Coordinated Operations of Hydrogen and Power Distribution Systems

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***Abstract*—With increasing penetrations of renewable energy in power distribution systems, operators is facing challenges on reducing renewable energy curtailment, which is caused by supply-demand mismatch, feeder congestion, and nodal voltage limits. Converting surplus renewable electricity into hydrogen by electrolyzors has been recognized a potential way to address this. To this end, we proposed a coordinated operation approach for hydrogen and power distribution systems, considering distribution level power and hydrogen pipeline flows, as well as storage capabilities provided by linepack. The proposed approach can be used to investigate the benefits from our coordinated approach on the basis of current separated practice. Our numerical simulations show that the proposed coordinated dispatch model can utilize the benefit of renewable power to minimum the total cost and improve the utilization of transmission lines.**

***Index Terms*—power distribution network, hydrogen storage, hydrogen transportation, renewable energy**

Nomenclature

Indices

b, t, z	Index for buses, time periods and zones

Sets

$\mathcal{B}$	Set of total buses
$\mathcal{B}_{root}$	Set of buses containing generators
$\mathcal{HE}$	Set of total electrolyzors
$\mathcal{HE}_b$	Set of electrolyzors connected with bus b
$\mathcal{HE}_z$	Set of electrolyzors in zone z
$\mathcal{HR}$	Set of total steam methane reformers
$\mathcal{HR}_z$	Set of steam reformers in zone z
$\mathcal{L}$	Set of transmission lines
$\mathcal{P}$	Set of hydrogen pipelines
$\mathcal{T}_s$	Set of hourly time periods
$\mathcal{Z}$	Set of total zones

Parameters

η_i	Efficiency of electrolyzor i
$\hat{\lambda}_t$	Price of electricity at time t
$\overline{E}_i^{pip}$	Maximum hydrogen storage of pipe i
$\overline{H}_i$	Maximum production of hydrogen producer i
$\overline{H}_z^{pip}$	Maximum hydrogen charging of zone z
$\overline{P}_i^{pip}$	Maximum hydrogen charging of pipe i
$\underline{V}_b, \overline{V}_b$	Lower/upper limit power of squared voltage magnitude at bus b
C_i^{prd}	Cost of steam methane reformer i
$D_{z,t}^{hyd}$	Hydrogen load of zone z at time t
$p_{b,t}^D$	Active load of bus b at time t
$q_{b,t}^D$	Reactive load of bus b at time t
$r_{m,n}, x_{m,n}$	Resistance, reactance of branch (m,n)
$S_{m,n}$	Maximum power capacity of branch (m,n)

Decision Variables

$e_{i,t}^{pip}$	Hydrogen storage of pipe i at time t
$f_{b,n,t}^P, f_{b,n,t}^Q$	Active/reactive flow from bus b to n at time t
$h_{z,t}^{pip\ ch}$	Hydrogen input of zone z at time t
$h_{z,t}^{pip\ dc}$	Hydrogen output of zone z at time t
$h_{i,t}$	Hydrogen generation of steam methane reformer i at time t
$p_{b,t}^{root}, q_{b,t}^{root}$	Active/reactive power generation of bus b at time t
$p_{i,t}^{HE}, q_{i,t}^{HE}$	Active/reactive power consumption of electrolyzor i at time t
$p_{i,t}^W, q_{i,t}^W$	Active/reactive power generation of solar power station i at time t
$q_{i,t}^{pip\ head}$	Hydrogen input of pipe i at time t
$q_{i,t}^{pip\ tail}$	Hydrogen output of pipe i at time t
$u_{b,t}$	Power rate of bus b at time t

I. Introduction

To reduce carbon emissions, the capacity of renewable energy sources, such as solar and wind plants, have increased rapidly in recent decades. The electricity generation from renewable energy is predicted to reach 25%-41% of the total energy by 2040 [1]. Meanwhile, in power distribution systems, it is challenge to reduce renewable energy curtailment caused by supply-demand mismatch, feeder congestion, and nodal voltage limits. With recent technological development in electrolyzers, converting surplus renewable energy to hydrogen becomes more appealing. Given the investments on renewable electricity substations and hydrogen supply chains are expected to increase, an approach that can be used to evaluate the benefits from coordinated operations is highly needed.

