An Incentive Scheme for Grid-Enhancing Technologies Based on the Shapley Value

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***Abstract*—Modernization of the transmission system via deploying grid-enhancing technologies (GETs) is a cornerstone of future grid design. New congestion patterns necessitating renewable energy curtailment highlight the significance of GETs. Despite the wide acknowledgment of the importance and benefits of GETs, their deployment remains fairly limited. One important barrier is the lack of proper incentives for deployment and efficient operation of GETs. This paper designs an incentive scheme to compensate GETs based on their performance in the intraday market. The rewards are determined based on the cost savings achieved by GET operations and are allocated to market participants using the Shapley value. The proposed incentive scheme is tested with numerical studies on modified IEEE RTS 24-bus and IEEE 300-bus systems. Results confirm that the designed incentive is aligned with the system objective: GET owners are compensated when cost savings are achieved. The benefits of a performance-based payment scheme are threefold: (i) it promotes efficient operation of existing GETs based on the state of the system, (ii) it attracts further GETs deployment, and (iii) moves the risk from ratepayers to the investors.**

***Index Terms*—Electricity market, grid-enhancing technologies, power flow control, transmission investment incentive, Shapley value, power system flexibility, transfer capability.**

NOMENCLATURE

Indices

i, j	GET owner
k	Transmission line
s	Segment of linearized generator cost functions

Parameters

$\overline{\mathbf{f}}$	Thermal capacities of transmission lines
$\overline{\mathbf{\Delta f}}$	GET nodal injections upper bounds
$\overline{\mathbf{p}}_s$	Maximum output of generator g in segment s
$\bar{I}_k$	Maximum current on line k
θ_k^{PST}	Maximum phase shift by PSTs on line k
$\underline{\mathbf{p}}$	Minimum output of generators
$\mathbf{0}$	Vector of zeros
$\mathbf{1}$	Vector of ones
$\mathbf{\Gamma}$	Generator placement matrix
$\mathbf{\Phi}$	Injection shift factor matrix
$\mathbf{\Psi}$	GET placement matrix
$\mathbf{A}$	Adjacency matrix
$\mathbf{c}_s$	Linear costs of generators in segment s
$\mathbf{d}$	Vector of nodal Demands
b_k	Susceptance of line k
C^{FACTS}	Cost of FACTS devices
C^{PST}	Cost of PSTs
S_k^{FACTS}	Rating of FACTS device on line k
V_k^{FACTS}	Maximum voltage injection by FACTS devices on line k

Variables

$\mathbf{\Delta f}$	GET nodal injections
$\mathbf{f}$	Active power flows
$\mathbf{p}$	Active power output of generators
$\mathbf{p}_s$	Active power output of generators in segment s

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I. INTRODUCTION

THE transmission system needs upgrades to maintain the operational efficiency of the power grid and accommodate the growing penetration of variable renewable energy sources (vRES). Grid-enhancing technologies (GETs), with prominent examples including impedance control, phase angle control, topology control, and dynamic line rating (DLR), provide a fast and cost-effective alternative to the expensive and lengthy processes of constructing new transmission lines. While new transmission lines may be necessary, GETs can offer immediate transfer capability enhancement and postpone the need for new transmission. Despite the maturity of the technology and wide acceptance of GETs benefits, their deployment remains limited. One of the main challenges contributing to this under-deployment is the lack of incentives for the installation and efficient operation of GETs.

Currently, GETs are considered as a component of the monopoly transmission system. Thus, GETs are regulated and receive regulated payments that are not linked to performance [1]. Regulated rate of return (RoR) payments often create an incentive to maximize the investment, which would lead to a tendency to build more lines rather than operating the existing system more efficiently [2]. This is a major reason for under-utilization of GETs [3]. Even when GETs are adopted, there is no incentive for efficient operation of GETs, which requires frequent adjustment of GETs setpoint [1]. A more appealing alternative would be to provide GETs operators with performance-based incentives.

