27}$$

$$g_{i,j}^{tfu,\min} \le g_{i,j}^{tfu} \le g_{i,j}^{tfu,\max} \tag{28}$$

where $q_i^{s,\max}$ and $q_i^{s,\min}$ are the upper and lower bounds of the gas source; $q_i^{ptg,\max}$ is the upper limit of PTG gas consumption; $q_{i,j}^{\max}$ is the transmission capacity of the pipeline i,j; $g_{i,j}^{\max}$ is the transmission capacity of the branch i,j; $g_{i,j}^{gfu,\max}$, $g_{i,j}^{gfu,\min}$, $g_{i,j}^{tfu,\max}$, and $g_{i,j}^{tfu,\min}$ are the upper and lower limits of GFU and traditional fossil unit, respectively.

The above optimal power flow of IEGS with hydrogen injection is a nonlinear optimization problem, which can be tentatively solved by nonlinear solvers such as fmincon function in MATLAB, IPOPT, etc. [14].

V. CASE STUDIES

In this section, an IEGS test system with hydrogen injection is constructed to validate the proposed optimal power flow technique. The test system consists of IEEE 24-bus RTS [15] and the Belgium gas transmission system [16]. The interconnection of the two systems is illustrated in [17]. The hydrogen production capacities of PTGs are set to 0.5 $\mathrm{Mm^3/day}$. The GCVs of hydrogen and natural gas are 12.75 and 41.04 MJ/m^3, respectively. The molecular weights of hydrogen, natural gas, and air are 2, 17.478, and 29 g/mol, respectively. The gas constant of air is 287 J/(kg*K). Temperature and pressure at STP are 288 K and 101325 Pa, respectively. The compressibility factor of gas is 0.8.

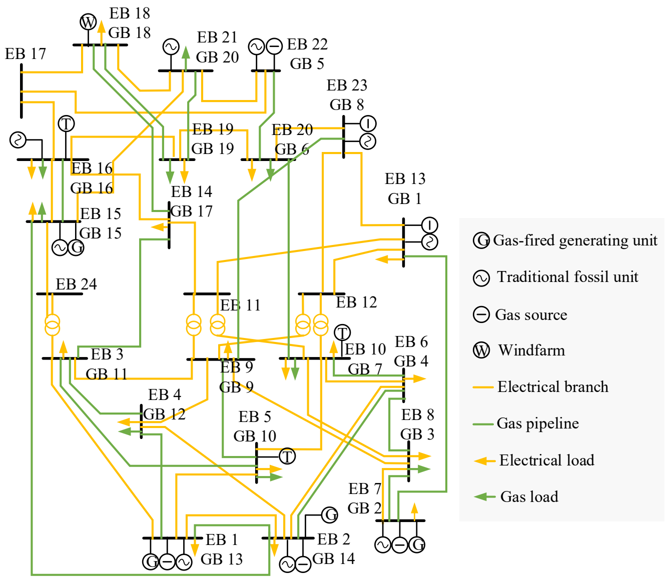

Fig. 3. Test system for IEGS with hydrogen injections

Table I - Table IV shows the results of the optimal electricity and gas power flow with hydrogen injections. The operating cost is $1.80\times10^{5}\ \$$, including the generation cost of $2.84\times10^{4}\ \$$, gas production cost of $1.69\times10^{5}\ \$$, and the subsidy of hydrogen production of $1.70\times10^{4}\ \$$. The nonlinear optimization problem is solved using IPOPT solvers on a Lenovo laptop with an Intel® Core™ i7-8565U 1.80GHz and a 16GB memory. The computation time is 1.90 seconds.

TABLE I. GAS PRODUCTION OF GAS SOURCES

No	Located gas bus	Gas production (Mm^3/day)
1	1	11.59
2	2	7.61
3	5	4.80
4	8	22.01
5	13	1.20
6	14	0.96

TABLE II. GAS PRODUCTION OF PTGS

No	Located gas bus	Located electricity bus	Gas production (Mm^3/day)
1	7	10	0.02
2	10	5	0.50
3	16	16	0.50

TABLE III. GAS PRESSURES AND OTHER PARAMETERS ON GAS BUSES

No	Gas pressure (bar)	Molar fraction of hydrogen	Molar fraction of natural gas	Specific gravity	GCV (MJ/m	Wobbe index (MJ/m
1	61.07	0.00	1.00	0.60	41.04	52.86
2	61.04	0.00	1.00	0.60	41.04	52.86
3	60.91	0.00	1.00	0.60	41.04	52.86
4	59.52	0.00	1.00	0.60	41.04	52.86
5	60.37	0.00	1.00	0.60	41.04	52.86
6	58.60	0.00	1.00	0.60	41.04	52.86
7	58.59	0.07	0.93	0.56	38.99	51.89
8	63.75	0.00	1.00	0.60	41.04	52.86
9	63.33	0.00	1.00	0.60	41.04	52.86
10	61.63	0.02	0.98	0.59	40.41	52.57
11	60.70	0.02	0.98	0.59	40.41	52.57
12	59.26	0.02	0.98	0.59	40.41	52.57
13	58.30	0.02	0.98	0.59	40.48	52.60
14	58.15	0.01	0.99	0.60	40.76	52.73
15	56.95	0.01	0.99	0.60	40.76	52.73
16	55.48	0.04	0.96	0.58	39.89	52.32
17	59.96	0.02	0.98	0.59	40.41	52.57
18	59.90	0.02	0.98	0.59	40.41	52.57
19	28.82	0.02	0.98	0.59	40.41	52.57
20	26.40	0.02	0.98	0.59	40.41	52.57

TABLE IV. GAS FLOW OF GAS PIPELINES

Gas pipeline	From	To	Gas flow (MJ/m
1	1	2	11.59
2	2	3	19.21
3	3	4	15.29
4	5	6	4.60
5	6	7	0.27
6	7	4	-4.98
7	4	14	10.31
8	8	9	22.01
9	9	10	22.01
10	10	11	14.52
11	11	12	12.35
12	12	13	10.20
13	13	14	11.40
14	14	15	22.46
15	15	16	15.57
16	11	17	2.17
17	17	18	2.17
18	18	19	2.17
19	19	20	1.95

VI. CONCLUSIONS

With the blending of hydrogen in the gas transmission pipelines, it is important to optimize the operating condition of the IEGS for controlling the hydrogen within a secured range. This paper proposes a steady-state optimal power flow technique for the IEGS with hydrogen injections. Firstly, the IEGS is modeled considering the impact of hydrogen injection. Then, the steady-state optimal power flow problem is formulated, considering the security constraints of the Wobbe index, the composition of hydrogen, and the Gross Calorific Value at various gas buses.

The proposed technique is validated using a test case. The optimization results of the gas production from gas sources and PTGs, the nodal gas pressure, gas flows in the pipelines, and the gas compositions at gas buses are presented. The steady-state optimal power flow technique developed in this paper can provide theoretical foundations for further analysis, such as reliability evaluation, unit commitment, planning, etc., for IEGS with hydrogen injections. The numerical results in the case studies can also serve as a benchmark for validating other potential advanced optimization methods for IEGS in future research.

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