Impacts of Energy Storage Facilities on Resilient Operation of Multi-Carrier Energy Hub Systems

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***Abstract*— Nowadays, with respect to the new strategic insight into the management of power systems, the grids are inevitably restructuring from centralized networks toward multiple sub-systems encompassing many local networks and microgrids. Hence, during the recent decade, the necessity for the deployment of multi-carrier energy hub schemes has assumed special attention. An energy hub scheme is a kind of multi-carrier system which is capable of converting, storing, and transmitting energy carriers from inputs toward outputs. The energy hub system acts as a connector and interface between consumers and energy infrastructures to maintain the demand reliably and optimally in terms of economy. Due to the uncertainty of parameters, volatile conditions, and widespread pervasiveness, the accurate modeling of hub systems seems to be indispensable. Such schemes have witnessed significant revolutionary developments and have undergone innovative progress during recent years. In this study, a new model for the hub scheme is proposed encompassing two types of thermal and electrical storage units in addition to an objective function for operation under normal and faulty conditions. Thus, the impacts of the presence of storage facilities on the optimal operation of the hub scheme regarding resilience objectives and total operation cost are investigated. This non-linear, non-convex, and non-smooth problem is optimized using a novel metaheuristic solver called Slime Mould Algorithm (SMA), which has demonstrated a stunning performance in terms of accuracy and computation metrics. The results allude to the prominent virtues of the proposed hub scheme in diminishing operation cost and augmenting reliability and resilience of supply.**

Keywords*— *Multi-Carrier Energy Systems, Energy Hub, Slime Mould Algorithm (SMA), Energy Storage, Resilience.

I. Introduction

In addition to the power system, which supplies the electricity demand of consumers, other types of energy carriers have a substantial role in the energy supply for consumers. At the current time, these infrastructures deploy separately, and the associated schedules conduct independently of each other. The combination of these infrastructures procures immense benefits such as reliability enhancement, flexibility increase in power supply, resilience improvement, and optimal operation. For the first time, through a project titled "The Perspective of Future Energy Grids" proposed at ETH University, a new concept called energy hub propounded, which alludes to assessing the integrated model of these infrastructures. An energy hub is a centralized unit that is capable of storing and converting various types of energy [1]. This unit functions as an interface between the energy infrastructures of upstream networks and end-users [2]. Energy hub schemes are characterized by different degrees of local control on different spatial scales, which can be implemented from the level of a single building to a broader range of a wider geographic region. The centralized storage and conversion capabilities procure particular flexibility that features effective usefulness for enabling the exploitation of intermittent renewable energy such as wind and solar [3],[4]. A fundamental question in the area of energy hub systems is to what extent the energy carriers must be purchased, converted, or stored in order to supply the demand of users effectively [5]. The presence of storage units provides high flexibility for this operation problem [6]. In this problem, optimization can be carried out based on various economic, environmental, and reliability objectives. Besides, some scholars have deployed multi-level multi-objective energy hub scheduling models [7],[8].

So far, various studies have surveyed the concept of an energy hub. In [9], a residential energy hub model is proposed in which electric vehicles are incorporated as storage facilities joined with small-scale renewable energy sources. The mathematical modeling of an energy hub, determination of the best configuration of components, and the different operational problems are counted of the most prevalent topics in the area of energy hubs, which assumed the interest of researchers [10]. The most prevalent model of the energy hub operation problem is so defined that the deterministic sets of load and price data must are used in order to minimize the objective function subject to satisfying prevailing constraints [11],[12]. However, in real operation, this problem is encountered with uncertainties and volatilities related to the price, load, and renewable energy generation. In previous studies, various approaches have been suggested to deal with uncertainties. The authors in [13], the Monte Carlo method is employed to model and forecast the stochastic behavior of the real-time market price profile. In [14], the gaining factors of converters are pinpointed using an accurate model of load and price and robust control modeling. Another similar work has investigated a hub model exploiting the potential of demand response resources [15]. In some studies, tree scenario generation modeling methods concerning the price, load, and wind forecasts are used to simulate uncertainties in the hub scheme. Such a model hardly reaches a global optimum and requires an extremely high computational burden. This study has incorporated energy storage facilities using a predictive control approach in order to compensate for the error of forecasts pertaining to renewable energy sources [16]. In [17]-[20], the energy hub scheduling problem is solved using predictive control aiming to obtain economic optimality. Due