Previous studies have proposed performance-based incentives for transmission investments. A widely employed approach is rewarding transmission projects using the surplus improvements they generate to incentivize investments in the socially optimal direction [4]. Such methods are employed in [5]–[9], where transmission expansion investors receive the social welfare positives created by their projects as a part of the payment. It is worth noting that the cost savings and social welfare improvements can be modeled as inelastic demand. Despite the research focusing on economic incentive design for transmission expansion investments, proposals on payoffs to GETs have been somewhat limited. Reference [10] proposes to use the social welfare change to recover the investments in flexible AC transmission system (FACTS) devices. A sensitivity-based payment scheme for operations of FACTS is proposed in [11], which uses the dual variable of the DC power flow equation as a payment factor. However, this method may be revenue inadequate and does not accurately reflect the cost savings produced by FACTS operations. A merchant market model is proposed in [1], where power flow controller (PFC) owners acquire financial transmission rights (FTR). FTR is a long-term right to congestion rent, as described in [12]. It serves several purposes, including hedging against spot market price volatility, financial management of access rights to the transmission grid in the deregulated environment, allocation of congestion rent, and providing the environment for additional auctions and bilateral contracts between market participants. In electricity markets, the initial FTRs are allocated based on the historical use of the transmission network by market players. The congestion rent collected from the spot market is distributed among market participants based on the share of FTRs obtained. These FTRs can be transferred in secondary markets so that different participant can tailor their FTRs based on the risk assessments [13]. Previous research has shown that GETs can improve the efficiency of FTR auctions and allow for more FTRs to be auctioned [14]. Therefore, part of the additional auctioned FTRs can be assigned to GET owners, with the hope that they can recover their investment in a competitive manner and help the liquidity of electricity markets [1]. FTRs can further be used to secure fundamental transmissions in market processes or infrastructure upgrades, which is also the case for GETs. For instance, [15] proposes an FTR model for transition from single-price electricity markets (as in the European Union) to nodal electricity market (as in PJM) without endangering consumer supply security or steep increases in electricity prices. The literature on allocating incremental FTRs to new GET projects to incentivize the deployment and optimal operation is, however, limited. Reference [14] has discussed that additional FTRs can be auctioned considering the role of FACTS devices in FTR markets but did not discuss how to allocate a share of these incremental FTRs to FACTS owners. Reference [1] has shown that FTR markets can be revenue adequate in the presence of FACTS if power flow directions are known and discussed that FACTS owners can request additional FTRs as long as it is feasible considering network constraints. Further research is required for a clear FTR allocation mechanism for FACTS owners. Since these challenges have not yet found appropriate solutions, FTR-based incentives for GETs cannot be readily developed and used.

The approach of using system benefits as compensations has recently attracted attention to designing incentives for GETs. The Working for Advanced Transmission Technologies (WATT) coalition proposed a shared savings incentive for GETs, which was a main topic at the workshop on performance-based rate-making hosted by the Federal Energy Regulatory Commission (FERC) [16], [17]. This proposal allows GET owners to receive a portion of the system-wide cost-saving benefits that they generate [18]. However, a key question remains: How should compensation be allocated to different GET owners? Often, multiple GETs operate within a single transmission system with the goal of minimizing the system-wide operating cost. While each asset contributes to this objective, it is not straightforward to calculate the benefits of GETs. More importantly, it is unclear how such benefits (if calculated) should be distributed to different GET owners. Additionally, technological advances in the field, such as the modular FACTS (M-FACTS) devices, e.g., the SmartValve [19] by Smart Wires Inc. and the UPFC PLUS [20] from Siemens, allow GET deployments in a more distributed manner. Therefore, it is essential to have a method to distribute the economic compensation fairly among market participants. In [5], the marginal contribution of each transmission expansion project in a single-price market to social welfare, which is used as a reward, is determined sequentially. However, such an approach for benefit allocation can be subject to the order in which the projects are carried out.

This paper fills the research gap by proposing an incentive scheme for hourly operation for GETs, with a benefit allocation method to distribute the payoffs. The proposed method considers GET deployments from different owners and calculates the cost savings created by GETs in hourly operation, and payoff distribution is completed by utilizing the Shapley value [21], a concept from cooperative game theory. Furthermore, we propose an improved Shapley value calculation, which resets the operating limits of GETs based on the grand coalition results to ensure market efficiency. Details of the modification and its effectiveness are presented in later sections. The Shapley value is a key method that provides value distribution in coalition games [22]. In previous studies, Shapley-value-based methods have been utilized to allocate compensations to transmission investors [6] and demand-side consumers participating in demand response programs [23]. In [24], the revenue for generators that bid as a coalition is allocated using the Shapley value, and a similar application of the Shapley value is presented in [25]. Other power system-related applications of the Shapley value include transmission cost allocation [26], [27] and profit allocation for distributed energy resources [28]. GET-related applications of the Shapley value are very limited. In [29], profits are allocated to the owners of transmission lines, thyristor-controlled series capacitor (TCSC) devices, and distributed generators using the Shapley value. However, in this allocation scheme, the whole of social welfare is distributed while considering transmission owners as a participant in the coalition game, which leads to the under-evaluation of GET contributions. Furthermore, the model developed in [29] is based on nonlinear AC power flow equations, which is incompatible with existing market management software tools.

The proposed scheme assumes that GET owners receive compensations calculated in the intraday market (IDM). There are two reasons behind this implementation. First, with the increasing penetration of the variable renewable energy, hourly optimal power flow (OPF) results can more accurately reflect the actual social welfare contributions of GET operations. Second, GETs, unlike transmission lines, need to adjust their setpoints frequently to facilitate efficient dispatch under different operating conditions. This is enabled by the fast-response features of the GETs. Granted, integrating GETs into energy management systems (EMS) is required to fully utilize their features and allow IDM participation. We show that the proposed scheme can be implemented using the models in the existing literature that co-optimize GET setpoints in power system operation. Moreover, this paper aims to show that the proposed scheme, with performance-based financial compensations, is a desirable approach to incentivize GET investments. As mentioned previously, the current common approach for transmission investment recovery is through regulated RoRs. Therefore, The payoffs to GET owners are compared with ones achieved under a regulated RoR to confirm the effectiveness of the proposed scheme.

