Probabilistic available transfer capability calculation considering static security constraints and uncertainties of electricity-gas integrated energy systems

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Abstract

The increasing share of natural gas-fired power plants (NGFPPs) has strengthened the linkage between electric power systems (EPSs) and natural gas systems (NGSs). It is imperative to analyze both systems jointly. In this paper, a probabilistic available transfer capability (PATC) model considering the static security constraints and uncertainties of electricity-gas integrated energy systems (IESs) is proposed. The concept of IES steady-state security regions is developed, and the mathematical model of ATC within IES security regions is formulated. The active constraint limiting the ATC is identified by the linear prediction and calculation (LPC) method, and then it is augmented into IES energy flow equations to determine the value of ATC. The uncertainties of correlated electricity/gas loads and wind power generations are also taken into account and are addressed by a combination of Latin hypercube sampling (LHS) and the Nataf transformation. Moreover, the corrective adjustment in NGSs can be adopted to ensure the fuel availability of NGFPPs. Finally, test results on the modified IEEE 118-bus system and a 20-node NGS are presented to verify the applicability of the proposed methodology.

Keywords: Probabilistic available transfer capability (PATC); Integrated energy system (IES) static security constraints; Active constraint; Latin hypercube sampling (LHS); Nataf transformation; Corrective adjustment

Nomenclature

Indices

i, j	Subscript indices of nodes in EPS
m, n	Subscript indices of nodes in NGS
k	Subscript indices of compressors in NGS
min	Superscript index for minimum value
max	Superscript index for maximum value
0	Superscript index for base value
(u)	Superscript index of u -th iteration

Variables and functions

V_i	Voltage magnitude of node i
θ_i	Voltage angle of node i
P_{ij}	Active power flow through branch i - j
Q_{ij}	Reactive power flow through branch i - j
$P_{gen,i}$	Active power output of i th generator

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$Q_{gen,i}$	Reactive power output of i th generator
$P_{load,i}$	Active load at node i
$Q_{load,i}$	Reactive load at node i
S_{ij}	Complex power flow through branch $i-j$
π_m	Node pressure of node m
F_{mn}	Natural-gas flow through pipeline $m-n$
$F_{com,k}$	Gas flow rate through compressor k
$F_{sup,m}$	Natural-gas supply at m th node
$F_{load,m}$	Natural-gas load at m th node
$F_{load,m}^{G,i}$	Equivalent gas load at m th node to supply the NGFPP at i th node
λ	Load parameter
$f(\square)$	IES energy flow function
$g(\square)$	IES static security constraints function
$f_e(\square)$	EPS power flow function
$h_e(\square)$	Function related to EPS active constraint
$h_g(\square)$	Function related to NGS active constraint

Parameters and constants

g_{ij}	The series conductance of branch $i-j$
b_{ij}	The series susceptance of branch $i-j$
b_{si}, g_{si}	The shunt values of node i
α, β, γ	Natural gas consuming parameters of compressor
$\alpha_{g,i}, \beta_{g,i}, \gamma_{g,i}$	Gas consumption coefficients of NGFPP at the i th node
K_P, K_Q, K_{gen}	Pre-specified change rate in load demands and power generations
$\mathbf{g}^{\max}, \mathbf{g}^{\min}$	Upper and lower bounds for IES security constraints

Abbreviations

NGFPP	Natural gas-fired power plants
EPS	Electric power system
NGS	Natural gas system
IES	Integrated energy system
ATC	Available transmission capability
LHS	Latin hypercube sampling
SRS	Simple random sampling
MCS	Monte Carlo simulation
LPC	Linear prediction and calculation
CPF	Continuation power flow
CDF	Cumulative distribution function

1. Introduction

1.1 Background

The natural gas-fired power plants (NGFPPs) have been developed in high proportion during the last few decades, which is attributed to their higher economics, quicker response and lower environment effects in comparison with fossil generating units [1-2]. Accordingly, electric power systems (EPSs) and natural gas systems (NGSs) are becoming deeply interdependent. Meanwhile, the power to gas technology has an edge over other storage technologies especially in terms of large-scale electricity storage [3], which facilitates the integration of renewable energy [4-5] and further strengthens the linkage between EPSs and NGSs. Hence, the integrated energy systems (IESs), composed of deeply interdependent electricity and natural gas infrastructures, opens up a promising pathway for constructing a sustainable low-carbon energy system [6].

Traditionally, EPSs and NGSs have been designed and operated separately. This conduct would gradually change with the rising installed capacity of NGFPPs. For instance, the fluctuations of loads and renewable-based generations in EPSs [7] are partly balanced by NGFPPs and further by NGSs. On the other hand, any disruption in NGSs, e.g., pressure losses, gas transmission congestion, or pipeline contingencies, could negatively impact EPS security and reliability to a greater extent [8-9]. To ensure a safe and reliable operation of EPSs and NGSs, it is necessary and important to analyze both systems collectively.

A number of papers addressing the interactions and couplings between EPSs and NGSs have recently been reported. A generic framework for an IES steady-state energy flow analysis was built by Martinez-Mares and Fuerte-Esquivel [10-11], where NGFPPs serve as a linkage between EPSs and NGSs. Similar to the value of power flow analysis to EPSs, energy flow analysis shall be valued as the cornerstone for additional IES studies. Coordinated planning and scheduling between EPSs and NGSs were investigated in [1, 12-14], where a lower expansion and operation cost for both systems was obtained. The interdependency between the electricity and gas market was studied in [15]. In [16], the NGFPP company was modeled as a price-taker in both the electric power and gas markets. Moreover, Chaudry *et al.* evaluated the reliability of IESs under various operation conditions [17], and the role of gas storage to IES reliability was highlighted.