The operations of both hydrogen and power distribution systems have been widely studied in the literature separately. For the power distribution systems, an approach is proposed in [2] to realize an integrated control and operation of devices that will enable a more optimal operation of the grid, resulting in a increased overall effectiveness of operation. [3] designed a renewable energy hybrid system consisting of photovoltaic (PV) panels and wind turbines for electricity and hydrogen production. [4] describes the hydrogen production and transmission model, which is a network optimization tool for identifying the lowest cost centralized production and pipeline transmission infrastructure within real geographic regions.

Operation of power systems with high penetration of renewable energy sources is challenging due to the fluctuating nature of renewables. To accommodate this fluctuation, rapid acting of other flexible resources may not always be available [5]. Alternatively, the surplus renewable energy utilization together with storage capabilities in hydrogen (H_2) systems can offer sufficient flexibility to address the fluctuation of renewable energy. Some recent works start to take the coupling of power and hydrogen systems into consideration. A new hybrid system is proposed in [6], in which a wind farm, a concentrated solar power plant with thermal energy storage, and an electric heater is included. The major role of the coordinated approach is to convert the redundant wind power into thermal energy. [7] presents the operation strategy of an isolated micro-grid with renewable energy and power-to-hydrogen scheme. In [8] and [9], a novel strategy is presented to control stand-alone hybrid renewable electrical systems with hydrogen storage. In their work, if the renewable sources produce more energy than the one required by the loads, the remained energy can be used either to charge the batteries or to produce H_2 in the electrolyzer. The control strategy optimizes how the remained energy is used. If the amount of energy demanded by the loads is higher than the one produced by the renewable sources, the control strategy determines the most economical way to meet the energy deficit. [10] establishes a detailed model to couple the power-to-heat and power-to-hydrogen processes. Then, a simplified Power-to-hydrogen dispatch model is proposed for the electricity-heat-hydrogen dispatch coordinated with active distribution networks and district heating networks.

These prior works explored several important aspects of power-hydrogen interactions, however, the coordination of hydrogen and power distribution systems networks can be further enhanced with more detailed considerations of the hydrogen system. For renewable energy penetrated distribution systems, such coordination is rarely investigated in the literature, especially considering flexibility from the linepack of hydrogen pipeline systems. To overcome these limitations and maximize the utilization of renewable generation, we present a coordinated operation approach for hydrogen and power distribution systems, considering distribution level power and hydrogen flows. When the electricity price from the wholesale market is low or the power from renewable power station is sufficient, the coordinated system could convert the surplus energy to hydrogen and transport them via the pipeline network. While when the power from electricity network cannot cover the demand of hydrogen system, it use a strategy to operate the production of hydrogen to minimize the total cost of the two systems.

The contributions of this work include the following.

1) A coordinated operation approach for hydrogen and power distribution systems is proposed with power flow and hydrogen pipeline considerations.

2) Through numerical simulations, we found coordinated operation with our proposed approach can save system cost compared with separate operations. Renewable energy curtailment appearing in the power distribution system can also be reduced.

II. Coordinated Dispatch for Hydrogen and Power Distribution Systems

The coordinated dispatch model for hydrogen and power distribution systems is described in this section. In our model, the hydrogen can be transformed from electricity by electrolyzors to minimum the operation cost. We follow a bottom-up description in this section, where power and hydrogen parts are elaborated separately first.

A. Power System Model

The physical characteristics of electricity delivery, renewable energy generation, and electrolysis are modeled in this subsection.