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to the closed-loop feature in this method, the error triggered by uncertainties will be corrected gradually during consecutive iterations. In [21]-[23], in order to boost reliability and resilience, thermal and electric storage facilities are included in the model. In [24], the application of an energy hub model for district heat and power supply is investigated. A comprehensive study is also conducted to examine the performance of interconnected multiple-hub systems while considering the impact of power exchange with the main grid [25]. In the conducted works described in the literature, the implication of the presence of storage facilities in simultaneous minimization of costs and maximization of reliability and resilience whenever a fault has occurred on the path of a carrier toward the hub has not been investigated. Reliability can be introduced as how much a system is reliable for a continuous energy supply. The stability assessment is important in terms of unwanted high-frequency contingencies with relatively low impacts. On the other hand, how much a system can withstand extremely low-frequency events with extremely high impacts is evaluated by resilience metrics. Hence, an energy hub, including thermal and electrical energy storage facilities, is modeled, and the impact of incorporating each storage is evaluated. Then, by supposing a fault at the entrance of each carrier at various intervals, the impact of the presence of each storage is elaborately analyzed. The results convey that the presence storage facility significantly decreases the detriments owing to faults. Moreover, the storage units mount the reliability and resilience of the hub system by improving the energy not supplied index.

II. ENERGY HUB MODELING

An energy hub system generally has multiple inputs and outputs. The connection between these inputs and outputs can be directly or by means of an intermediary converter. Energy hub systems also encompass intrinsic energy storage facilities. Energy converters are classified into four types as follows: single-input single-output, single-input multiple-outputs, multiple-inputs single-output, and multiple-inputs multiple-outputs. In Fig. 1, the model of a multiple input-multiple output converter is depicted [26].

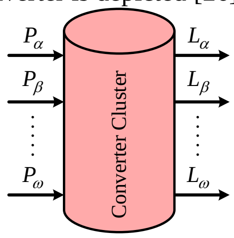

Fig. 1. The model of a multiple input-multiple output converter

Suppose a single input-single output converter, which converts the energy carrier of α at the input to the energy carrier of β at the output. At the steady-state, the relation between input and output can be described as:

$$L_\beta = C_{\alpha\beta} P_\alpha \tag{1}$$

In this equation, $C_{\alpha\beta}$ is called a mutual factor. This term is also called converter efficiency in single input-single output models. The following equation is valid for all converters:

$$P_\alpha \le L_\beta \to 0 \le C_{\alpha\beta} \le 1 \tag{2}$$

By generalizing the above equations, the relations of a multiple input-multiple output converter can be obtained. If we suppose (P_α, P_β, …, P_ω) as the inputs and (L_α, L_β, …, L_ω) as the outputs, the interrelation for a multiple input-multiple output converter can be expressed as Eq. (3):

$$\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & C_{\beta\alpha} & \cdots & C_{\omega\alpha} \\ C_{\alpha\beta} & C_{\beta\beta} & \cdots & C_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ C_{\alpha\omega} & C_{\beta\omega} & \cdots & C_{\omega\omega} \end{bmatrix} \times \begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix} \tag{3}$$

In the above, the C matrix is defined as a mutual matrix of the converter. As shown in Eq. (4), the output energy is always equal to or lower than the input energy in a converter. Besides, according to Eq. (5), the summation of output from an input is not possible to be more than the input.

$$0 \le C_{\alpha\beta} \le 1 \quad , \quad \forall \alpha, \beta \in \varepsilon \tag{4}$$

$$0 \le \sum_\beta C_{\alpha\beta} \le 1 \quad , \quad \forall \alpha, \beta \in \varepsilon \tag{5}$$

The energy hub model will be completed by modeling the energy storage facility. This component is assumed to be ideal and is included in the hub model as an interface system. The interface affects the charge/discharge activities as well as the quality of power at the input. Figure 2 illustrates a storage model along with its interface [27].

