Dual-aware EV charging scheduling with traffic integration

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ABSTRACT

Electric vehicle adoption is a trend in many countries, and the demand for charging station infrastructure is at a rapid pace. The placement of charging stations is the key research topic of many researchers, but charging scheduling is also a problem that is going to rise in the near future. The proper charger utilization, maintaining coordination between charging stations, and satisfying users' demands are some of the key challenges. The traffic pattern is uncertain, coordination of distances between charging stations and users is done by Euclidean distance. The traffic-aware fair charging scheduling (TAFCS) strategy is proposed, which will have a balance on charger utilization and user prioritization, and keep the fairness by equal distribution of electric vehicles among all the charging stations having a centralized charging system monitored by an aggregator. The distribution of the traffic pattern of electric vehicles is performed by Monte-Carlo simulation. The proposed system is tested on the IEEE 33 bus standard system using the predefined voltage limits of each bus and limiting power loss to lessen its burden. The discharging process of 50 electric vehicles (V2G) is performed by optimal placement by obtaining the weakest buses, which makes it an intelligent distribution system. This proposed charging framework is validated on MATLAB R2020a.

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1. INTRODUCTION

The electric vehicles are considered the future alternative to internal combustion engines (IC engines) running on gasoline and will deplete depending on usage. According to the reports [1], the first half of 2024, India had 16% growth in the registration of electric vehicles. The sale of electric vehicles in each segment has increased over the last decade [2]. Among all categories, there is a steady rise in the two-wheeler and three-wheeler segments. In May 2024, 2 W electric vehicle sales increased from 65,364 units to 76,848 units, and 3 W electric rickshaw sales rose from 31,798 units to 39,476 units. Tata Motors is leading in the four-wheeler segment and holds 66% market share. MG Motors and Mahindra & Mahindra are the key players. India emerged as the global market leader in the three-wheeler segment [3], [4]. The global market for three-wheelers (3Ws) experienced a 13% growth in 2023, reaching 4.5 million units sold, with electric models representing 21% of these sales, an increase from 18% in 2022. In 2023, India surpassed China to become the largest market for electric three-wheelers, achieving more than 580,000 sales. In India, electric car registrations have increased by 70% on a year basis. The EV adoption is promoted by the inclusion of government policies like the FAME II program. Manufacturing and production of EVs are taken care of by the production-linked incentive (PLI) schemes, tax benefits that gave a boost to the demand in recent years. By the introduction of the go electric campaign, new models also gained popularity since 2023. In addition, domestic car manufacturers have retained a significant market share because of favorable import tariffs, with local brands like Tata Motors and Mahindra & Mahindra making up 80% cumulative electric car sales since 2010 [5], [6].

One of the key components in optimizing EV charging scheduling is the consideration of Traffic dynamics. Traffic congestion can significantly impact the travel time of EV owners, particularly during peak hours, and can affect their charging schedules. Therefore, integrating real-time traffic data into the charging scheduling process is crucial for minimizing time [7], [8] and ensuring that EV owners can charge their vehicles efficiently without delays. The scheduling system should take into account factors such as the time of day, traffic conditions, and the distance between the charging station and the EV owner's destination. By incorporating these factors, the system can prioritize charging times based on traffic patterns, ensuring that vehicles are charged during off-peak periods, thus reducing overall time spent by the EV owner on the road [9].

2. METHOD

The proposed traffic-aware charging scheduling (TAFCS) flowchart is shown in Figure 1. The priority conditions of users are done by equal distribution using a priority algorithm, and the arrival of electric vehicles is done by a first-come, first-served (FCFS) algorithm. In Figure 1, the proposed TAFCS scheduling relies on the combined efforts of aggregators, distribution companies (DISCOMs), and original equipment manufacturers (OEMs). This proposed approach is tested by using the IEEE-33 radial bus system by considering all parameters as from [10] as shown in Figure 2 and modified by the introduction of EV charging stations and parking lots, along with aggregators, as shown in Figure 3.