1) Power Distribution System Cost: The cost for electricity from the bulk power system is modeled. $\mathcal{B}_{root}$ is the substation bus. $\hat{\lambda}_t$ is the local marginal price (LMP) from the wholesale electricity market, while $p_{b,t}$ is the power generation from each substation bus at time t.

$$\vartheta_s = \sum_{t\in\mathcal{T}_s}\sum_{b\in\mathcal{B}_{root}} \hat{\lambda}_t p_{b,t}^{root}. \tag{1}$$

2) Power Balance: We model power flow balance for active and reactive power respectively in constraints (2a) and (2b). Constraint (2c) is added to limit the power flow to zero in disconnected branches.

$$\sum_{(b,n)\in\mathcal{L}} f_{b,n,t}^{P} - \sum_{(m,b)\in\mathcal{L}} f_{m,b,t}^{P} = 1_{b\in\mathcal{B}_{root}} \cdot p_{b,t}^{root} + \sum_{i\in\mathcal{W}^b} p_{i,t}^{W} - \sum_{i\in\mathcal{HE}_b} p_{i,t}^{HE} - p_{b,t}^{D},\ \forall b\in\mathcal{B}, \forall t\in\mathcal{T}_s, \tag{2a}$$

$$\sum_{(b,n)\in\mathcal{L}} f_{b,n,t}^{Q} - \sum_{(m,b)\in\mathcal{L}} f_{m,b,t}^{Q} = 1_{b\in\mathcal{B}_{root}} \cdot q_{b,t}^{root} + \sum_{i\in\mathcal{W}^b} q_{i,t}^{W} - \sum_{i\in\mathcal{HE}_b} q_{i,t}^{HE} - q_{b,t}^{D},\ \forall b\in\mathcal{B}, \forall t\in\mathcal{T}_s, \tag{2b}$$

$$f_{m,n,t}^{P} = 0, f_{m,n,t}^{Q} = 0, \quad \forall (m,n)\notin\mathcal{L}, \forall t\in\mathcal{T}_s. \tag{2c}$$

The amount of power change is equal to the difference value of power generation, including power generation of substation bus $p_{b,t}^{root}$ and renewable power $p_{i,t}^{W}$, and power consuming, including base load $p_{b,t}^{D}$ and hydrogen production cost $p_{i,t}^{HE}$. What should be emphasized is that only the root bus has the parameter $p_{b,t}^{root}$. Other buses can only accept the power from market by transmission lines and their power generation is equal to 0. The reactive power has the same pattern.

3) Power Flow: The active and reactive power flow in line is limited by the voltage in both ends in (3a) and the maximum load of line in (3b), and the voltage magnitude bounds are shown in (3c), i.e.

$$u_{m,t} - u_{n,t} = 2\left(r_{m,n}\cdot f_{m,n,t}^{P} + x_{m,n}\cdot f_{m,n,t}^{Q}\right), \quad \forall (m,n)\in\mathcal{L}, \forall t\in\mathcal{T}_s, \tag{3a}$$

$$f_{m,n,t}^{P\ 2} + f_{m,n,t}^{Q\ 2} \le S_{m,n}^{2}, \quad \forall (m,n)\in\mathcal{L}, \forall t\in\mathcal{T}_s, \tag{3b}$$

$$\underline{V}_b^2 \le u_{b,t} \le \overline{V}_b^2, \quad \forall b\in\mathcal{B}, \forall t\in\mathcal{T}_s. \tag{3c}$$

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Flow limit constraints in (3b) can be linearized in (4) with n_k linear constraints.

$$\phi^k_{m,n} f^P_{m,n,t} + \chi^k_{m,n} f^Q_{m,n,t} \leq \psi^k_{m,n},$$
$$\forall (m,n) \in \mathcal{L}, \forall t \in \mathcal{T}_s, \forall k = 1,..,n_k. \quad (4)$$

where, $\phi^k_{m,n} = \cos(2k\pi/n_k)$, $\chi^k_{m,n} = \sin(2k\pi/n_k)$, and $\psi^k_{m,n} = S_{m,n} \cdot \cos(\pi/n_k)$.

B. Hydrogen System Model

The hydrogen production, pipeline transportation and storage are modeled in this section II-B.