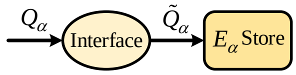

Fig. 2. Energy storage model

In this model, L_α stands for energy stored in the storage, $\tilde{Q}_\alpha$ represents the entering energy to the storage, and Q_α shows the converted energy. In the steady-state, Eqs. (6) and (7) demonstrate how an energy storage facility acts in a hub.

$$\tilde{Q}_\alpha = e_\alpha Q_\alpha \tag{6}$$

$$e_\alpha = \begin{cases} e_\alpha^+ \\ 1/e_\alpha^- \end{cases} \tag{7}$$

e^+_α and $1/e^-_\alpha$ show the charging and discharging velocity of the storage. The storage component can be placed, whether before or after the converter. The mathematical equations related to when the total stored energy is transferred toward output are represented below:

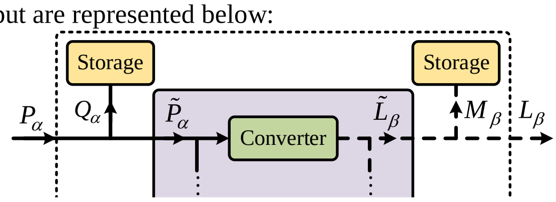

Fig. 3. The configuration of the hub system, including an energy storage

$$L + M = C[P - Q] \tag{8}$$

$$L = C[P - Q] - M = CP - M^{eq} \tag{9}$$

$$M^{eq} = CQ + M \tag{10}$$

$$M^{eq} = C_{\alpha\beta} Q_\alpha + M_\beta = (C_{\alpha\beta}/e_\alpha)\dot{E}_\alpha + (1/e_\beta)\dot{E}_\beta \tag{11}$$

In the abovementioned equations, M_{eq} denotes the total energy stored in the hub.

$$\begin{bmatrix} M_\alpha^{eq} \\ M_\beta^{eq} \\ \vdots \\ M_\omega^{eq} \end{bmatrix} = \begin{bmatrix} S_{\alpha\alpha} & S_{\beta\alpha} & \cdots & S_{\omega\alpha} \\ S_{\alpha\beta} & S_{\beta\beta} & \cdots & S_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ S_{\alpha\omega} & S_{\beta\omega} & \cdots & S_{\omega\omega} \end{bmatrix} \times \begin{bmatrix} \dot{E}_\alpha \\ \dot{E}_\beta \\ \vdots \\ \dot{E}_\omega \end{bmatrix} \tag{12}$$

In Eq. (12), the S matrix represents the mutual storage matrix. Thus, the overall relationship between inputs and outputs incorporating the storage model can be pointed out by Eq. (13) [28].

$$L = CP - S\dot{E} = [C - S]\begin{bmatrix} P \\ \dot{E} \end{bmatrix} \tag{13}$$

III. The Proposed Objective Function

In order to investigate the impact of storage on the operation of the hub as well as the role of the storage facility in the power supply when a fault occurs, a hub model, as shown in Fig. 4, is taken into account encompassing transformer, CHP, heat exchanger, electrical storage facility, and heat storage facility. The following equations describe the relationships of our targeted hub model [29].

$$C=\begin{bmatrix}\eta_{ee}^{T} & \eta_{ge}^{CHP} & 0\\ 0 & \eta_{gh}^{CHP} & \eta_{hh}^{HE}\end{bmatrix} \tag{14}$$

$$S=\begin{bmatrix}1/e_e\\ 1/e_h\end{bmatrix},\ e_e=\begin{cases}e_e^{+}\\ 1/e_e^{-}\end{cases},\ e_h=\begin{cases}e_h^{+}\\ 1/e_h^{-}\end{cases} \tag{15}$$