The distribution of hourly traffic patterns for a week in Bengaluru (outside city roads or highways) is shown in Figure 4; the parameters are validated by Gupta *et al.* [11] and the arrival pattern is from Yadav *et al.* [12]. Aggregators include fleet operators and charging service providers responsible for the efficient demand coordination, managing EV scheduling, and optimizing charger availability while enabling market participation through dynamic pricing and demand response. The grid integration with V2G [13] allows electric vehicles during peak demand to supply energy back to the grid. DISCOMs focus on grid stability and monitoring fluctuations and optimizing charging loads to prevent congestion while aligning EV charging patterns with traffic integration [14]. OEMs enhance the vehicle grid compatibility with grid infrastructure and optimized chargers for dynamic load management and battery performance monitoring [15], [16].

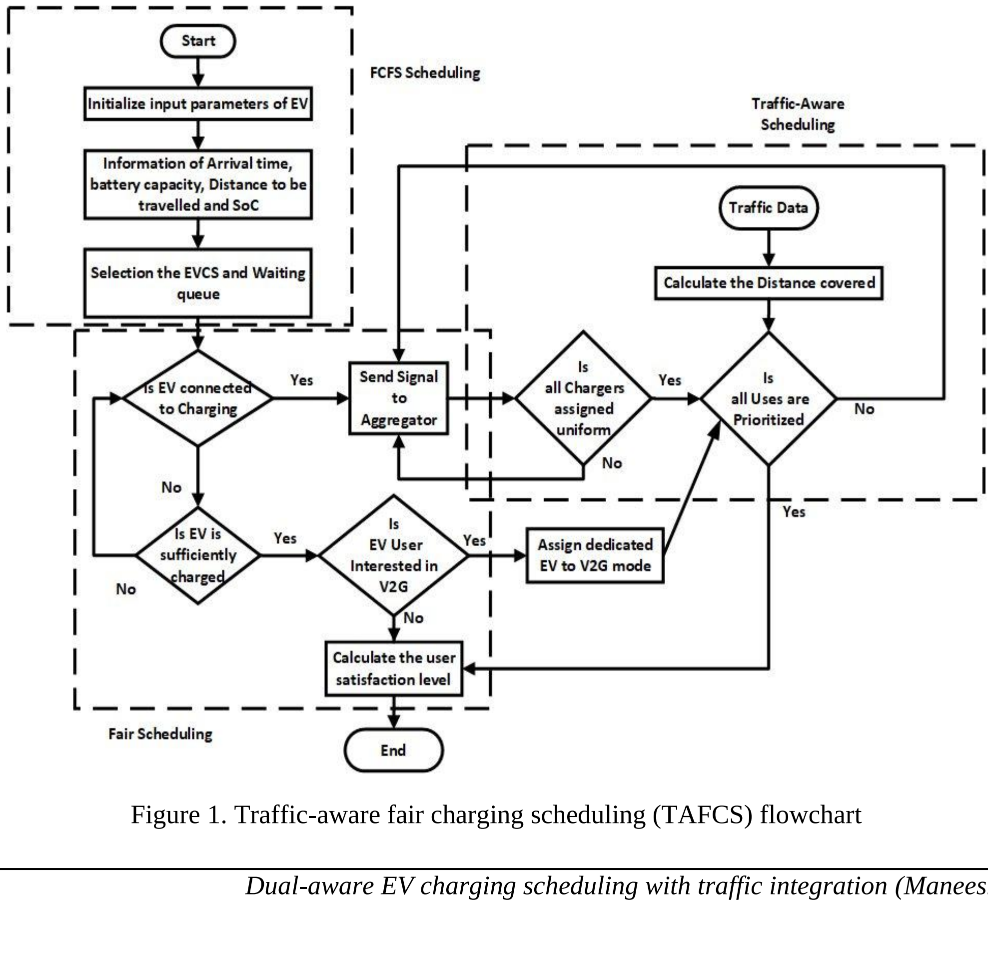

Figure 1. Traffic-aware fair charging scheduling (TAFCS) flowchart

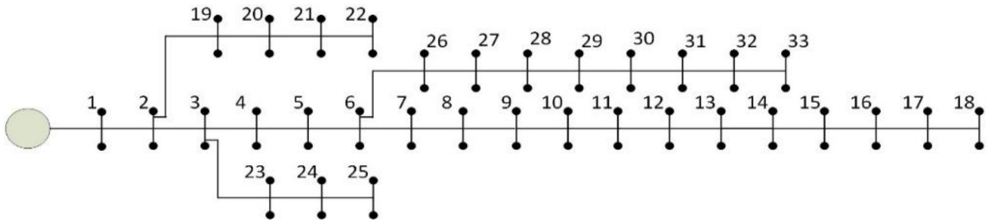

Figure 2. Basic line diagram of the IEEE 33 bus system

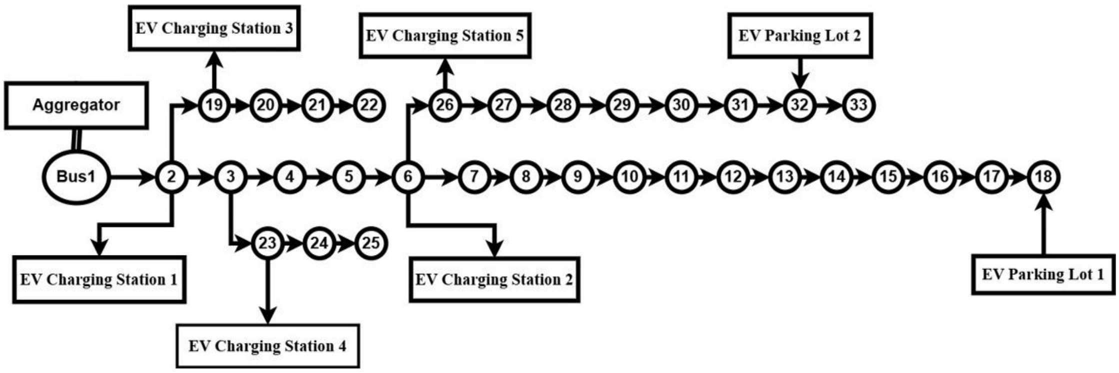