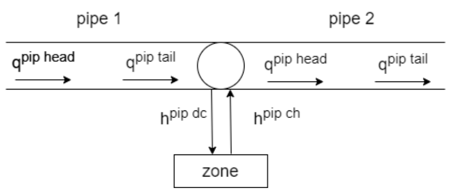

Fig. 1. Example for hydrogen mass flow

1) Hydrogen Network Cost: The cost for hydrogen production is modeled in (5), where the C^{prd}_i is the cost of hydro generation of steam methane reformer, usually a constant value. The amount of hydrogen production of steam methane reformer i at time period t is defined as $h_{i,t}$, i.e.

$$\varphi_s = \sum_{t \in \mathcal{T}_s} \sum_{i \in \mathcal{HR}} C^{\text{prd}}_i \cdot h_{i,t} \quad (5)$$

2) Hydrogen Mass Balance: The hydrogen quantity in each zone changes according to the pipeline transformation. As (6) shows, the difference of hydrogen production and hydrogen base load in zone i is equal to the difference of hydrogen outflow and inflow by pipeline in zone i, in which $q^{\text{pip head}}_{i,t}$ is the energy flow at the head of pipeline i, while $q^{\text{pip tail}}_{i,t}$ is the flow at tail. These values can be positive or negative to control the flow direction. (z,n) means the pipeline from zone z to n, where z is defined as the head of pipeline and n is the tail. η_i is the efficiency of transformation from electricity to hydrogen in electrolyzor i.

$$\sum_{i \in \mathcal{HR}_z} h_{i,t} + \sum_{i \in \mathcal{HE}_z} \eta_i \cdot p^{HE}_{i,t} - \sum_{i|i=(z,n) \in \mathcal{P}} q^{\text{pip head}}_{i,t} +$$
$$\sum_{i|i=(m,z) \in \mathcal{P}} q^{\text{pip tail}}_{i,t} = D^{\text{hyd}}_{z,t}, \forall z \in \mathcal{Z}, t \in \mathcal{T}_s. \quad (6)$$

3) Hydrogen Production: The bounds for two types of hydrogen production units are shown in (7a) and (7b).

$$0 \leq h_{i,t} \leq \overline{H}_i \quad \forall i \in \mathcal{HR}, t \in \mathcal{T}_s. \quad (7a)$$
$$0 \leq \eta_i \cdot p_{i,t} \leq \overline{H}_i \quad \forall i \in \mathcal{HE}, t \in \mathcal{T}_s. \quad (7b)$$

4) Pipeline with Linepack Consideration: To keep the whole formulation tractable, we use a simplified pipeline model. The net hydrogen flow to each zone z, is defined as the difference of charge and discharge flows $h^{\text{pip dc}}_{z,t} - h^{\text{pip ch}}_{z,t}$, equals to total flow from connected pipelines as shown in Fig. 1. Each pipe has a storage and the $q^{\text{pip head}}_{i,t}$ and $q^{\text{pip tail}}_{i,t}$ are not necessary to be equal. This flow balance constraint is modeled in (8a). For each zone, there's a limit for the charging hydrogen to pipeline in (8b). Both directional hydrogen flows from and to the pipeline network in each zone are bounded in (8c) and (8d). For each pipeline, hydrogen flows at both ends of the pipeline are limited by line capacity. We model this feature in (8c)–(8d). Linepack storage dynamics of each pipeline are presented in (8e). The state of charge (SOC) of line pack storage for each pipeline is limited by its capacity in (8f). The recycle conditions for linepack storage are presented in (8g).