It is supposed that the stored energy level at the beginning and at the end of the simulation time horizon will remain equal. This rate is supposed to be 30% of energy storage capacity. Hence, the following objective function is suggested to optimize the operation of the hub system.

$$Min\ Cost=\sum_{t=1}^{24}\left(\pi_e^t P_e^t+\pi_g^t P_g^t+\pi_h^t P_h^t+Voll_e UP_e^t+Voll_h UP_h^t\right) \tag{16}$$

In this equation, π_e^t, π_g^t, and π_h^t stand for the prices of electricity, gas, and local heat, respectively, within different hours of a daylong period. UP_e^t and UP_h^t denote the amount of energy not supplied at each interval. $VOLL_e$ represents the value of lost load as a penalty for unsupplied electrical demand, and $VOLL_h$ shows the value of lost heat load as a penalty for unsupplied heat demand.

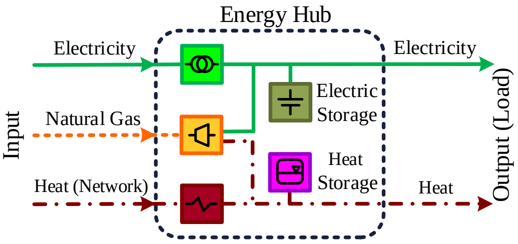

Fig. 4. The paradigm of the targeted energy hub scheme

IV. Slime Mould Algorithm (SMA) Mathematical Model

Slime mould algorithm (SMA) is a new stochastic optimization technique [30], which attempts to emulate the behavior of slimes (Physarum polycephalum) in nature. The SMA uses the weights to create three different morphotypes by simulating the negative and positive feedback given by slime mould during the foraging process. The latter, which is considered a novel concept, entails making a distinction in search space in order to find new solutions.

One of the most intriguing features of thin mould is its unusual design, which allows SMA to customize multiple food sources at once, building a venous network that connects them together. This pattern allows this metaheuristic solver to widely explore parts of the search space while avoiding local optima. Slime mould can dynamically change or adjust its search techniques efficiently based on a high-quality diet. When the quality of the food sources is good, the slime mould uses the region-limited search approach, which means it only looks at the food sources it has found. Otherwise, if the food sources discovered are poor with low quality, they forsake the food source and seek out new ones in the vicinity. Slime mould can build the optimal food path to tie food substantially better based on negative and positive feedback responses. The following sections will show the mathematical model of some slime mould mechanisms and properties.

A. *food approaching*

The SMA can readily reach food through the scent in the air. This contraction behavior is mathematically described by Eq. (17):

$$\overrightarrow{X(t+1)}=\begin{cases}\overrightarrow{X_b(t)}+\overrightarrow{\upsilon b}.\left(\overrightarrow{W}.\overrightarrow{X_A(t)}-\overrightarrow{X_B(t)}\right), & r<p\\ \overrightarrow{\upsilon c}.\overrightarrow{X(t)} & ,\ r\geq p\end{cases} \tag{17}$$

Where v_b is a parameter within the range of [$-a$, a], v_c falls linearly from 1 to 0. The current iteration is represented by t. X_b denotes the individual position linked with the currently maximum smell concentration. The position of each individual in the SMA is represented by X, while X_A and X_B are two randomly generated individuals from the population. The weight of slime mould is W. Eq. (18) expresses the relationship associated with the parameter p.

$$p=tanh\left|S(i)-DF\right| \tag{18}$$

DF is the best fitness gained in all iterations, whereas $S(i)$ is the fitness value of X. The following is how b is defined: υ_b = [$-a$, a]

$$a=arctanh\left(-\left(iter/(max-iter)\right)+1\right) \tag{19}$$

The weight of slime mould can be represented by:

$$\overrightarrow{W(SmellIndex)}=\begin{cases}1+r\cdot log\left(\dfrac{bF-S(i)}{bF-wF}+1\right), Condition\\ 1-r\cdot log\left(\dfrac{bF-S(i)}{bF-wF}+1\right), \quad Others\end{cases} \tag{20}$$

Eq. (21) simulates the negative and positive feedback between the concentration of foods and the vein width of the SMA.

$$SmellIndex=sort\ \ (S) \tag{21}$$

where r is a randomly generated number in the range [0,1], and bF is the best fitness value attained in this iteration. wF is currently the poorest fitness value realized in the iterative procedure. *SmellIndex* defines the sorted series of fitness values. The *log* makes numerical value changes easier when the contraction frequency value does not change much.