The main contributions of this paper are summarized as follows:

- An incentive scheme for the optimal operation of GETs is proposed, which allows owners to receive financial compensation for the socially optimal adjustment of their GETs' setpoints. The payoffs are calculated in the IDM, allowing the benefits of GETs to be more accurately captured, which is also in line with their flexibility. The Shapley value is utilized to allocate the benefits fairly to GET owners. The proposed scheme is based on system operation models compatible with existing EMS. To the best of our knowledge, this paper is the first paper to thoroughly study the effectiveness of a game-theory-based method in providing incentives to GETs.
- The proposed scheme employs an improved Shapley value approach, which not only considers the players' participation in coalitions but also reflects their actual contribution based on the results of the grand coalition. This design is intended to ensure market efficiency.

The rest of this paper is organized as follows: the proposed payment scheme is presented in Section II; Section III presents simulations studies on two test systems; Finally, Section IV concludes the paper.

II. Methodology

In this paper, we propose calculating the financial compensation to GET owners based on hourly dispatch results. This section first presents the problem formulation of (DC optimal power flow) DCOPF with GET operation, followed by a brief introduction of the Shapley value. Detailed steps of the proposed incentive scheme are then presented.

Including GETs in power system operation models increases the computational complexity. Various models have been proposed in previous research to efficiently co-optimize the setpoints of different GETs in power system operation [30]–[34]. In this paper, prominent voltage source converter-based FACTS (VSC-FACTS) devices, such as the static synchronous series compensator (SSSC) and the UPFC, and phase-shifting transformers (PSTs) are used to study the proposed incentive scheme. Both technologies are well-studied in the existing literature and have seen developments and deployments in the industry. Moreover, their modeling using the nodal injection model [31] helps preserve the linearity of DCOPF. Additionally, such modeling regards the GET adjustments to transmission grid parameters as nodal power injections, which helps preserve the original topology of the system and allows the injection shift factors (ISFs) to be used without changes. Devices such as the variable-impedance FACTS devices are beyond the scope of this paper. However, we expect similar results for these devices.

A. Co-optimizing GET operation in DCOPF

The DCOPF formulation with ISFs involving GET operations is shown as follows:

$$(\mathbf{P1}:)\ \text{minimize}\ \Pi = \sum_{s=1}^{\bar{s}} \mathbf{c}_s^{\mathrm{T}} \mathbf{p}_s \tag{1}$$

s.t.

$$\sum_{s=1}^{\bar{s}} \mathbf{p}_s = \mathbf{p}, \tag{2}$$

$$\mathbf{0} \le \mathbf{p}_s \le \mathbf{p}_s^{\max}, 1 \le s \le \bar{s}, \tag{3}$$

$$\underline{\mathbf{p}} \le \mathbf{p}, \tag{4}$$

$$\mathbf{f} = \mathbf{\Phi}(\mathbf{\Gamma p} - \mathbf{d} - \mathbf{A}^{\mathrm{T}}\mathbf{\Psi}\mathbf{\Delta f}), \tag{5}$$

$$-\bar{\mathbf{f}} \le \mathbf{f} + \mathbf{\Psi}\mathbf{\Delta f} \le \bar{\mathbf{f}}, \tag{6}$$

$$\mathbf{1}^{\mathrm{T}}\mathbf{p} - \mathbf{1}^{\mathrm{T}}\mathbf{d} = 0, \tag{7}$$

$$-\overline{\mathbf{\Delta f}} \le \mathbf{\Delta f} \le \overline{\mathbf{\Delta f}}, \tag{8}$$

The objective of the DCOPF is to minimize total production cost, as shown in (1). A piece-wise linearized model with $\bar{s}$ segments is adopted for production cost functions for the generating units. Equation (2) specifies that the sum of the output in each linearized segment is equal to the total output of a generator. The generator output upper bounds of each segment are shown in (3). Minimum output requirements for generators are presented in (4). In (5), the ISF matrix calculates power flows based on nodal power injections, which consist of generator outputs, demands, and GET nodal injections. Power flows are bounded by line thermal limits, as shown in (6). The system-wide active power balance constraint is shown in (7). The constraints on GET nodal injections are specified in (8), with the elements of $\overline{\mathbf{\Delta f}}$ presented as follows for the VSC-FACTS devices [33]:

$$\overline{\Delta f}_k = V_k^{\mathrm{FACTS}} |b_k|. \tag{9}$$

The modeling in (9) can be used for prominent VSC-FACTS devices. The bounds of PST nodal injections are shown as follows [35]:

$$\overline{\Delta f}_k = \theta_k^{\mathrm{PST}} |b_k|. \tag{10}$$

Note that the PST and the VSC-FACTS share similar modeling, as seen from (9) and (10). Thus, the constraints (8) represent the operation of both types of technology.