$$h^{\text{pip dc}}_{z,t} - h^{\text{pip ch}}_{z,t} = \sum_{i|i=(m,z) \in \mathcal{P}} q^{\text{pip tail}}_{i,t} - \sum_{i|i=(z,n) \in \mathcal{P}} q^{\text{pip head}}_{i,t},$$
$$\forall z \in \mathcal{Z}, t \in \mathcal{T}_s, \quad (8a)$$
$$0 \leq h^{\text{pip ch}}_{z,t} \leq \overline{H}^{\text{pip}}_z, \quad 0 \leq h^{\text{pip dc}}_{z,t}, \quad \forall z \in \mathcal{Z}, t \in \mathcal{T}_s, \quad (8b)$$
$$-\overline{P}^{\text{pip}}_i \leq q^{\text{pip head}}_{i,t} \leq \overline{P}^{\text{pip}}_i, \quad \forall i \in \mathcal{P}, t \in \mathcal{T}_s, \quad (8c)$$
$$-\overline{P}^{\text{pip}}_i \leq q^{\text{pip tail}}_{i,t} \leq \overline{P}^{\text{pip}}_i, \quad \forall i \in \mathcal{P}, t \in \mathcal{T}_s, \quad (8d)$$
$$e^{\text{pip}}_{i,t} = e^{\text{pip}}_{i,t-1} + q^{\text{pip head}}_{i,t} - q^{\text{pip tail}}_{i,t}, \quad \forall i \in \mathcal{P}, t \in \mathcal{T}_s, \quad (8e)$$
$$0 \leq e^{\text{pip}}_{i,t} \leq \overline{E}^{\text{pip}}_i \quad \forall i \in \mathcal{P}, t \in \mathcal{T}_s, \quad (8f)$$
$$e^{\text{pip}}_{i,|\mathcal{T}_s|} = e^{\text{pip}}_{i,0} \quad \forall i \in \mathcal{P}, s \in \mathcal{S}. \quad (8g)$$

C. Coordinated Dispatch Model

Finally, the proposed coordinated dispatch model is formulated in (9), wherein the objective function is the sum of the operation cost for hydrogen and power distribution systems. The physical constraints of the two systems are also incorporated in the constraints, i.e., (6)-(8) for hydrogen part and (2)–(4a) for the power part.

$$\min \quad \sum_{s \in \mathcal{S}} (\vartheta_s + \varphi_s) \quad (9a)$$
$$\text{s.t.} \quad (2) - (4), (6) - (8) \quad (9b)$$

III. Case Study

A. System Settings

We use a modified IEEE 33-bus power distribution system and a 4 zones hydrogen system as our testing case. The performance of both separate and coordinated operations are evaluated to demonstrate the advantages of our proposed approach. All optimization problems are solving by Gurobi 9.0.3 on a computer with i9-9900 core and 64GB RAM. To study a system with renewable energy, we modified the IEEE 33-bus system. Three solar stations are connected to the 3 nearest buses to provide renewable energy. A representative 24-hour time period is used in our simulation.

We present the hydrogen pipeline system in Fig. 2, in which there are four zones, six pipelines and two steam methane reformers. Steam methane reformers belong to zones 3 and 4, while zones 1 & 2 have a base load and need hydrogen supplementation from the zones 3 & 4. Zones 3 and 4 are also connected with the electricity network with electrolyzors.

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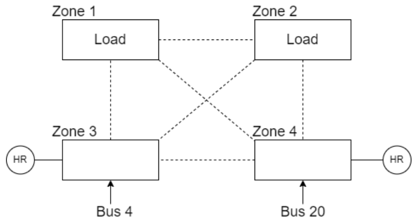

Fig. 2. Pipeline network

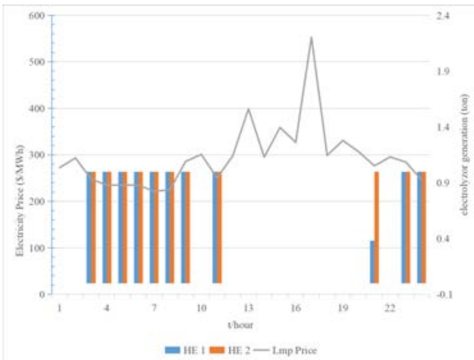

Fig. 3. Price and energy conversion of electrolyzors

B. Coordinated versus Separate Operations

We compare our proposed coordinated dispatch model with a separate model, which makes the power transmission system and the hydrogen transportation system separately without considering candidate electrolyzor units. The separate dispatch model in fact ignores the coupling between these two systems. As indicated, the coordinated dispatch has benefits in reducing the overall annualized investment and operational cost in comparison to the separate model. From the perspective of integrated power and hydrogen system, electrolyzor provides an alternative option to relieve such deliverability and/or congestion issues through converting electricity power to hydrogen to serve the hydrogen loads.