B. *Food wrapping*

The following formula will update the position of a slime mould:

$$\overrightarrow{X^{*}}=\begin{cases}rand.(ub-lb)+lb, & rand<z\\ \overrightarrow{X_b(t)}+\overrightarrow{\upsilon b}.\left(W.\overrightarrow{X_A(t)}-\overrightarrow{X_B(t)}\right) & r<p\\ \overrightarrow{\upsilon c}.\overrightarrow{X(t)}, & r\geq p\end{cases} \tag{22}$$

The above equation shows the upper and the lower search space boundaries denoted by u_b and l_b, respectively.

C. *Catching food*

The success of the SMA is largely determined by its oscillation parameters υb and υb, which were utilized to introduce stochastic nature into the model, assisting individuals in locating high-concentration food. The detailed characteristics of the SMA are given in [26]. Like other meta-heuristic algorithms, the SMA begins the optimization process by spreading individuals as the first solutions across the search space. Each person in a population represents a potential solution to the optimization problem, which is then evaluated using a chosen objective function to determine the minimum value for minimization and the largest value for maximization. Following that, at each iteration, the individuals change their positions based on several equations describing slime mould movement in nature along with various factors. The updating process is repeated in the next stage until a terminal requirement is met. The ideal solution that corresponds to the best individual attained thus far is memorized in the final stage. The flowchart corresponded with the proposed algorithm is shown in Fig. 5.

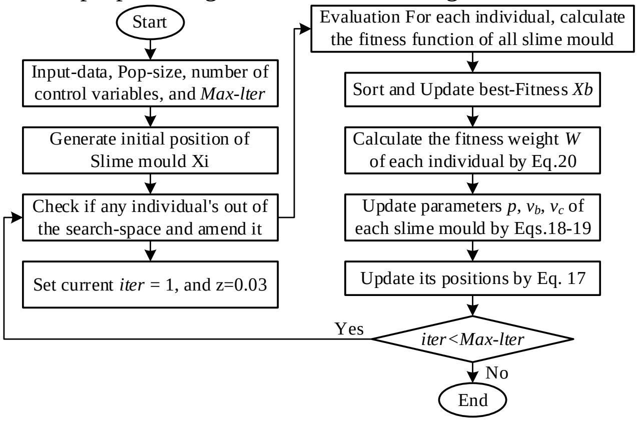

Fig. 5. Flowchart of Slime mould algorithm (SMA)

V. Simulation and Numerical Results

In this study, a new hub model is proposed, including two types of thermal and electrical storage units. In addition, an objective function is contemplated for operation under normal and faulty conditions. The data associated with the hourly thermal and electrical loads as well as the corresponding hourly prices are given in Fig. 6. The invoked rules of the upstream network impose the prices of heat and gas consumption by 3.5 and 8.2 ($/p.u.). The penalty related to the value of the lost electrical load is set by 230 $/h. Similarly, the penalty related to the value of the lost thermal load is set by 175 $/h. The technical characteristics of the employed hub scheme are also shown in Tables I and II.