Available transfer capability (ATC) is defined as the remaining power that can be transferred from one area (or point) to another area (or point) for a given initial system state. According to the North America Electric Reliability Council's (NERC)'s definition [18], ATC can be calculated using total transfer capability (TTC) minus transmission reliability margin (TRM) and minus capacity benefit margin (CBM). TRM is the reserved capacity accounting for a reasonable range of uncertainties in network conditions. As for CBM, it is the transfer capability reserved by load serving entities to meet generation reliability, and its calculation can be considered independent from ATC evaluation [19-20]. The information for ATC is regarded as a reference for electric power market participants to perform transactions in a deregulated power system. The methods to calculate ATC can be classified into two categories: deterministic [21-24] and probabilistic [19-20, 25-26] methods. The results of deterministic ATC (DATC), typically based on the worst case, are conservative and overly cautious, leading to an inefficient use of transmission capacity. In contrast, probabilistic ATC (PATC)

approaches can address the probabilistic nature of ATC; hence, the ATC under certain confidence intervals (e.g., 95%) or the risk of transferring a certain amount of power can be determined. Among all those methods for PATC assessment, the simple random sampling (SRS) based Monte Carlo simulation (MCS) is usually adopted as a reference to validate the other methods [20, 25]. Moreover, the correlations between input random variables shall be inexcusably considered [26-27].

Although numerous studies provide elegant foundations for ATC assessment in EPSs, the security constraints in NGSs have not been well integrated into the ATC calculation. In fact, as NGFPPs usually sign interruptible contracts, the active power generations of them are restricted not only by their installed capacities but also by the gas fuel availability [13]. In short, without the considerations of NGS security constraints, the ATC calculation results are probably too optimistic, posing a threat to NGS security and consequently resulting in multiple forced outages in EPSs.

1.2 Proposed method

To the best of our knowledge, no previous work concerning NGS security-constrained ATC has been reported, let alone investigating the effect of IES uncertainties to ATC assessment. In response, this paper aims to develop a PATC model considering the security constraints and uncertainties of both EPSs and NGSs. First, the concept of IES steady-state security regions is proposed, and the mathematical model of DATC within IES security regions is developed. Next, the linear prediction and calculation (LPC) method proposed by Audomvongseeree *et al.* [25] is used to calculate the DATC with IES security constraints. After that, the uncertainties and correlations between input random variables are addressed by a combination of Latin hypercube sampling (LHS) and the Nataf transformation [28-29]. Finally, a feasible corrective adjustment strategy in NGSs, which takes advantage of the gas storage capacities and aims to enlarge the NGS steady-state security regions, is proposed.

1.3 Contributions

The main contributions of this paper can be concluded as follows:

- 1) The ATC model with IES security constraints is primitively proposed.
- 2) The impact of various uncertainties in the IES on the ATC assessment is analyzed.
- 3) The proposal can provide an accurate and real-time PATC estimation, enabling the electric power market participants to plan their transactions.
- 4) With the corrective adjustment in NGSs, the potential of gas market players (or gas storage owners) trading on the electric power market is investigated.
- 5) The established ATC case implies that with improved coordination and information sharing between EPSs and NGSs, more economic benefits would be acquired and the security (or reliability) concerns for IESs could be mitigated.

1.4 Manuscript organization

In the remainder of this paper, the DATC model with IES security constraints is introduced in Section 2. In

Section 3, the LPC method to DATC calculation is presented. The probabilistic approach combining LHS and Nataf transformation is described in Section 4. Section 5 illustrates the procedure of the proposal and the test results are presented and interpreted in Section 6. Finally, Section 7 draws the conclusions.

2. DATC model with IES security constraints

2.1 Modeling of EPSs

The state variables of EPS power flow equations include the node voltage magnitude vector $\mathbf{V}$ and the node voltage phase angle vector $\boldsymbol{\theta}$. Once $\mathbf{V}$ and $\boldsymbol{\theta}$ are obtained, the operating conditions of EPSs can be determined.

For each branch connecting nodes i and j , the active and reactive branch power are modeled as:

$$P_{ij} = (g_{si} + g_{ij})V_i^2 - g_{ij}V_iV_j \cos \theta_{ij} - b_{ij}V_iV_j \sin \theta_{ij} \quad (1)$$

$$Q_{ij} = -(b_{si} + b_{ij})V_i^2 + b_{ij}V_iV_j \cos \theta_{ij} - g_{ij}V_iV_j \sin \theta_{ij} \quad (2)$$

The power balance of each node in EPSs should be satisfied:

$$P_{gen,i} - P_{load,i} - \sum_{j \in i} P_{ij} = 0 \quad (3)$$

$$Q_{gen,i} - Q_{load,i} - \sum_{j \in i} Q_{ij} = 0 \quad (4)$$

Apart from the power flow equality constraints (Eqs. (3) and (4)), the performance of EPSs is also restricted by the inequality constraints, including active power generation limits (Eq. (5)), voltage magnitude limits (Eq. (6)), and transmission line capacity constraints (Eq. (7)):

$$P_{gen,i}^{\min} \leq P_{gen,i} \leq P_{gen,i}^{\max} \quad (5)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (6)$$

$$|S_{ij}| \leq S_{ij}^{\max} \quad (7)$$

where $|S_{ij}| = \sqrt{P_{ij}^2 + Q_{ij}^2}$.

2.2 Modeling of NGSs

NGSs resemble EPSs to some degree, and the similarities between both systems can be summarized as follows:

- 1) Both systems are designed to carry energy from suppliers (electric power generators or gas fields) at distant sites to (residential, commercial or industrial) consumers through the transmission and distribution systems.
- 2) Owing to the transmission branch resistance, the energy (electricity or natural gas) flow from upstream to downstream results in a voltage or pressure loss.
- 3) The total energy flowing into and flowing out of each node (in EPSs or NGSs) should be equal.
- 4) Security constraints should be observed to ensure a secure and reliable operation for both systems.

In view of the above-mentioned similarities, the electric power flow techniques can be applied to analyze

natural gas flow [30].