Figure 3. Intelligent distribution system with 5 charging stations and 2 parking lots

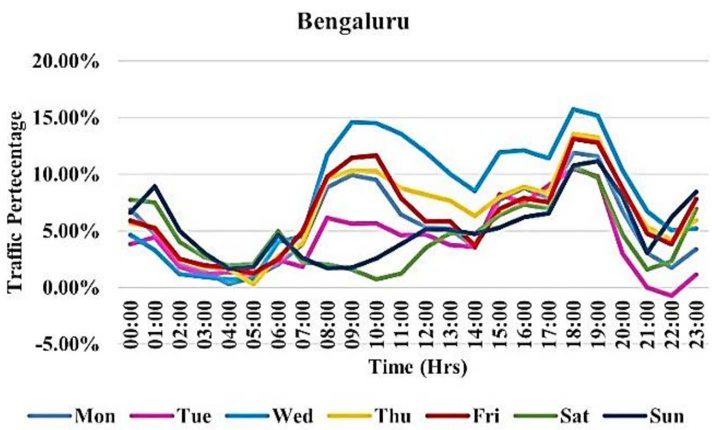

Figure 4. Traffic pattern of Bengaluru (outside city)

3. PROBLEM FORMULATION

This study focuses on developing an intelligent distribution system (IDS) framework that leverages intelligent scheduling, dual awareness strategies, and traffic integration to enhance EV owner benefits and maximize the utilization of renewable energy resources.

3.1. Scenario I

Consider there are four cases involving 75, 150, 225, and 300 EVs [17]. The proposed system consists of five locations, each having a charger of 7.2 kW, as shown in Table 1. During peak times, the 7.2 kW charger [18] will operate as per the time slot cost given in the result section for each day of the week in ₹ per kWh, plus a penalty as per the demand of the charging station, as given in Table 1.

- For G2V mode

$$SoC_{mn} \leq SoC_{initial} \leq SoC_{mx} \quad (1)$$

SoC_{mn}: represents the minimum SoC level at which charging of EV starts. Here, the value is set at 30%, meaning that EVs enter charging mode when their SoC drops below 30% [19], [20]. SoC_{mx}: is the maximum permissible SoC level at which charging of EV stops/disconnect is set at 90%.