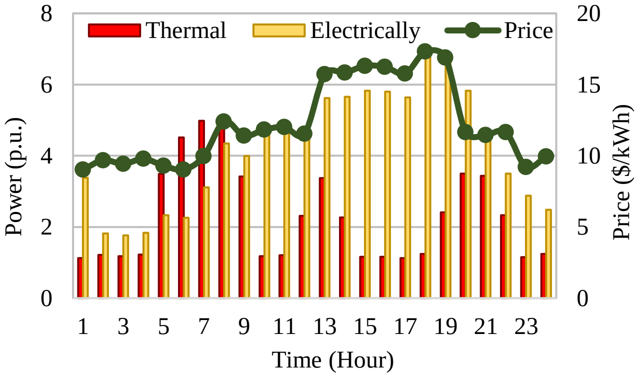

Fig. 6. The Characteristics of loads and hourly prices

TABLE I. The Characteristics of the Employed Energy Hub System

η_{ee}^{T}	η_{ge}^{CHP}	η_{gh}^{CHP}	η_{hh}^{HE}
0.9865	0.41	0.47	0.91
e_h^{+}	e_h^{-}	e_e^{-}	e_e^{+}
0.91	0.91	0.988	0.988

TABLE II. The Prevailing Constraints in the Employed Energy Hub System

$0 \le P_e \le 4.7$	$0 \le P_g \le 7$	$0 \le P_h \le 3.5$
$0 \le E_e \le 4.7$	$0 \le E_h \le 3.5$	$0 \le Q_{e,h} \le 3.5$

The proposed objective function for the hub operation is simulated via four scenarios, in which the presence and absence of two types of storage units in normal and faulty conditions are tested. To better understand how the energy hub works, first, the simulation results in the presence of both types of storage in the normal state are presented in detail. Figure 7 shows the optimal amount of electricity, gas, and thermal input energy. It is observed that in order to supply the load (especially during peak intervals), the electrical input power has reached its maximum value within 10 to 21 o'clock.

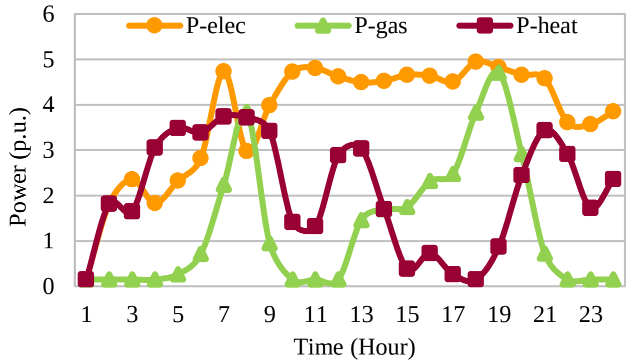

Fig. 7. The optimal energy input of the hub

Figure 8 shows the energy of the storage devices in the optimal state. According to Fig. 8, at the hours before the peak, when the price of electricity is lower, the storage starts to charge, and evidently, it will discharge during the peak hours. Thus, in addition to reducing operating costs, the percentage of unsupplied load is reduced to zero due to limited input power. During peak hours, the CHP supplies some of the power, and because the charge is low in the early hours, the CHP does not enter the supply circuit.

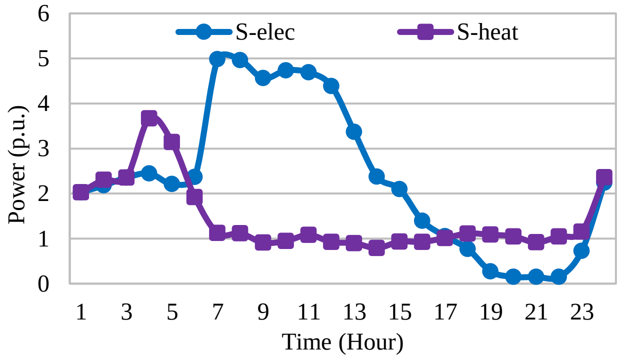

Fig. 8. The stored energy in the energy storage units

Table III shows the costs of operating the energy hub in the normal mode under different scenarios. Four contemplated scenarios are:

Scenario 1: None of the storage devices are called for supply.
Scenario 2: Only heat storage is committed.
Scenario 3: Only the electrical storage is integrated.
Scenario 4: Both storage contribute to the supply process.