The gas flow extending from node m to node n depends on the pressure difference between upstream and downstream nodes and technical parameters [30]:

$$F_{mn} = k_{mn} s_{mn} \sqrt{s_{mn} (\pi_m^2 - \pi_n^2)} \quad (8)$$

$$s_{mn} = \begin{cases} +1 & \pi_m - \pi_n \geq 0 \\ -1 & \pi_m - \pi_n < 0 \end{cases} \quad (9)$$

where k_{mn} is the pipeline constant dependent on friction, diameter, length, temperature, and compressibility factor.

With the gas transmission in pipelines, a loss of pressure downstream occurs due to the frictional resistance. To maintain the needed pressure to transport gas from one location to another, compressors are installed along gas pipelines. In most cases, compressors are driven by gas turbines and would consume additional natural gas as illustrated in Fig. 1:

$$H_{com,k} = B_k F_{com,k} \left(\left(\frac{\pi_m}{\pi_n} \right)^{Z_k} - 1 \right) \quad (10)$$

$$\tau_{com,k} = \alpha + \beta H_{com,k} + \gamma H_{com,k}^2 \quad (11)$$

where B_k and Z_k are constants corresponding to the design of compressor k .

Fig. 1 The compressor driven by a gas turbine

When NGSs operate under steady-state conditions, the nodal gas flow balance must be satisfied, as given by:

$$F_{sup,m} - F_{load,m} - \left(\sum_{n \in m} F_{mn} + \sum_{k \in m} \text{sgn}_k(m,n) F_{com,k} + \sum_{k \in m} \tau_{com,k} \right) = 0 \quad (12)$$

$$\text{sgn}_k(m,n) = \begin{cases} +1 & \text{node } m \text{ is the inlet of compressor } k \\ -1 & \text{node } m \text{ is the outlet of compressor } k \end{cases} \quad (13)$$

Analogous to EPSs, NGSs should operate within some security constraints to ensure the reliable supply of natural gas. The limitations of gas supply (Eq. (14)), nodal pressure (Eq. (15)) and pipeline transmission capacity (Eq. (16)) are considered:

$$F_{sup,m}^{\min} \leq F_{sup,m} \leq F_{sup,m}^{\max} \quad (14)$$

$$\pi_m^{\min} \leq \pi_m \leq \pi_m^{\max} \quad (15)$$

$$|F_{mn}| \leq F_{mn}^{\max} \quad (16)$$

2.3 Electricity and natural gas coupling constraints

NGFPPs withdraw the gas from NGSs and inject the electric power into EPSs. Thus, NGFPPs link the primary (natural gas) and secondary (electric) energy networks. For NGSs, an NGFPP can be regarded as a positive load; however, for EPSs, it is a negative load simultaneously. Hence, in IESs, NGFPPs act as energy converters. The gas flow consumed by an NGFPP is associated with its electric power production as follows:

$$F_{load,m}^{G,i} = \alpha_{g,i} + \beta_{g,i} P_{G,i} + \gamma_{g,i} P_{G,i}^2 \quad (17)$$

2.4 Conventional DATC model

ATC is the maximum increase of transferred power without any violations of security constraints. To calculate the ATC, a load parameter λ is introduced [25]:

$$\begin{cases} P_{gen,i} = P_{gen,i}^0 + K_{gen,i} \lambda \\ P_{load,i} = P_{load,i}^0 + K_{P,i} \lambda \\ Q_{load,i} = Q_{load,i}^0 + K_{Q,i} \lambda \end{cases} \quad (18)$$

where the physical meaning of λ is the normalized ATC.

With the electric power generations and demands growing as described by Eq. (18), the conventional DATC problem can be formulated as:

$$obj \quad \max \lambda \quad (19-a)$$

$$s.t. \quad \text{equality constraints: Eqs. (3)-(4)} \quad (19-b)$$

$$\text{inequality constraints: Eqs. (5)-(7)} \quad (19-c)$$

The conventional DATC model merely takes into account the static security constraints of EPSs but without considering the fuel availability of NGFPPs or the operating limits of NGSs. However, if there is congestion in NGSs or if gas suppliers have reached their generation capacity, the fuel adequacy and availability of NGFPPs would be somewhat limited. Furthermore, when the pressures of NGFPPs are out of their security ranges, multiple NGFPPs would be forced to go off-line. Consequently, the ATC results obtained from the conventional model (Eq. (19)) may be too optimistic, posing a threat to NGS security and in turn resulting in forced outages in EPSs.

2.5 IES steady-state security regions

The steady-state security region of an EPS is defined as a set of power injections for which the power flow equations and security constraints imposed by equipment operating limits are satisfied [31]. As shown in Fig. 2, the concept of EPS steady-state security regions can be extended to NGSs and further to IESs.

Fig. 2 Steady-state security regions of IESs

The steady-state security regions of NGSSs, represented by regions B and C in Fig. 2, are comprised of gas flow (Eq. (12)) and security constraints (Eqs. (14)-(16)). Moreover, based on the definition of EPS steady-state security regions, the steady-state security region of an IES can be defined as a set of electric power and natural gas injections for which there is a solution to the energy flow equality constraints that satisfies the inequality constraints. IES equality constraints include power flow Eqs. (3), (4) and (18) in the EPS, natural gas flow Eq. (12) in the NGS, and the electricity-gas coupling in Eq. (17). Similarly, IES inequality constraints consist of EPS security constraints (Eqs. (4)-(6)) and NGS security constraints (Eqs. (14)-(16)). Therefore, the steady-state security regions of IESs are the intersections of EPS and NGS steady-state security regions. Namely, in Fig. 2, only region B is the feasible region for DATC. Region A is secure for the EPS, but from the perspective of a unified power and gas energy system, it is actually insecure.