Table 1. Parameter specification of EVs operating in G2V mode

Specifications	Case 1 (75 EVs)	Case 2 (150 EVs)	Case 3 (225 EVs)	Case 4 (300 EVs)
Battery size	40.7 kWh	40.7 kWh	40.7 kWh	40.7 kWh
Available Space	20 (7.2 kW) per CS	20 (7.2 kW) per CS	50 (7.2 kW) per CS	50 (7.2 kW) per CS
Time slot	8	8	8	8
Initial SoC	30%	30%	30%	30%
Final SoC	90%	90%	90%	90%
Ch. Eff.	0.9	0.9	0.9	0.9
Charging cost	As per the time slot price	As per the time slot price	As per the time slot price	As per the time slot price

CCR: Charger charging rate, CS: Charging station, Ch. Eff.: Charging efficiency

- Energy required and charging time for G2V mode

The total energy required for charging the number of EVs at all charging stations is given as (2).

$$E_{ch_{req\_i,j}} = \sum_{j=1}^{m} \left\{ \sum_{i=1}^{n} B_{tot_{i,j}} * (SoC_{mx_{i,j}} - SoC_{initial_{i,j}}) \right\} \quad (2)$$

Where the number of EVs charging at one charging station is represented by i and j represents the number of charging stations taken as 5. $B_{tot_{i,j}}$ is total battery capacity in kWh for each EV 'i' at respective charging station 'j', the battery capacity taken as 40.7 kWh [21].

- Charging time slot

$$t_{slot_{i,j}} = \left\lfloor E_{tot_{req\_i,j}} / \left(\eta_{ch} * EV_{ch_{cap}} \right) \right\rfloor \quad (3)$$

Where $t_{slot_{i,j}}$ is the time to charge one EV at either of the EVCS charging stations 'j', $EV_{ch_{cap}}$ is the charging power of the charger at 7 kW, with having charging efficiency $\eta_{ch}$of 95% have charging time constraints.

- Charging time slot constraints

The multiplication of the charging time slot ($t_{slot_{i,j}}$) and charger's charging power should always be less than the maximum charging limit of the battery.

$$\left(t_{slot_{i,j}} * \ EV_{ch_{cap}} \right) < SoC_{mx_{i,j}} \quad (4)$$

- Charging cost in G2V mode

The total charging cost during the G2V process is given by (5).

$$\xi_{ch} = \xi_{peak\_ch} + \xi_{off\_peak\_ch} \quad (5)$$

Charging costs are determined by the hourly time slot, market price, and the day of the week [22].

- Peak period

$$\xi_{peak\_ch} = \left(\sum_{k=1}^{N} (\xi_{ts,k} - \xi_{pen,k}) * \eta_{ch} * EV_{ch_{cap}} \right) * D_{index} \quad (6)$$

Where k is the time slot in hours and 'N' represents 24 24-hour time slots, $\xi_{ts,k}$ is the time slot price given in Table 2 according to the day index (D_{index}) varies from 1 to 7.

- Off-peak period

$$\xi_{off\_peak\_ch} = \left(\sum_{k=1}^{N} \xi_{ts,k} * \eta_{ch} * EV_{ch_{cap}} \right) * D_{index} \quad (7)$$

There will be no penalty in off-peak time slots and charged as per the time slot market price of that day.