B. The Shapley Value

The Shapley value is a widely used game theory method to allocate benefits or costs among players forming a coalition. The allocation is based on the marginal contribution of each player to all possible coalitions it participates in. The calculation of the Shapley value for player i, denoted as $\phi(i)$, is shown as follows:

$$\phi(i) = \sum_{\mathcal{S} \subseteq \mathcal{N} \setminus i} \frac{|\mathcal{S}|!(n-|\mathcal{S}|-1)!}{n!} (v(\mathcal{S} \cup \{i\}) - v(\{\mathcal{S}\})), \quad (11)$$

where $\mathcal{N} = \{1, 2, ..., n\}$ is the grand coalition which consists of the complete set of players, and $\mathcal{S}$ is a set of players not included i in the game. Additionally, $v(\cdot)$ denotes the characteristic function, which represents the value of a coalition.

The Shapley value provides a fair and unique distribution solution [27]. Additionally, essential features of the Shapley value that are related to the application in this paper are presented as follows [23]:

- Efficiency: the entirety of benefits is distributed to all the players in the grand coalition, as shown in (12).

$$\sum_{i \in \mathcal{N}} \phi(i) = v(\mathcal{N}); \quad (12)$$

- Symmetry: two players receive equal rewards if they contribute equally, which is presented as follows [36]:

$$\text{if } v(\{i\} \cup \mathcal{S}) = v(\{j\} \cup \mathcal{S}), \quad (13)$$

$$\text{then } \phi(i) = \phi(j). \quad (14)$$

C. Shapley value-based incentives for GETs operations

The incentive scheme for GET owners is considered a coalition game, with the characteristic function being the cost savings achieved by GETs operations. In the proposed scheme, players are GET owners who invested in deploying GETs in the power grid. Each player can own assets at one or multiple locations. Players in this coalition game are assumed to be obligated by contracts to adjust the setpoints of their devices according to the results of power system operation models.

The characteristic function of a coalition is the cost savings they achieve, which is presented as follows:

$$\begin{aligned} v(\mathcal{S}) &= \mathbf{P1}\{\mathcal{F}(\emptyset)\} - \mathbf{P1}\{\mathcal{F}(\mathcal{S})\} \\ &= \mathbf{P1}\{\mathbf{0}\} - \mathbf{P1}\{\mathcal{F}(\mathcal{S})\}, \end{aligned} \quad (15)$$

where $\mathbf{P1}\{\cdot\}$ denotes the objective function value when solving $\mathbf{P1}$ with a vector representing the operating limits of GETs. $\mathcal{F}(\cdot)$ represents a function that maps a coalition of players to the corresponding operating constraints. Therefore, $\mathbf{P1}\{\mathbf{0}\}$ represents a base case where the DCOPF is solved with no GET operation, and (15) calculates the cost savings achieved by coalition $\mathcal{S}$.

Certain GET deployments may not operate at their full limits, particularly when the system congestion level is low. Therefore, to improve market efficiency, the proposed scheme is designed with steps to accurately measure the marginal contribution of each participant in the grand coalition $\mathcal{N}$. Such design is further discussed in Section III.

The incentive scheme is presented as follows:

1) For the current hour in the IDM, get $\mathbf{P1}\{\mathbf{0}\}$;
2) Solve $\mathbf{P1}\{\mathcal{F}(\mathcal{N})\}$;
3) Check if all the operating constraints (8) are binding in step 2. If yes, go to step 5. If no, continue to step 4;
4) Reset GET operating ranges using the values from step 2;
5) Calculate the cost savings for each coalition using (15);
6) Calculate the Shapley values using (11);
7) Use Shapley values calculated in step 6 as payoffs to GET owners for this hour.
8) Accumulate the results of step 7 for the whole contract length.

We assume that the GET owners are under the obligations of contracts, and payoffs are settled by accumulating each IDM payoff after the contracts conclude. For example, GET owners can receive payoffs annually. However, with the advances in the GET designs, more flexibilities in the planning process are granted, allowing more options in the payoff cycles. This will be further discussed in Section III.

III. Case Studies

Numerical case studies are conducted on modified IEEE RTS 24-bus [37] and IEEE 300-bus [38] test systems. The systems are modified to increase congestion, in order to generate reasonable levels of cost savings through GET operations. The 24-bus system is modified following a similar approach presented in [39]. A total of 480 MW of load is shifted from buses 14, 15, 19, and 20 to bus 13, with load at each bus then increased by 5%. The capacities of lines A21, A22, A25-1, and A25-2 are all reduced by 50%. For the IEEE 300-bus system, we use the OPF case from PGlib [40]. The 300-bus system is further modified by reducing the thermal capacities of a group of transmission elements (lines and transformers) under heavy utilization. The thermal capacities of elements 61, 91, 101, 115, 137, 365, and 395 are all reduced by 50%. Additionally, element 268 has its thermal capacity reduced by 25%. For the case studies on the 300-bus system, we consider GET owners that own a group of GET devices. Maximum voltage injections of VSC-FACTS devices are specified in per-unit (pu) values, and the actual values are dependent on the rating of the transmission line where the devices are deployed. The PSTs are assumed to have a maximum angle adjustment of 10 degrees [35].