According to the concept of IES steady-state security regions, the mathematical model of DATC with integrated NGS security constraints (or DATC considering IES static security constraints) can be expressed as:

$$obj \quad \max \quad \lambda \quad (20-a)$$

$$s.t. \quad f(V, \theta, \pi, \lambda) = 0 \quad (20-b)$$

$$g^{\min} \leq g(V, \theta, \pi, \lambda) \leq g^{\max} \quad (20-c)$$

where Eq. (20-b) indicates the steady-state energy flow equations of IESs and Eq. (20-c) represents the static security constraints of IESs.

Continuation power flow (CPF) is considered as a common method for DATC calculation [21-22]. When CPF is implemented to solve the proposed DATC model (Eq. (20)), λ is gradually increased until the solution to Eq. (20-b) violates the operating limits (Eq. (20-c)). CPF does have some attractive edges, in mainly two aspects: 1) its accuracy is satisfying; and 2) different types of constraints can be easily checked after the solution to Eq. (20-b) is converged. Nevertheless, CPF is not applicable to real-time ATC assessment due to its demanding computation.

3. The LPC method to DATC estimation

The core idea of LPC is to determine when the boundary of the security region is reached, *i.e.*, the active inequality constraint that limits the DATC becomes an equality [25, 32]. Then, the active constraint is augmented into IES energy flow equations by treating λ as a new variable (augmented into IES state

variables as well). In the end, by using Newton's method to solve the augmented energy flow equations [10-11], the value of λ is determined.

The procedure of LPC can be divided into three main steps: 1) calculate the sensitivities of security constraints to λ ; 2) identify the active constraint based on the sensitivities from step 1; and 3) augment the active constraint into energy flow equations.

3.1 The calculation of sensitivities

The sensitivities of EPS security constraints to λ are computed as:

- Active power generation

$$\frac{\partial P_G}{\partial \lambda} = K_{gen} \quad (21)$$

- Voltage magnitude

$$\begin{bmatrix} \frac{\partial V}{\partial \lambda} \\ \frac{\partial \theta}{\partial \lambda} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta} \\ \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial P}{\partial \lambda} \\ \frac{\partial Q}{\partial \lambda} \end{bmatrix} \quad (22)$$

- Branch complex power flow

$$\frac{\partial |S_{ij}|}{\partial \lambda} = \frac{\partial |S_{ij}|}{\partial P_{ij}} \left(\frac{\partial P_{ij}}{\partial V} \frac{\partial V}{\partial \lambda} + \frac{\partial P_{ij}}{\partial \theta} \frac{\partial \theta}{\partial \lambda} \right) + \frac{\partial |S_{ij}|}{\partial Q_{ij}} \left(\frac{\partial Q_{ij}}{\partial V} \frac{\partial V}{\partial \lambda} + \frac{\partial Q_{ij}}{\partial \theta} \frac{\partial \theta}{\partial \lambda} \right) \quad (23)$$

Analogous to EPSs, the sensitivities of NGSs include:

- Natural-gas supply

$$\frac{\partial F}{\partial \lambda} = \frac{\partial F}{\partial P_G} \frac{\partial P_G}{\partial \lambda} \quad (24)$$

- Nodal pressure

$$\frac{\partial \pi}{\partial \lambda} = \left(\frac{\partial F}{\partial \pi} \right)^{-1} \frac{\partial F}{\partial \lambda} \quad (25)$$

- Pipeline gas flow

$$\frac{\partial |F_{mn}|}{\partial \lambda} = \frac{\partial |F_{mn}|}{\partial \pi} \frac{\partial \pi}{\partial \lambda} \quad (26)$$

3.2 The identification of active constraint

The active constraint is the one that first reaches its operating limits with the continuous increase of λ . The sensitivity of a constraint with respect to λ can be understood as its speed moving from the initial state towards the operating limit. Meanwhile, the available margin of a constraint determines its distance from the initial state to the operating limit. Therefore, the time (referred to as the value of λ) when different categories of security constraints reach their operating limits depends on both their sensitivities to λ and their available margins.

For EPS security constraints, the linear prediction of λ can be computed as

$$\lambda_{p_G} = \frac{P_G^{\max} - P_G^0}{\frac{\partial P_G}{\partial \lambda}} \quad (27-a)$$

$$\lambda_V = \begin{cases} \frac{V^{\max} - V^0}{\frac{\partial V}{\partial \lambda}} & \frac{\partial V}{\partial \lambda} > 0 \\ \frac{V^{\min} - V^0}{\frac{\partial V}{\partial \lambda}} & \frac{\partial V}{\partial \lambda} < 0 \end{cases} \quad (27-b)$$

$$\lambda_{s_{ij}} = \frac{S_{ij}^{\max} - |S_{ij}^0|}{\frac{\partial |S_{ij}|}{\partial \lambda}} > 0 \quad (27-c)$$

where λ_{p_G} , λ_V and $\lambda_{s_{ij}}$ are the linear predictions of λ constrained by the active power generation, voltage magnitude, and branch complex power flow, respectively.

Define $\lambda_e = \min(\lambda_{p_G}, \lambda_V, \lambda_{s_{ij}})$. Then, the constraint with its predicted DATC value being λ_e is the active constraint for EPSs. It should be noted that the DATC value λ_e may be located in either the secure region (*i.e.*, region B in Fig. 2) or the insecure region (*i.e.*, region A in Fig. 2).

It is necessary to clarify that the reactive power generation limits in the EPS should also be considered for ATC assessment, but they are not included in the inequality constraints (Eqs. (5-7)) directly. Instead, the constraints of reactive power generation capacity are implicitly taken into account. After the convergence of power flow solution, the reactive power generation constraints are checked. If the output reactive power of a generator has reached its limit, the node type of this generator will be switched from PV to PQ. On the other hand, with the continuous increase of λ , the violation against reactive power generation limits does not mean the transferred power has reached its maximum amount. Namely, the reactive power generation constraints should never become the active constraint that determines the value of DATC.