Table 2. Real time hourly market price

Time slot (Hrs)	Monday (₹ per kWh) ($D_{index}=1$)	Tuesday (₹ per kWh) ($D_{index}=2$)	Wednesday (₹ per kWh) ($D_{index}=3$)	Thursday (₹ per kWh) ($D_{index}=4$)	Friday (₹ per kWh) ($D_{index}=5$)	Saturday (₹ per kWh) ($D_{index}=6$)	Sunday (₹ per kWh) ($D_{index}=7$)
1	2.21	2.76	2.63	1.72	2.26	2.23	2.86
2	1.91	2.40	2.10	1.77	1.92	2.46	2.82
3	1.92	2.48	1.81	1.51	1.81	2.50	2.51
4	1.75	2.43	1.51	1.51	1.91	1.99	2.58
5	2.35	2.83	2.85	2.28	2.58	2.86	2.98
6	3.22	3.60	3.42	3.20	3.30	3.36	3.39
7	3.66	4.70	4.29	3.82	4.27	4.10	3.45
8	4.28	6.97	6.21	4.24	5.84	4.95	3.77
9	4.96	8.50	4.87	4.27	5.37	4.11	3.60
10	4.41	5.24	4.87	3.88	4.81	3.78	3.52
11	3.44	3.73	3.40	3.14	4.21	3.19	3.39
12	3.40	3.58	3.42	3.00	3.76	2.92	3.19
13	3.21	3.40	2.91	2.82	3.53	2.86	2.79
14	2.15	2.67	2.44	2.52	2.94	1.94	2.38
15	3.39	3.42	3.26	3.11	3.52	2.80	3.06
16	4.05	3.93	3.67	3.64	4.49	3.75	3.34
17	6.48	7.52	4.70	6.04	7.58	6.62	3.96
18	10.00	10.00	8.74	10.00	10.00	10.00	4.20
19	10.00	10.00	9.00	8.75	10.00	10.00	2.93
20	4.67	3.92	3.61	3.58	4.06	3.47	2.87
21	3.67	3.69	3.25	3.57	3.95	3.48	3.59
22	3.26	3.36	2.35	3.06	3.15	3.22	3.14
23	3.18	3.12	2.49	2.90	3.05	3.09	2.63
24	2.86	2.89	2.32	2.32	2.88	2.95	2.08

3.2. Scenario II

In this scenario, the two buses of the IEEE 33 bus system are considered as the source that will provide the power by a combination of EVs having the same battery capacity as in Table 1. The bus numbers 18 and bus number 33 are selected, which are the weakest buses in the IEEE 33 bus system. The group of EVs is at least 5 years old, which participate in V2G mode and operate at 0.7 discharging efficiency as follows:

- SoC level and discharging time constraint for V2G mode

$$SoC_{dis\_mn} \leq SoC_{dis} \leq SoC_{dis\_mx} \quad (8)$$

- Energy received and discharged time for V2G mode

The energy received during the discharge of the number of EVs at all charging stations is given as (9).

$$E_{dis_{rec\_i,j}} = \sum_{pl=1}^{M} \left\{ \sum_{i=1}^{n} B_{tot_{i,j}} * (SoC_{initial_{i,j}} - SoC_{mn_{i,j}}) \right\} \quad (9)$$

Where the number of parking lots taken as 2 represented by j, one at bus 18 and another at bus 32. $B_{tot_{i,j}}$ is the total battery capacity in kWh for each EV 'i' at respective parking lot 'l'.

$$0 \leq T_{dis} \leq T_{cus\_mx} \quad (10)$$

T_{cus_mx}: defines the maximum time threshold for discharging in V-2-G mode; here, it is assumed and set as 2 Hrs, ensuring that batteries are not excessively drained. In the case of V2G mode, the charged EVs will participate based on customers' interest, and similarly, the time allotted for discharging based on the customer as given in (10). Table 3 presents the specifications of 50 EVs operating in the V2G mode.

- Total incentive in the V2G process

The total incentive for discharging EVs during the V2G process is given by (11).

$$\xi_{dis} = \xi_{peak} + \xi_{off\_peak} \quad (11)$$

The discharging cost depends on the hourly time slot and market price at that time slot accordingly the incentive will be disbursed during peak hours to EV users. It also depends on the day of the week.