Note that simulation studies in this paper focus on the operation aspect, and the optimal allocation of GETs is beyond its scope. However, different allocation policies (APs) of GETs are employed to reveal the effect of planning on benefit distribution, with detailed results in the following subsections. DCOPF problems are modeled using CVXPY [41] and solved with CPLEX 22.10 on an Apple M2 Pro CPU with 16 GB of RAM.

A. IDM examples

1) IDM Case 1: We consider three GET owners who have invested in the system, with their corresponding GET deployments shown as follows:

- **GET Owner 1**: One VSC-FACTS device deployed at line A21 which has a maximum voltage injection of 0.05 pu.
- **GET Owner 2**: One PST device deployed on line A22.
- **GET Owner 3**: One VSC-FACTS device deployed at line A25-1 with a maximum voltage injection of 0.1 pu.

GETs, in this case, are deployed on three of the most utilized lines in the system. This is a commonly used engineering judgment in previous studies for FACTS placement [10], [32], [39] and is referred to as AP1 in this paper. The system is operating under peak load.

Following the incentive scheme presented in Section II, we first get the result of the grand coalition, which is shown in Table I.

TABLE I
GRAND COALITION RESULTS OF CASE 1

GET owner	Location	Type	Setpoint (MW)	Binding?
1	A21	FACTS	51.55	Y
2	A22	PST	66.68	N
3	A25-1	FACTS	-63.16	Y

It can be seen from Table I that the PST on Line A22 is not operating at its maximum. Therefore, to accurately capture the marginal contributions, this setpoint is used in calculating the characteristic function values for other coalitions as the new operating range for this device.

The Shapley value results are presented in Table II. The sum of the Shapley value is equal to the total cost savings achieved by the grand coalition, thus reflecting the desirable feature of efficiency for the Shapley value.

TABLE II
SHAPLEY VALUE RESULTS OF CASE 1

GET Owner	Shapley value ($)
1	1498.83
2	1958.40
3	43.61

2) IDM Case 2: We again consider three GET owners in this case, with their assets listed as follows:

- **GET owner 1**: One VSC-FACTS device deployed at line A23 which has a maximum voltage injection of 0.05 pu;
- **GET owner 2**: One PST device deployed on line A28;
- **GET owner 3**: One VSC-FACTS device deployed at line A18 with a maximum voltage injection of 0.1 pu.

The results for Case 1 show that the VSC-FACTS device on the transmission line A25-1 provides a very marginal contribution to congestion alleviation. In Case 2, AP2, which is based on the susceptance price [11], is employed. The sensitivity obtained from DCOPF dual solutions reflects the impact of GET operation on cost savings. Again, the DCOPFs are solved assuming a peak load hour. The grand coalition of the three devices achieved a cost-saving of $12,364, with detailed results presented in Table III.

TABLE III
GRAND COALITION RESULTS OF CASE 2

GET owner	Location	Type	Setpoint (MW)	Binding?
1	A23	FACTS	-84.75	Y
2	A28	PST	-758.84	Y
3	A18	FACTS	208.33	Y

In Case 2, all the GET operating constraints are binding, thus allowing the step of resetting operating bounds to be skipped. The Shapley value results are shown in Table IV.

TABLE IV
SHAPLEY VALUE RESULTS OF CASE 2

Device ID	Shapley value ($)
1	1625.47
2	8122.30
3	2616.68

Note that the result of Case 2 shows that the game presented in this paper is not necessarily superadditive, which is different from some of the profit allocation schemes in previous studies, such as [28]. The superadditivity can be affected by the allocation of GETs, as shown in this paper. Non-superadditivity means that each GET deployment reward, based on Shapley value, is not guaranteed to be any more than the compensation received when acting alone. However, the GET owners receive subsidies for the socially optimal operation of their assets, incentivizing them to participate and stay in the grand coalition.

B. Annualized return and comparison with regulated RoR

To study the effectiveness of the proposed method in incentivizing investments in GETs, numerical studies are conducted to estimate the potential annualized returns based on the Shapley value, which are then compared to RoRs.

1) IEEE RTS 24-bus system: Simulation studies are first conducted using the IEEE RTS 24-bus system. The year-long hourly load profile data is obtained from [37]. Typical days from each season are selected following the approach in [42]. Summer is represented by the fourth, fifth, and sixth days of week 25, whereas the fourth, fifth, and sixth days of week 51 are used to represent winter. The fourth, fifth, and sixth days of week 11 represent spring and fall, as the two seasons have similar load profiles. The total of 72-hour DCOPF problems is solved, and the returns for each GET owner are calculated using the Shapley value. We then use such results to approximate the annualized Shapley value (ASV) return of GETs. The results are shown in Tables V-VI.