In a similar way, the active constraint information for NGSs can be determined as:

$$\lambda_{F_{\text{sup}}} = \frac{F_{\text{sup}}^{\max} - F_{\text{sup}}^0}{\frac{\partial F_{\text{sup}}}{\partial \lambda}} \quad (28-a)$$

$$\lambda_{\pi} = \begin{cases} \frac{\pi^{\max} - \pi^0}{\frac{\partial \pi}{\partial \lambda}} & \frac{\partial \pi}{\partial \lambda} > 0 \\ \frac{\pi^{\min} - \pi^0}{\frac{\partial \pi}{\partial \lambda}} & \frac{\partial \pi}{\partial \lambda} < 0 \end{cases} \quad (28-b)$$

$$\lambda_{F_{mn}} = \frac{F_{mn}^{\max} - |F_{mn}^0|}{\frac{\partial |F_{mn}|}{\partial \lambda}} > 0 \quad (28-c)$$

where $\lambda_{F_{\text{sup}}}$, λ_{π} and $\lambda_{F_{\text{mn}}}$ are the linear predictions of λ constrained by the gas supply, nodal pressure, and gas pipeline flow, respectively.

Define $\lambda_g = \min(\lambda_{F_{\text{sup}}}, \lambda_{\pi}, \lambda_{F_{\text{mn}}})$. Thus, λ_g indicates when NGSs will reach the operating limits and what the active constraint is.

3.3 The determination of DATC

In this period, the active inequality constraint is handled as an equality and is added into IES energy flow equations. With one more equality equation, the value of λ is treated as a new variable, which can be solved by using Newton's method together with IES state variables.

Comparing the value of λ_e and λ_g , LPC-based DATC information can be determined as follows:

- $\lambda_e < \lambda_g$

If $\lambda_e < \lambda_g$, it is the security constraint in the EPS that limits the DATC. Under this circumstance, λ_e is located in the secure region, and there is no reason to consider the security constraints in NGSs. In the calculation procedure for LPC, the active constraint is augmented into EPS power flow equations:

$$f_e(\mathbf{V}, \boldsymbol{\theta}, \lambda) = 0 \quad (29)$$

$$h_e(\mathbf{V}, \boldsymbol{\theta}, \lambda) = 0 \quad (30)$$

where Eq. (29) represents the power flow equations for EPSs and Eq. (30) is related to the active constraint that is set as an equality equation.

When Newton's method is applied to solve the augmented power flow Eqs. (29) and (30), the iterative equations are given as:

$$\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \\ \Delta h_e \end{bmatrix}^{(u)} = \begin{bmatrix} \frac{\partial \mathbf{P}}{\partial \mathbf{V}} & \frac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{P}}{\partial \lambda} \\ \frac{\partial \mathbf{Q}}{\partial \mathbf{V}} & \frac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}} & \frac{\partial \mathbf{Q}}{\partial \lambda} \\ \frac{\partial h_e}{\partial \mathbf{V}} & \frac{\partial h_e}{\partial \boldsymbol{\theta}} & \frac{\partial h_e}{\partial \lambda} \end{bmatrix}^{(u)} \begin{bmatrix} \Delta \mathbf{V} \\ \Delta \boldsymbol{\theta} \\ \Delta \lambda \end{bmatrix}^{(u)} \quad (31)$$

$$\begin{bmatrix} \mathbf{V} \\ \boldsymbol{\theta} \\ \lambda \end{bmatrix}^{(u+1)} = \begin{bmatrix} \mathbf{V} \\ \boldsymbol{\theta} \\ \lambda \end{bmatrix}^{(u)} + \begin{bmatrix} \Delta \mathbf{V} \\ \Delta \boldsymbol{\theta} \\ \Delta \lambda \end{bmatrix}^{(u)} \quad (32)$$

where the shaded block submatrix in Eq. (31) is the Jacobian matrix derived from the EPS power flow analysis.

- $\lambda_e > \lambda_g$

In this case, the active constraint limiting the DATC is one of the security constraints in the NGS. Therefore, the NGS security constraints must be taken into account for the LPC-based DATC assessment. The augmented IES energy flow equations are formulated as:

$$f(\mathbf{V}, \boldsymbol{\theta}, \boldsymbol{\pi}, \lambda) = 0 \quad (33)$$

$$h_g(\boldsymbol{\pi}, \lambda) = 0 \quad (34)$$

where Eq. (34) is associated with the active constraint in the NGS.

The iterative equations for Eqs. (33) and (34) are expressed as

$$\begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \\ \Delta \mathbf{F} \\ \Delta h_g \end{bmatrix}^{(u)} = \begin{bmatrix} \frac{\partial \mathbf{P}}{\partial \mathbf{V}} & \frac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}} & 0 & \frac{\partial \mathbf{P}}{\partial \lambda} \\ \frac{\partial \mathbf{Q}}{\partial \mathbf{V}} & \frac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}} & 0 & \frac{\partial \mathbf{Q}}{\partial \lambda} \\ 0 & 0 & \frac{\partial \mathbf{F}}{\partial \boldsymbol{\pi}} & \frac{\partial \mathbf{F}}{\partial \lambda} \\ 0 & 0 & \frac{\partial h_g}{\partial \boldsymbol{\pi}} & \frac{\partial h_g}{\partial \lambda} \end{bmatrix}^{(u)} \begin{bmatrix} \Delta \mathbf{V} \\ \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{\pi} \\ \Delta \lambda \end{bmatrix}^{(u)} \quad (35)$$

$$\begin{bmatrix} \mathbf{V} \\ \boldsymbol{\theta} \\ \boldsymbol{\pi} \\ \lambda \end{bmatrix}^{(u+1)} = \begin{bmatrix} \mathbf{V} \\ \boldsymbol{\theta} \\ \boldsymbol{\pi} \\ \lambda \end{bmatrix}^{(u)} + \begin{bmatrix} \Delta \mathbf{V} \\ \Delta \boldsymbol{\theta} \\ \Delta \boldsymbol{\pi} \\ \Delta \lambda \end{bmatrix}^{(u)} \quad (36)$$

where the shaded block submatrices in Eq. (35) are the Jacobian matrices derived from EPS and NGS energy flow analysis.