TABLE III. The Condition of the Hub in a Normal Operation

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
The cost of buying energy	1354.664	1371.843	1350.384	1345.082
value of lost load	301.731	0	0	0
Total cost ($)	1659.982	1371.843	1350.384	1345.082
Thermal energy not supplied	0	0	0	0
Electrical energy not supplied	1.526	0	0	0

As can be seen, with the presence of each of the storage devices, the total cost is reduced, which implies the positive impact of the presence of an electrical storage device. The results also show that the presence of at least one storage unit in the system is necessary to supply the load effectively.

A. Fault on electricity supply entrance

To model an electrical fault, it is assumed that the amount of input electrical power is halved at the peak hour of the electric demand at 18 o'clock. The simulation results are presented in Figs. 9 and 10 and Table IV.

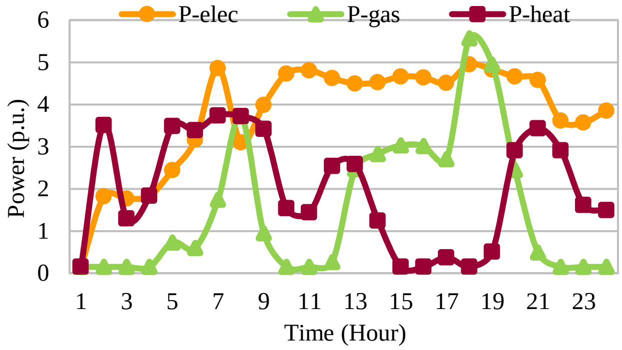

Fig. 9. The optimal amount of power absorption during the faulty period

From 10 o'clock, the input power no longer responds sufficiently to the demanded electric power by loads, and the storage device begins to discharge (Fig. 10). Also, in this case, CHP intervenes to help supply the load. At 18 o'clock, when the CHP is at maximum power, the storage is discharged to its minimum to compensate for the lack of energy for the load.

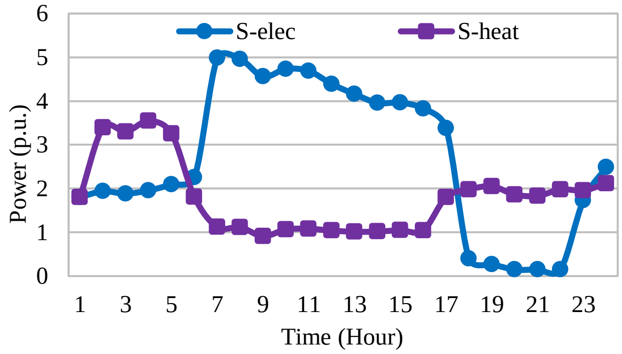

Fig. 10. The optimal level of energy stored in the storage units during the period of electrical supply fault at the entrance of the hub

TABLE IV. THE STATE OF THE ENERGY HUB OPERATION DURING THE FAULTY PERIOD

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
The cost of buying energy	1321.743	1350.597	1352.490	1346.999
value of lost load	768.520	308.057	0	0
Total cost ($)	2090.322	1648.460	1352.513	1350.526
Thermal energy not supplied	0	0	0	0
Electrical energy not supplied	3.833	1.540	0	0

In the event of an electrical fault, in the absence of an electrical storage device, the system will not be able to supply the load entirely and will therefore incur the cost of an outage. The important point is the role of the heat storage device in reducing the unsecured electrical power in such a way that incorporating the heat storage device allows the CHP to enter the circuit because the CHP produces both electrical and thermal energy. This device produces both thermal and electrical energy, and by adding the heat storage in operation, the generated heat that the system does not need should be stored in this storage device, and the generated electrical energy is transferred to the load. As can be seen, by calling the electrical storage for operation, the unsupplied power will be reduced to zero, and this point indicates the importance of having electrical storage in the energy hub to improve reliability and resilience.

B. Failure on the heat supply entrance

The amount of incoming thermal power is halved to model the assumed thermal failure at the peak of the heat load time at 7 o'clock. The simulation results of this condition are shown in Figs. 11 and 12, as well as Table V. Figure 12 demonstrates the optimal amount of input energy in an unwanted failure at the thermal input. As can be seen, at 7 o'clock, when a thermal failure has occurred, the CHP helps to provide the heat load at this hour by taking more natural gas from the inlet than normal.