The returns under a regulated RoR are calculated based on the investment cost (IC). Therefore, to compare the payoffs of the proposed scheme and that of a regulated RoR, ICs for GETs are calculated. The cost of VSC-FACTS device is set at $C^{\text{FACTS}} = \$150/\text{kVA}$ [2]. The ratings of the VSC-FACTS devices are calculated as follows [43]:

$$S_k^{\text{FACTS}} = V_k^{\text{FACTS}} \overline{I}_k. \tag{16}$$

TABLE V
SEASONAL AND ANNUALIZED RETURN RESULTS FOLLOWING AP1 IN THE 24-BUS SYSTEM

GET owner	1	2	3
72h return (Spring & Fall) ($k)	0.284	0.406	0.003
72h return (Summer) ($k)	45.582	86.818	0.590
72h return (Winter) ($k)	48.011	78.189	0.952
ASV ($M)	2.864	5.044	0.047

TABLE VI
SEASONAL AND ANNUALIZED RETURN RESULTS FOLLOWING AP2 IN THE 24-BUS SYSTEM

GET owner	1	2	3
72h return (Spring & Fall) ($k)	0.170	0.261	0.261
72h return (Summer) ($k)	18.526	114.705	65.607
72h return (Winter) ($k)	36.268	183.278	95.995
ASV ($M)	1.677	9.080	4.931

The current in (16) can be approximated using the following DC power flow approximation in the per-unit system:

$$\overline{I}_k^{\mathrm{pu}} = \overline{f}_k^{\mathrm{pu}}. \tag{17}$$

Then, the current in the actual value is calculated using the following equation:

$$\overline{I}_k = \overline{I}_k^{\mathrm{pu}} I^{\mathrm{base}} = \overline{f}_k^{\mathrm{pu}} S^{\mathrm{base}} / V^{\mathrm{base}}. \tag{18}$$

The IC of a VSC-FACTS device installed on line k is then calculated as follows:

$$C_k^{\mathrm{FACTS}} = C^{\mathrm{FACTS}} S_k^{\mathrm{FACTS}} \tag{19}$$

Similarly, the calculation of the PST investment cost on line k is presented as follows [35]:

$$C_k^{\mathrm{PST}} = C^{\mathrm{PST}} S_k = \overline{f}_k C^{\mathrm{PST}} \tag{20}$$

The value of C^{PST} are vastly different in previous studies [35], [44], varying from 10$/kVA to 100$/kVA. Therefore, we estimate the IC of PSTs in this paper using the CAISO project [45] as a reference. This project involves the deployment of a PST on an 800MVA-rated transmission line, with the installation cost estimated between $55M to $68M. The value of C^{PST} is set at 76.875$/kVA.

The IC of each GET deployment is shown in Table VII. Additionally, Table VII presents the annualized regulated revenue (ARR), assuming 10% regulated RoR [46] and an interest rate of 6%, provided to the GET owners. Previous studies have made various assumptions regarding the lifespan of the devices, varying from 5 to 30 years [35], [47]–[50]. The lifespan of devices is set at 15 years in this paper.

TABLE VII
INVESTMENT COST FROM GET OWNERS IN THE 24-BUS SYSTEM

GET owner	1	2	3
IC under AP1($M)	1.875	19.219	3.750
IC under AP2($M)	3.750	38.438	7.500
ARR under AP1($M)	0.212	2.177	0.424
ARR under AP2($M)	0.425	4.353	0.849

The comparison between the ARR and the annualized return under the proposed scheme for each GET deployment is presented in Fig 1 and Fig 2.

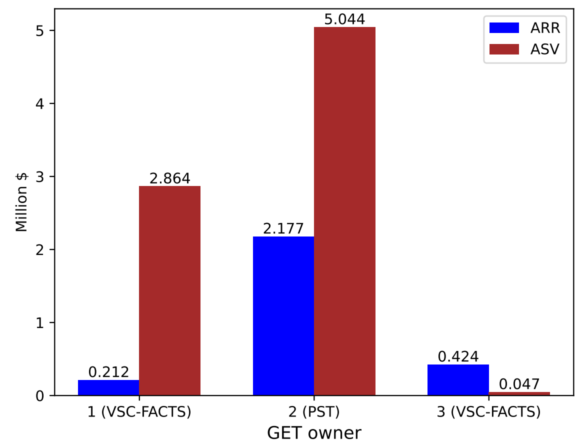

Fig. 1. Comparison between RoR and the proposed scheme under AP1 in the 24-bus system