The LPC method only needs two energy flow calculations, and its computation burden is considerably less when compared with CPF. Moreover, based on the solution to the augmented energy flow equations, DATC results provided by the LPC method are strictly accurate as long as the active constraint is identified correctly.

As illustrated above, the correct identification of the active constraint is of vital importance to an accurate DATC calculation, whereas a false identification of the active constraint derived from the linear prediction may happen because both EPSs and NGSs are inherently nonlinear. A direct way to distinguish between the correct and false identification of the active constraint is to check whether there are any violations against IES security constraints (Eq. (20-c)). If there is no violation, then end the DATC calculation; otherwise, compute the sensitivities at the current operating states and repeat the LPC process.

3.4 The corrective adjustment in NGSs

The main difference between EPSs and NGSs lies in the fact that natural gas is easy to store on a large scale while electric power cannot be stored efficiently. The gas storage capacity is critical to NGS security and reliability [17].

When the power generation capacity of NGFPPs is limited by NGS security constraints, i.e., $\lambda_e > \lambda_g$, the corrective adjustment of NGS initial operating states can be adopted. Fortunately, the active constraint information helps to expose the weak point for NGS initial operating states, and thus provide a reference for the corrective adjustment in NGSs aimed at promoting the gas supply ability at the weak point. By increasing

the injection of gas storage whose gas distance to the active constraint might as well be short, this corrective adjustment facilitates enlarging the security regions of NGSs and consequently enhancing the power exchange ability in EPSs.

4. Probabilistic approach combining LHS and Nataf transformation

A probabilistic method combining the LHS and Nataf transformation is proposed to tackle the PATC problem by considering the correlations between input variables.

4.1 IES uncertainties

This research mainly focuses on the stochastic behavior of electricity/gas demands and wind power generations. The correlations between input random variables are also considered. Both the electricity and gas demand uncertainties are modeled as multivariable normal distributions with known correlation matrices. The variations in wind speeds are represented via correlated Weibull probability distribution functions.

4.2 LHS

The representative generation of samples from probability distributions of inputs is completed through LHS to ensure the entire sampling space of each input random variable is evenly covered. For LHS, each dimension is subdivided and once a sample is taken from a dimension, this dimension will not be sampled again. However, for SRS, several sample points may belong to the same interval or dimension.

LHS covers a larger search space than SRS with the same sample size and therefore overshadows SRS for a higher sampling efficiency. In addition to the sampling process, the permutation is also essential to LHS to accommodate the correlations between samples of different input variables to the desired levels. In this study, the Cholesky decomposition is adopted in the permutation process. More details regarding LHS can be found in [29].

4.3 Nataf transformation

Let $\mathbf{X} = (X_1, X_2, \dots, X_t)$ denote the t -dimensional input random variables, and let $\mathbf{Z} = (Z_1, Z_2, \dots, Z_t)$ denote the t -dimensional standard normal random variables. The transformation from $\mathbf{Z}$ to $\mathbf{X}$ is expressed as:

$$X_l = F^{-1}(\phi(Z_l)) \quad l=1,2,\dots,t \quad (37)$$

where $F(\cdot)$ is the cumulative distribution function (CDF) of $X_1, X_2, \dots, X_t$ and $\phi(\cdot)$ is the CDF of $Z_1, Z_2, \dots, Z_t$.

Suppose $\mathbf{C}_X$ and $\mathbf{C}_Z$ are the correlation coefficient matrices of $\mathbf{X}$ and $\mathbf{Z}$, respectively. Given the desired value of $\mathbf{C}_X$, $\mathbf{C}_Z$ can be computed by using the algorithms in [28].

Once $\mathbf{C}_Z$ is determined in accordance with $\mathbf{C}_X$, $\mathbf{Z}$ can be obtained by the following orthogonal transformation:

$$\mathbf{Z} = \mathbf{B} \cdot \mathbf{Y} \quad (38)$$

$$\mathbf{C}_z = \mathbf{B} \cdot \mathbf{B}^T \quad (39)$$

where $\mathbf{Y}$ are the t -dimensional independent standard normal variables. $\mathbf{B}$ is the lower triangular matrix from Cholesky decomposition of $\mathbf{C}_z$.

According to Eqs. (37) and (38), the dependent variables $\mathbf{X}$ are easily transformed into independent standard normal variables $\mathbf{Y}$, which is the basic idea of the Nataf transformation.

The probabilistic method proposed here takes advantages of LHS to improve the sampling efficiency and the Nataf transformation to handle the correlation between input variables. In short, the process of the proposed probabilistic method is summarized as follows:

- 1) Given a sample size of N , generate the sampling matrix $\mathbf{H}_{t \times N}$ by sampling the t -dimensional variables $\mathbf{Y}$ based on LHS.
- 2) Calculate the correlation matrix $\mathbf{C}_z$ to ensure a desired correlation level between input variables, and do the Cholesky decomposition of $\mathbf{C}_z$.
- 3) Obtain the sample matrix $\mathbf{T}_{t \times N}$ of the t -dimensional variables $\mathbf{Z}$ by using $\mathbf{T} = \mathbf{B} \cdot \mathbf{H}$.
- 4) The final sampling matrix $\mathbf{S}$ is obtained by transforming the samples in every row of $\mathbf{T}$ according to Eq. (37).

5. Computational procedure

Figure 3 depicts the flowchart of the proposal featured in this study. The main processes of the flowchart are:

- 1) The correlated sample matrix is generated from a combination of LHS and Nataf transformation.
- 2) The DATC problem that considers IES static security constraints is solved by the LPC method, which consists of the calculation of sensitivities, the identification of active constraints and the solution to augmented energy flow equations.
- 3) If needed, corrective adjustment can be adopted to increase the value of ATC.