Table 3. EVs specification operating in V2G mode

Specifications	Bus18 (30 EVs)	Bus33 (20 EVs)
Battery Size	40.7 kWh	40.7 kWh
Initial SoC	80%	80%
Final SoC	50%	50%
EDR	7.2 kW	7.2 kW
Dis. Eff.	0.7	0.7
Incentive rate	As per the slot price	As per the slot price

EDR: EVD is charging rate, Dis. Eff.: discharging efficiency

3.3. Scenario III

- Peak period

$$\xi_{peak} = \left(\sum_{T_{dis}=0}^{T_{cus\_mx}} (\xi_{ts,k} + \xi_{inc,k}) * \eta_{dis} * EV_{ch_{cap}}\right) * D_{index} * Ci \quad (12)$$

Where η_{dis} is the discharging efficiency is set at 0.7, which includes the profit margin of the operator at the charging station. ($\xi_{ts,k}$ is the time slot market price as in Table 4). $\xi_{inc,k}$ is the incentive price given to an EV customer. Ci is the binary value that depends on the interest of the customer. ‘0’ means not participating in discharging and ‘1’ means participating in discharging.

- Off-peak period

There will be no incentive in off off-peak period.

$$\xi_{off\_peak} = \left(\sum_{T_{dis}=0}^{T_{cus\_mx}} \xi_{ts,k} * \eta_{dis} * EV_{ch_{cap}}\right) * D_{index} * Ci \quad (13)$$

- Intelligent distribution system (IDS)

This formulation focuses on the objectives, system components, and constraints essential to designing a robust IDS framework for EV charging and energy exchange.

- Intelligent distribution system constraints

$$V_{mn} \leq V_{IDS} \leq V_{mx} \quad (14)$$

$$I_{IDS} \leq I_{mx} \quad (15)$$

Where V_{mn} and V_{mx} are the minimum and maximum voltage limits of the intelligent distribution system.

- Energy consumption constraints

$$E_{coni.j} \leq E_{tot_{req_{i,j}}} + (P_{IDS} + P_{loss}) * t_{slot_{i,j}} \quad (16)$$

The consumption of energy should be less than or equal to the total energy consumption at the charging station and the battery capacity of the charging EV.

Table 4. Comparative study of EV charging scheduling

Ref. No.	Coordinated charging	Power loss	Voltage deviation	User preferences	Traffic pattern	Time slot price	G2V mode	V2G mode	Both mode
[23]	Yes	No	No	Yes	No	No	Yes	Yes	No
[24]	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes
[25]	No	No	Yes	Yes	No	No	Yes	Yes	Yes
[26]	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes
[27]	No	Yes	Yes	Yes	No	No	Yes	Yes	No
P.Work	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	

4. RESULTS AND DISCUSSION

The comparative study related to the charging scheduling of EVs is shown in Table 4, which covers different objectives in previous studies. The comparative analysis of TAFCS with the existing strategies like FCFS, Greedy algorithm, and priority scheduling is given in Table 5. This table not only covers the above four cases of EV fleet size, but it also calculates for larger EV fleet sizes up to 1000 EVs.

The distribution based on the traffic pattern in Figure 5 by applying Monte Carlo simulation for the arrival and departure of 225 EVs for all days of the week, arranged for timeslots in hours of the whole day

[23] and the respective charging utilization and traffic congestion in Figure 6. Total charging cost on the arrival of 225 EVs is given in Table 6.

Table 5. Comparative analysis with existing strategies

Fleet size	Strategy	TTR (%)	ELS (kWh)	CU (%)	Fleet size	Strategy	TTR (%)	ELS (kWh)	CU (%)
75	FCFS (Base)	0	0	74.6	300	FCFS (Base)	0	0	66.4
	Greedy	9.2	4.1	85.2		Greedy	12.3	15.6	89.3
	Priority	14.5	9.7	88.3		Priority	19.3	47.6	92.0
	TAFCS	22.5	18.3	91.4		TAFCS	27.9	81.7	95.5
150	FCFS (Base)	0	0	71.3	500	FCFS (Base)	0	0	61.2
	Greedy	10.8	7.9	87.1		Greedy	13.4	21.3	87.4
	Priority	16.2	20.4	89.7		Priority	21.6	63.2	93.2
	TAFCS	24.6	38.5	93.2		TAFCS	30.5	103.2	97.2
225	FCFS (Base)	0	0	69.1	1000	FCFS (Base)	0	0	59.5
	Greedy	11.7	11.5	88.5		Greedy	14.9	29.5	89.6
	Priority	17.9	34.3	91.1		Priority	24.2	92.7	95.3
	TAFCS	26.4	59.4	94.8		TAFCS	33.6	158.6	98.1