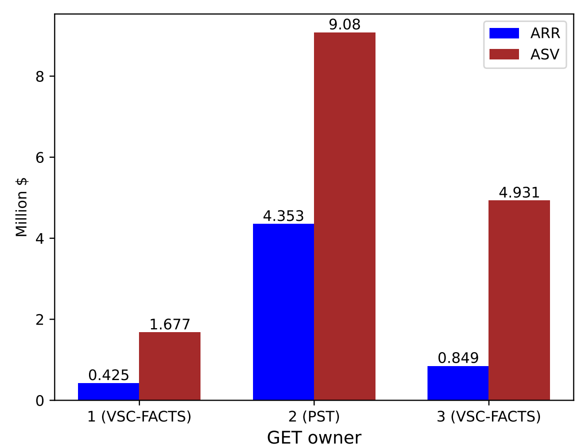

Fig. 2. Comparison between RoR and the proposed scheme under AP2 in the 24-bus system

The results show a significant payoff increase under the proposed scheme compared to a regulated RoR for five of the six GET owners in the two cases. GET owner 3 in Case 1 receives a meager payoff as the GET deployment makes a minimal contribution to the cost savings. The results show that the payoffs are performance-based and are affected by the planning of GETs. The results will be further discussed in the following subsection.

2) IEEE 300-bus system: The proposed scheme is further studied with simulations conducted on a modified IEEE 300-bus system. In this case, we consider three GET owners, with their GET assets presented as follows:

- **GET owner 1**: Three VSC-FACTS devices deployed at lines 91, 182, and 358. Each device has a maximum voltage injection of 0.1 pu.
- **GET owner 2**: One VSC-FACTS device deployed at line

177 with a maximum voltage injection of 0.05 pu. Two VSC-FACTS devices deployed at lines 105 and 178, each having a maximum voltage injection of 0.1 pu.
- **GET owner 3**: Two PSTs deployed at lines 83 and 180.

Note that the locations of GET deployments are selected following AP2, which is shown to be more effective in previous subsections.

The results of 72-hour returns and ASVs are shown in Table VIII, and the IC of each GET owner is presented in Table IX. The comparison between ASV and ARR is shown in Fig. 3.

TABLE VIII
SEASONAL AND ANNUALIZED RETURN RESULTS IN THE 300-BUS SYSTEM

GET owner	1	2	3
72h return (Spring & Fall) ($k)	284.853	125.488	112.744
72h return (Summer) ($k)	377.727	168.751	151.426
72h return (Winter) ($k)	432.178	183.468	170.853
ASV ($M)	41.963	18.347	16.661

TABLE IX
INVESTMENT COST FROM GET OWNERS IN THE 300-BUS SYSTEM

GET owner	1	2	3
IC($M)	38.460	13.298	35.055
ARR($M)	4.356	1.506	3.970

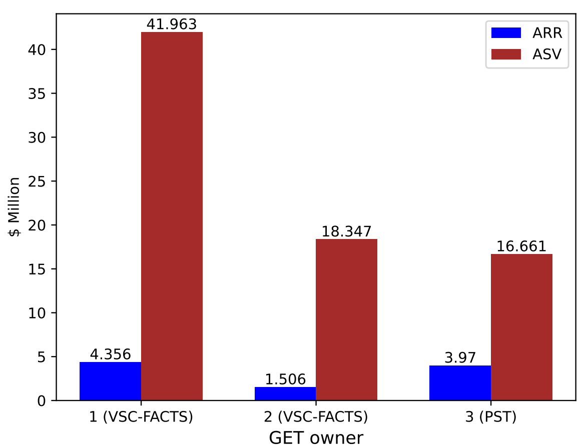

Fig. 3. Comparison between RoR and the proposed scheme in the 300-bus system

The results show that, for the IEEE 300-bus system, the proposed scheme provides massively more financial compensation to GET owners compared to the regulated RoR. The proposed scheme outperforms the regulated RoR even more for the IEEE RTS 24-bus system. This is mainly because of two reasons. First, the IEEE 300-bus system is much larger and has a higher value of flexibility congestion cost (FCC), at peak load hour, of $28,562 compared to the FCC of $15,464. The FCC is the cost reduction that can be achieved if all the DC power flow constraints are relaxed in DCOPF, essentially turning the transmission system into a transportation network. Second, the IEEE 300-bus system still has a fair level of congestion under light loading conditions. The IEEE RTS 24-bus system bears no congestion cost with a load factor of 0.6, whereas, under such circumstances, a congestion cost of $14,106 still exists for the IEEE 300-bus system. This allows the GET owners to get considerable returns for GET operations in the spring and fall seasons. The results further illustrate how the proposed scheme can effectively provide incentives for GET owners, as more financial returns can be achieved with their investments in a larger system with more congestion.