To provide valuable reference information for energy market participants to bid the lowest price of electricity trading in a deregulated EPS (or further IES), the Federal Energy Regulatory Commission (FERC) requires that the ATC information should be available on a publicly accessible open-access same-time information system on hourly and daily basis. If the wind power penetration is significant, ultra-short ATC calculation every fifteen minutes will be more desirable. Whatever the time scale for ATC calculation is (fifteen minutes, an hour or a day), a same time scale of NGS data is available with appropriate synergies between EPSs and NGSs. It is also relevant to note that there is no energy sector (private or state-owned) that has access to the parameter information of both EPSs and NGSs at present. Thereupon, an implicit assumption of the proposal is that it has the authority and ability to obtain the basic operating data of integrated electricity-gas energy networks.

Fig. 3 The flowchart of PATC calculation considering IES static security constraints and uncertainties

6. Case studies

To illustrate the performance of the proposal, a case study is conducted on the modified IEEE 118-bus system (from MATPOWER [33]) operating interdependently with a 20-node NGS [34-35].

6.1 Network description

The IEEE 118-bus system is partitioned into three areas as in [36]. The power capacities of all generators

are increased by 50%. Six wind farms, with the same 60 MW capacity, are connected to nodes 17, 20, 21, 51, 57 and 63, respectively. The 20-node NGS, depicted in Fig. 4, consists of two gas suppliers, two compressors, seventeen pipelines and four gas storages. The generators of nodes 10, 25 and 26 in area 1, of nodes 65 and 66 in area 2, and of node 80 in area 3 are assumed to be NGFPPs and are connected to the 20-node NGS as shown in Fig. 4. More operating parameters of the 20-node NGS and NGFPPs can be found in the Appendix.

Fig. 4 Structure of the 20-node NGS

A variation level of 5% is set for electricity/gas load uncertainties. The correlation coefficient between electricity loads is equal to 0.7 within the same area and is equal to 0.5 in different areas. Additionally, gas loads in the 20-node NGS are dependent with a correlation coefficient of 0.6. As for wind farms, the correlation matrices between wind speeds are given in Eqs. (40) and (41). The parameters of the Weibull distribution and the power generation characteristic of the wind farms are set the same as in [37]. As the Nataf transformation is adopted, the correlations between the samples are in accordance with the desired correlated levels.

$$C_I = \begin{matrix} & \begin{matrix} 17 & 20 & 21 \end{matrix} \\ \begin{matrix} 17 \\ 20 \\ 21 \end{matrix} & \begin{pmatrix} 1 & 0.8 & 0.8 \\ 0.8 & 1 & 0.9 \\ 0.8 & 0.9 & 1 \end{pmatrix} \end{matrix} \quad (40)$$

$$C_{II} = \begin{matrix} & \begin{matrix} 51 & 57 & 63 \end{matrix} \\ \begin{matrix} 51 \\ 57 \\ 63 \end{matrix} & \begin{pmatrix} 1 & 0.9 & 0.8 \\ 0.9 & 1 & 0.8 \\ 0.8 & 0.8 & 1 \end{pmatrix} \end{matrix} \quad (41)$$

6.2 The influence of NGS security constraints on ATC

To demonstrate the necessity of incorporating NGS security constraints into the ATC assessment, two scenarios are defined (the uncertainties are not considered in this case):

Scenario 1: The value of ATC is determined only by EPS security constraints, *i.e.*, the conventional DATC model.

Scenario 2: The security constraints of both EPSs and NGSs are considered for the ATC assessment.

In comparing scenarios 1 and 2, the results in Table 1 show that for the ATC from area 2 to areas 1 and 3,

it is the security constraint in the IEEE 118-bus system that limits the amount of power transfer, leading to the same ATC value. In other cases, the active constraint lies in the 20-node NGS, indicating that the operating states in scenario 1 are prone to a location in insecure regions (*i.e.*, region B in Fig. 2). Take the ATC from area 3 to area 2 for example. The security regions for both scenarios are shown in Fig. 5. With the continuous increase of ATC, the voltage magnitude of node 5 is within its security constraint until the value of ATC is equal to 442.5 MW. However when the amount of transferred power is greater than 139.2 MW, the security constraints of NGSs will be violated. As a result, the operating states under an amount of ATC from 139.2 MW to 442.5 MW are inherently insecure from the integrated point of EPS and NGS security regions.

To conclude, the ATC calculation results obtained from scenario 1 might be over-estimated and pose an additional threat to IES security. This illustrates the importance of considering NGS security constraints when evaluating the power transfer capacity in EPSs.

It is important to clarify that when the uncertainties of input random variables are taken into account, the active constraint information might not be constant, which will be illustrated in the next subsection.

Table 1 Comparison of ATC results for scenario 1 and scenario 2

From area	To area	Scenario 1		Scenario 2	
		ATC/MW	Active constraint	ATC/MW	Active constraint
1	2	433.1	node 53 voltage	411.5	node 5 pressure
1	3	750.7	node 38 voltage	411.5	node 5 pressure
2	1	508.1	node 38 voltage	508.1	node 38 voltage
2	3	962.4	node 118 voltage	962.4	node 118 voltage
3	1	518.1	node 38 voltage	139.2	node 20 pressure
3	2	442.5	node 53 voltage	139.2	node 20 pressure

Fig. 5 Scenarios 1 and 2 security regions for the ATC from area 3 to area 2

6.3 Probabilistic results

Because the effectiveness of LHS and Nataf transformation to address the correlated uncertainties in EPSs has been well validated [28], more attention will be paid to the performance of the proposal to address the

varying gas demands in NGSs. The probabilistic results for the ATC from area 1 to area 2 (or area 3) and from area 3 to area 2 (or area 1), where NGS security constraints probably limit the ATC, are thereby analyzed.