1) Cost Benefit Analysis: The relationship between electricity price of market and the amount of power generation of two electrolyzors without solar power is shown in Fig. 3. The coordinated approach prefers to buy power from the wholesale market and convert electricity to hydrogen when the electricity price is low, while when it is high the system will use steam methane reformers to produce hydrogen instead of electrolyzors.

We use 3 different time period scenarios to evaluate the performance of our coordinated model, while the performance is shown in Fig. 4. In scenario 1, we consider the performance during night, with no solar power input. In this scenario, our proposed coordinated model save 7% money from $14,415 to $13,427, as only the difference of hydrogen and electricity generation cost can be utilized. In scenario 2, the solar power is enough to cover the load of hydrogen system, and the only cost is the load of part electricity buses, where the solar power can not totally cover because of the limitation of transmission lines. In scenario 3, the solar power is utilized but cannot cover the total cost of electricity and hydrogen load, which is the most common situation of reality system. In this scenario we save 53.03% cost by our proposed coordinated system.

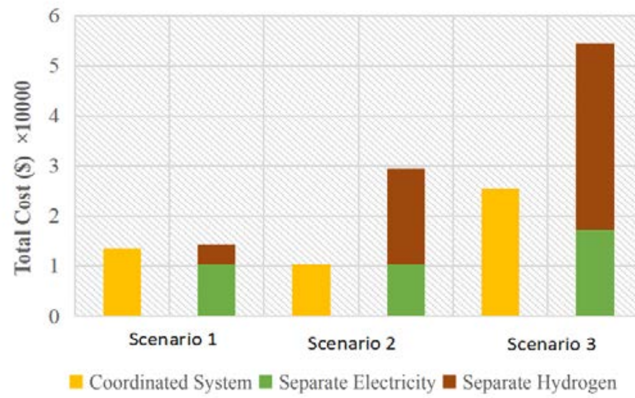

Fig. 4. Cost of coordinated and separate systems

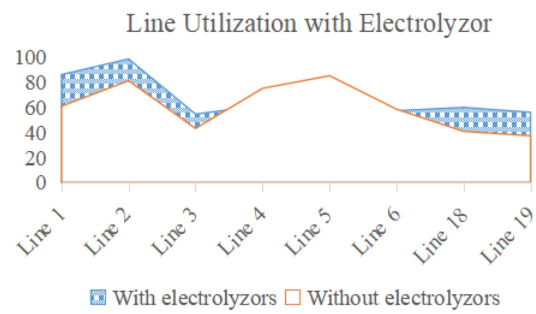

Fig. 5. Improvement in line utilization with electrolyzors

2) Line Utilization Analysis: A number of branches used in energy transformation are listed in Table I, where P_c and Q_c are the active and reactive power in coordinated model, while P_s and Q_s are the active and reactive power in separate system. Table I records the load of these in branches in an hour. For branches (3,4), (2,19), (19,20), they connect with the electrolyzors directly. Therefore, they're sensitive to the adding of coordinated system, The load of the 3 branches increase around 100%. Other nearby lines also have a over 50% improvement. Fig. 5 shows improvement in the network utilization of the IEEE 33 bus system. It is seen that the utilization of some lines is increased without addition of new lines and while ensuring that all lines operate within their

TABLE I
LOAD OF TRANSMISSION LINES OF COORDINATED AND SEPARATE SYSTEMS

Branch	P_c	Q_c	P_s	Q_s	Impro
(2,3)	1.636	0.652	1.224	0.781	47%
(2,19)	0.436	0.185	0.150	0.286	115%
(3,4)	1.039	0.562	0.674	0.494	99%
(19,20)	0.425	0.183	0.123	0.282	126%
(1,2)	1.221	0.481	0.835	0.636	56%