C. Discussions

1) Effectiveness of performance-based schemes: The comparisons between the proposed scheme and a regulated RoR emphasize the effectiveness of a performance-based method. The GET deployments contributing significantly to the cost savings will receive higher returns, and the proposed scheme is much more attractive than the RoR. However, the rewards are insignificant for devices that only marginally contribute to cost savings, e.g., the VSC-FACTS on line A25-1 under AP1 and the VSC-FACTS on line 23 under AP2 in the 24-bus system. The returns can be even less than a regulated RoR, if GET does not contribute much to system efficiency. Such results also emphasize the importance of adequately planning GET deployments. The case studies in this paper are all examples only involving power system operations. Rigorous planning studies should be conducted to determine the optimal allocations of GETs, and ineffective projects should be discarded. In other words, ineffective GETs in our simulation studies should not be built in the first place; the reason for their inclusion in simulation studies is to precisely show that the developed compensation method is able to correctly allocate little compensation to ineffective installations.

2) Planning flexibilities of GETs: The results show that the ASVs are much smaller in the spring and fall when the systems generally endure low congestion. This also means that GET assets are likely over-planned during these seasons. This issue can be addressed by the recent developments in the mobile deployments of FACTS devices [51], which provide even more operational flexibility. Mobile deployment can allow GET owners to gain even more payoffs during these seasons, as their devices can be redeployed to systems with a different congestion pattern or contribute to other projects, such as overload alleviation.

3) Market efficiency design: As mentioned in Section II, the proposed scheme resets the operating range of GET deployments when the operation constraints are not binding. This ensures that the Shapley value return is calculated based on the actual setpoint of the technologies rather than their full operating ranges. The results of the following numerical study illustrate the effectiveness of this step. Suppose in the IEEE RTS 24-bus system, the VSC-FACTS of GET owner 1 now has a maximum voltage injection of 0.1 pu. The difference in the payoffs provided by the improved Shapley value compared to the traditional Shapley value approach is shown in Fig. 4. The results reveal that if the traditional Shapley value approach is adopted, GET owner 1 can receive a payoff that almost doubles its contribution to the grand coalition with more investments. However, the extra investments only provide $0.006M social welfare positives. Essentially, the over-investment from GET owner 1, while providing minimal contributions to the surplus, still grants a high RoR considering the IC. This is also hurting the interests of the other GET owners, as shown in Fig. 4. This reveals the potential market inefficiency of applying the traditional Shapley value.

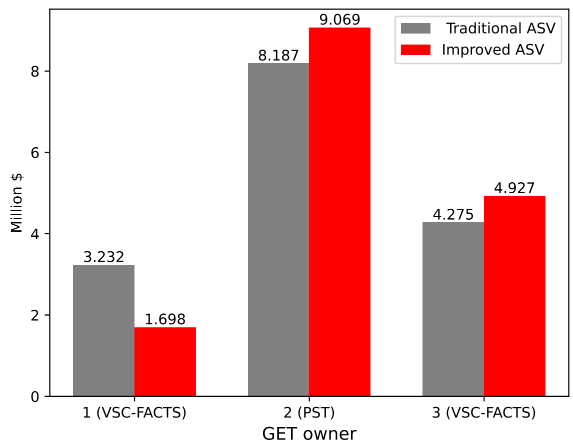

Fig. 4. Comparison between improved and traditional Shapley value methods

This design of the proposed scheme is essential to ensure proper planning for GET deployments. Investors and system operators will be inclined to plan GETs in sufficient yet not wasteful magnitudes. Furthermore, if the power flow or congestion pattern varies due to changes to the system, GET owners will intend to adjust their deployments, especially with the developments in the modular and relocatable design of the technologies, as mentioned previously.

4) Future directions: The proposed scheme allocates all social welfare changes to GET owners in the IDM. However, the percentage of the allocation could be different depending on the design of the incentive scheme. Additionally, the scheme presented in this paper does not consider one aspect of the benefit of GETs, which is cost savings related to the no-load and start-up costs of conventional generators in the DAM clearing process. Such topics will be further studied in future work. It is also worth noting that, as seen from (11), Shapley value calculation requires the characteristic functions for 2^n possible coalitions. This poses computational challenges to grid operation models, especially when the number of players is large. Proposals in the existing literature on improving computational efficiency focus on using sampling methods to estimate Shapley values [23], [52], [53]. Finding an efficient approach to calculate the Shapley value is beyond the scope of this paper and will be addressed in future work.

IV. Conclusion

The utilization of GETs in the power system is hindered by the lack of proper incentives both for their deployment and efficient operation. This paper presents a payoff scheme in the IDM based on the improved Shapley value to incentivize investments in GETs. The social welfare enhancements created by GET deployments are allocated to the GET owners as financial compensation for their investments. To improve market efficiency, the Shapley value is modified to accurately reflect the contributions of GETs deployments. The proposed scheme is analyzed through simulation studies conducted on the modified IEEE RTS 24-bus and 300-bus systems and compared with the returns under a regulated rate of return. The results show that a performance-based incentive scheme is highly effective in rewarding investments in GETs and, thus, can be expected to facilitate their deployments to enhance the utilization of the existing grid.

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