TTR = Total time reduction, ELS = Energy loss savings, CU = Charger utilization, FCFS = First come first serve, TAFCS = Time aware fast charging scheduling (proposed)

Table 6. Total charging cost based on traffic pattern arrival and hourly market price

TS(hr)	M (₹)	T (₹)	W (₹)	Th(₹)	F (₹)	S (₹)	Su(₹)
1	205.75	146.83	122.43	114.38	75.145	237.27	209.21
2	50.81	255.36	41.89	47.082	127.68	343.54	393.81
3	102.14	49.476	12.04	20.083	12.036	166.25	216.99
4	23.275	16.159	10.04	10.041	25.403	92.634	51.471
5	46.88	37.639	18.95	30.324	120.10	76.076	39.634
6	21.413	23.94	22.743	0	43.89	111.72	0
7	24.339	31.255	85.585	101.61	56.791	190.85	229.42
8	313.08	46.350	82.593	197.37	116.50	65.835	150.42
9	395.81	1073.9	291.47	454.33	607.08	81.994	23.94
10	498.55	487.84	550.55	335.43	703.70	100.55	140.45
11	526.15	520.89	271.32	292.33	335.96	42.427	112.72
12	248.71	380.91	318.40	219.45	225.04	97.09	233.34
13	106.73	271.32	270.92	262.54	140.85	114.11	241.19
14	100.08	35.511	129.81	201.10	117.31	180.61	142.44
15	157.80	113.72	195.11	165.45	93.632	242.06	264.54
16	269.32	392.02	219.65	435.71	268.73	324.19	111.05
17	646.38	800.13	593.84	522.16	453.66	704.37	395.01
18	399	1795.5	871.81	864.5	1064	1263.5	363.09
19	1596	1263.5	1017.5	1512.9	1396.5	1463	253.3
20	683.22	469.22	504.14	357.10	485.98	461.51	324.45
21	268.46	147.23	216.12	213.66	525.35	208.27	429.72
22	195.11	0	109.39	183.14	125.68	42.826	146.17
23	21.147	0	99.351	115.71	162.26	82.194	262.34
24	76.076	153.75	61.712	123.42	325.58	196.18	221.31

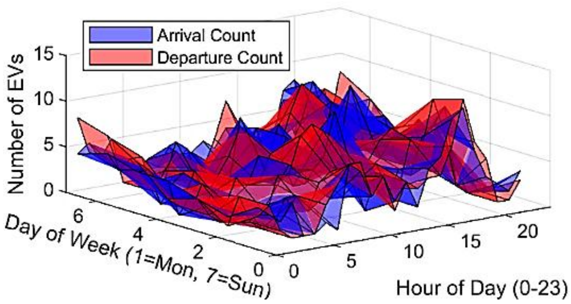

Figure 5. Hourly arrival and departure of 225 EVs based on D_{index}

In V2G mode operation at intelligent distribution system the distribution of 50 EVs is distributed such that the voltage (p.u.) at bus 18 is improved from 0.9131 to 0.9423 and at bus 33 is improved from

0.9166 to 0.9390 as shown in Figure 7. In the Figure 8 all four cases (75, 150, 225, and 300 EVs) are considered which are uniformly distributed along five charging stations during V2G mode of operation. The assignment of EVs is further continued with heavy loading [28] to check the voltage limit violations even at heavy loading with V2G mode of operation as shown in Figure 9.