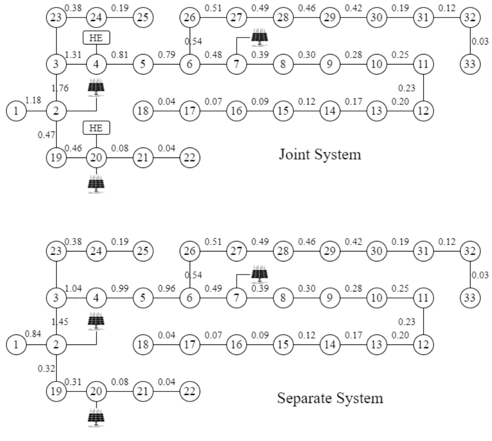

Fig. 6. Average load of transmission lines

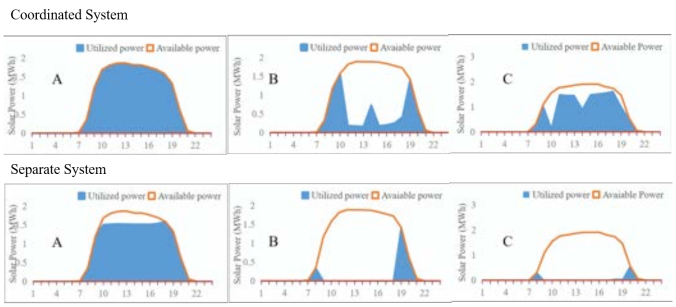

Fig. 7. Available and Utilization Power in Coordinated and Separate system

limits.

The daily average load of the total system can be viewed in Fig. 6. With the adding of electrolyzors, the average load of branches (2,19), (19,20) increase around 50%, because the network need to get renewable power from bus 2 to supply the hydrogen system when the. This also happens on branch (2,3), (3,4), but they increased only 20% - 30% because of the capacity limitation of branch (3,4). The loads of branch (4,5), (5,6) decrease because most solar power of bus 2 is converted to hydrogen and the system turns to solar substation B for the demand of buses 6-18, 26-33. The load of tail branches do not change because their only task is to supply the buses in the tail of supply chain. The daily utilization level of all transmission lines in the separate dispatch model is 47.57%. While in the coordinated dispatch model, the utilization level of transmission lines in the same situation improves to 57.08%. In this case, converting part of power to hydrogen can improve the line utilization level of transmission lines.

3) Renewable Energy Curtailment Analysis: Our coordinated model can not only reduce the cost energy systems but also improve the utilization of renewable power. The daily solar power output of the three solar panel stations is listed in Fig. 7. In separate system, only the power of solar substation A could be utilized efficiently, which is close to the root node. Most power, especially the remote solar substation, is wasted. However, the hydrogen system provide a new potential way to utilize the renewable power. We could convert the solar power to hydrogen to satisfy the load of hydrogen system, or store them in the pipeline. In Fig. 7, we notice that the power of substation A is nearly fully utilized. The usage of power of substation C get a sharply increase because it connected to hydrogen system directly by bus 20. The usage of substation B is limited by the capacity of system branches but also has a significant improvement. As a result, The solar energy utilization level of the solar panel substations increases from 41.1% to 86.5% with the coordinated dispatch model.

IV. Conclusion

To address improve the operation efficiency of hydrogen and power distributed systems, this paper proposed a coordinated dispatch approach, which leverages the flexibility from the hydrogen system to accommodate renewable energy fluctuations. Our simulation results show that, with the ability of energy converting, the coordinated dispatch could reduce over 53% system cost in the specific test system. The efficiency of renewable power utilization is also improved (in average 40%). On the other hand, the converting of surplus renewable energy can also increase the utilization level of transmission lines from 47% to 57%.

Acknowledgement

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