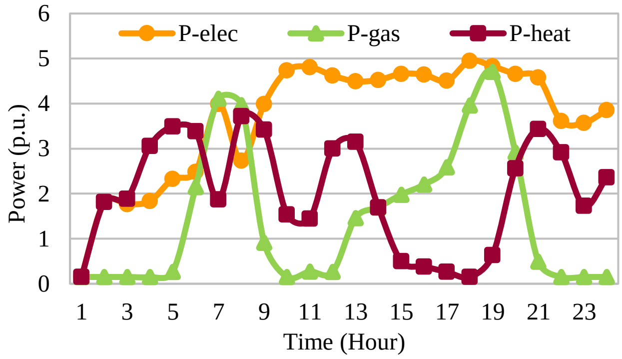

Fig. 11. The optimal energy supply entering the hub during heat failure

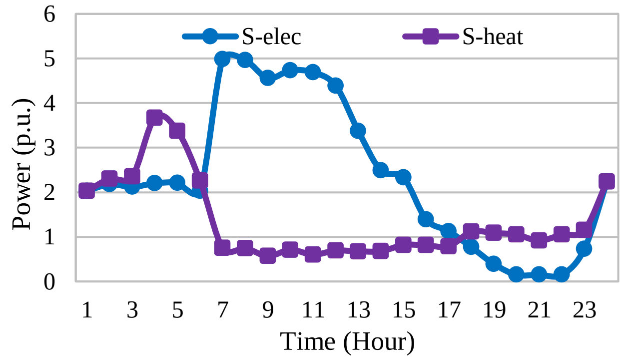

Fig. 12. The optimal level of energy stored in the storage units during the period of heat supply failure at the entrance of the hub

Taking Fig. 12 into account, at first glance, it seems that the heat storage device does not react well to a thermal failure, but in fact, the lack of sufficient capacity in the hub model to receive or store electrical energy prevents the CHP from supplying heat sufficiently.

TABLE V. THE OPERATIONAL STATE OF THE HUB DURING THE PERIOD OF HEAT FAILURE AT THE ENTRANCE OF THE HUB

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
The cost of buying energy	1363.354	1381.297	1359.074	1354.536
value of lost load	317.604	0	12.345	0
Total cost ($)	1681.029	1381.391	1371.443	1354.536
Thermal energy not supplied	0	0	0.082	0
Electrical energy not supplied	1.526	0	0	0

According to Table V, it can be seen that by adding a heat storage device in operation, it is possible to prevent the occurrence of unsupplied heat energy after a failure at the hub heat input. The commitment of an electric storage device to meeting loads reduces the cost of an electrical outage to zero but has no effect on the heat supply, which is due to the limited capacity of the electrical storage. Because, as mentioned before, when there is no need for more electrical energy in the system, the CHP can enter the circuit provided that it is possible to store the additional energy produced. As a result, the CHP can only remain in the circuit until the electrical storage reaches the maximum charging capacity.

VI. CONCLUSIONS

In recent years, in the operation of systems involving multi-agent and multiple energy carriers, an integrated approach called energy hub has been propounded, which yields benefits such as increased efficiency, reduced costs, and increased security, reliability, and resilience. In this paper, the behavior of an energy hub, including storage devices, is studied concerning undesired and unwanted faults. In this regard, first, the relationships governing an energy hub with storage devices are presented. Then the proposed objective function for optimal operation of the hub in the presence of two types of electrical and thermal storage is introduced. The proposed objective function is simulated in four scenarios (different states of presence and absence of storage) in two normal states and the occurrence of two types of electrical and thermal faults. The simulation results imply that the faults at the electrical input of the energy hub can have more adverse effects than a thermal accident. It incurs more operational costs and a higher energy supply. However, according to the obtained results, the presence of each storage device significantly reduces the cost of unwanted damages due to different faults and reduces the unsupplied energy, which translates to more resilient load-serving with a considerable reliability improvement, which plays a decisive role in the field of operation of multi-carrier systems.

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