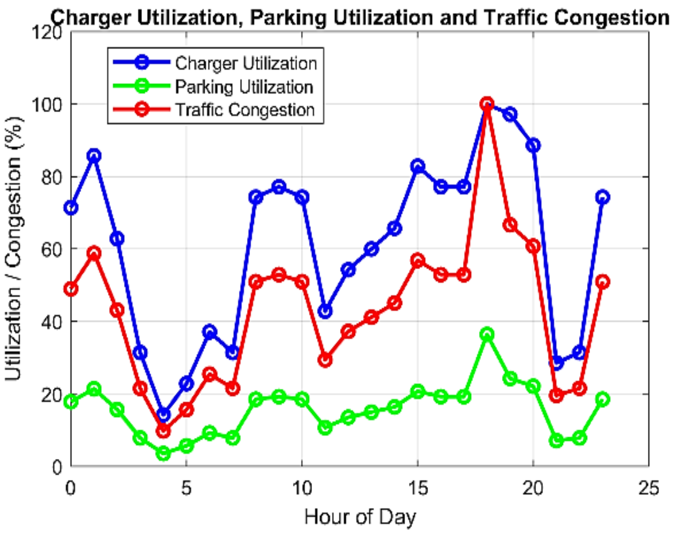

Figure 6. Charger utilization, parking utilization, and traffic congestion

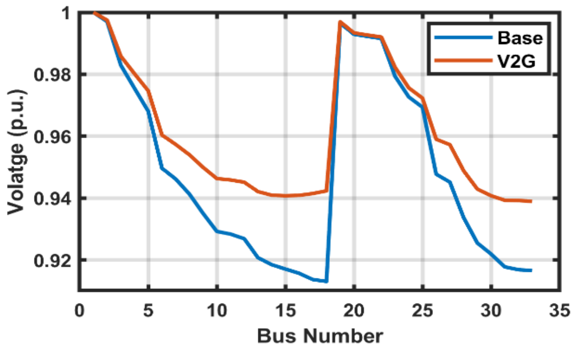

Figure 7. V2G mode operation at bus 18 and bus 33

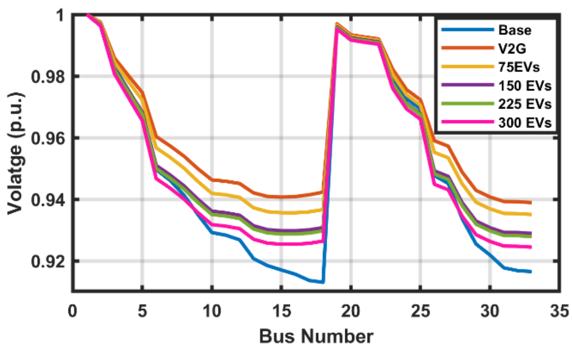

Figure 8. Comparison of all four cases with V2G mode

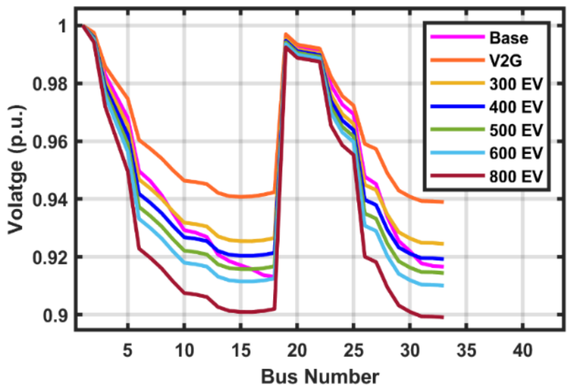

Figure 9. Comparison of heavy loading conditions along with V2G mode

5. CONCLUSION

This paper discusses the charging and discharging of EVs with a 40.7 kWh battery in an intelligent distribution system. The performance evaluation across varying fleet sizes, ranging from 75 EVs to 1000 EVS, highlights the effectiveness of the proposed scheduling method (TAFCS) over traditional methods. The experimental results show that 22.5%, 24.6%, 26.4% and 27.9% travel time reduction for fleet size 75, 150, 225, and 300 EVs, respectively. The integration of V2G with the grid improves the voltage profile from 0.9131 to 0.9423 at bus 18 and from 0.9166 to 0.9390 at bus 33. The proposed system would form a strong basis for further research and development into EV charging scheduling. Future work may include studying the impact of seasonal traffic variations on charging schedules and incorporating different pricing mechanisms for various categories of consumers, such as residential, commercial, and fleet users. More importantly, the system's scalability can be tested in more robust and complex distribution networks, so it can be proven that the system adapts and performs under varying conditions.

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Jayanta Kumar Sahu					✓	✓				✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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