The comparisons of MCS-LHS and MCS-SRS (with a sample size of 10000) are shown in Fig. 6 and Table 2. As seen, all probabilistic indices, including the CDF curves, mean and standard values, obtained from LHS and SRS are quite close. Moreover, the fluctuation degree of the ATC from area 1 to area 2 (or area 3) is considerably larger than the ATC from area 3 to area 1 (or area 2). This phenomenon can be illustrated that for the ATC from area 1 to area 2 (or area 3), the pressure of node 5 is the key factor limiting the ATC. The variations in gas loads for nodes 6 and 7 significantly affect the pressure of node 5 and further the value of ATC. While for the ATC from area 3 to area 1 (or area 2), there is no gas load in nodes 18, 19 or 20 (with node 20 pressure constraint being the active constraint). The influence level of gas load fluctuations on ATC is considerably smaller. The wide fluctuations of ATC thus underscore the importance of integrating the IES uncertainties into the ATC evaluation.

Fig. 6 Comparisons of MCS-SRS and MCS-LHS for CDF curves

Table 2 PATC result comparisons of SRS and LHS

From area	To area	ATC (MW)			
		Mean		Standard	
		SRS	LHS	SRS	LHS
1	2	360.9	359.8	89.6	89.4
1	3	412.1	410.7	120.8	121.2
3	1	139.1	139.0	8.32	8.34
3	2	139.1	139.0	8.33	8.35

Table 3 shows the active constraint information and identification accuracy of LPC. For the ATC from area 1 to area 2, the active constraint is changeable, with 44.50% in the EPS. This is because its deterministic results for scenarios 1 and 2 (shown in Table 1) are relatively close. In addition, although confronted with various inputs and changeable active constraints, LPC still owns a high identification accuracy, and the number of times needed to execute the LPC process is no more than two (one in most cases). Accordingly, the LPC method can correctly identify the active constraint and calculate the value of DATC in a fast way.

Table 3 Active information obtained from the LPC method

From area	To area	Active constraint			
		Locating in (%)		Identification accuracy (%)	
		EPSs	NGSs	1st*	2nd*
1	2	44.50	55.50	99.84	100
1	3	0.22	99.78	99.73	100
3	1	0	100	99.95	100
3	2	0	100	99.93	100

*: 1st and 2nd represent the correct identification percentage of active constraint at the first and second time

6.4 Corrective adjustment in NGSs

The variations in the PATC results with respect to the corrective adjustment in NGSs are shown in Fig. 7 and Fig. 8. With the increase of gas storage injection, two aspects of its positive effects on ATC are discovered: 1) the active constraint gradually switches from NGSs to EPSs, leading to a stronger power transfer capability; and 2) the fluctuation level of ATC is depressed effectively, which provokes electric power market participation and enables a more efficient use of interconnected electric power transmission systems. Based on the active constraint information from LPC, the corrective adjustment in NGSs greatly enhances the flexibility in electric power transmission. Meanwhile, gas storage capabilities are crucial to the corrective adjustment.

Fig. 7 The enhancement of ATC from area 1 to area 3 by increasing the gas storage injection at node 5

Fig. 8 The proportion of active constraint in EPSs variations with respect to the increase in gas storage injection

For EPS operators because they expect that gas fuels for NGFPPs should be adequate, the gas storage injection should increase as much as possible. But for NGS operators, sometimes they are unwilling to do the corrective adjustment because it brings about an extra pumping cost. A feasible strategy to handle this issue is to determine a minimum increase in gas storage injection in which gas fuels for NGFPPs are adequate under certain confidence intervals. The increased amount of gas storage injection under different confidence intervals is shown in Fig. 9.

Fig. 9 Increased amount of gas storage injection under different confidence intervals

In practice, the corrective adjustment of gas storages might depend on both the gas storage capabilities and synergies between EPS and NGS operators. If corrective adjustment is needed, electric companies should compensate gas companies to some extent.

7. Conclusions

The ATC model considering IES security constraints and uncertainties was primitively proposed in this paper. The security constraints and uncertainties have a substantial impact on the value of ATC because the gas fuel of NGFPPs is not always available. In particular, for every possible combination of electricity/gas loads and wind power injections, the active constraint was identified correctly by LPC. Additionally, the ATC results provided by the LPC and LHS methods were fast and accurate enough. Moreover, the corrective adjustment in NGSs could greatly enhance the flexibility of the power transfer capability.

To summarize, future research direction will focus on integrating the outages of electricity/gas transmission lines and suppliers into PATC assessment. On the other hand, the transient stability constraints in both EPSs [24] and NGSs [38] will also be discussed.

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Appendix

See Tables A1 through A4. The pipeline and compressor branch data can be found in [34-35].

Table A1 Node data of the 20-node NGS

Node	Supplier (Mm ³ /D)	Demand (Mm ³ /D)	Pressure upper bound (Bar)	Pressure lower bound (Bar)
1	---	0	80	40
2	8.4	0	80	40
3	0	3.918	80	40
4	0	0	80	40
5	0.815	0	80	30
6	0	5	80	30
7	0	7	80	30
8	---	0	75	40
9	0	0	75	40
10	0	6.365	75	40
11	0	0	75	40
12	0	2.12	75	40
13	1.2	0	75	40
14	4.16	0	75	40
15	0	6.848	75	40
16	0	15.3	75	40
17	0	0	75	40
18	0	0	75	40
19	0	0	75	25
20	0	0	75	25

Table A2 Known-nodal Pressure

Node	Pressure (Bar)
1	55
8	57

Table A3 The ratio of compressors

From	To	ratio
8	9	1.1
17	18	1.2

Table A4 Gas consumption coefficients of NGFPPs

α_g (Mm ³ /D)	β_g (Mm ³ /D/MW)	γ_g (Mm ³ /D/MW) ²
0	0.005	0

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