Optimal Charging Schedule of Electric Vehicle Using Evolutionary Programming to Minimise Costs

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ABSTRACT

Electric vehicle (EV) technology presents new opportunities to the transportation sector and car manufacturers worldwide. However, this development is becoming a concern to utility operators because when the number of EVs increases, power demand from EVs will also increase. When all EVs at the grid are charged simultaneously, overloading might occur, especially during peak hours. This condition can affect the stability of the grid. Since EV is considered as an additional load to the power grid, a suitable charging coordination must be presented in order to optimise grid operation. This study introduces an EV charging schedule on an IEEE 33-bus residential network using evolutionary programming (EP) for cost optimisation. Some constraints, such as power and voltage limits of the grid are taken into consideration to ensure the efficacy of the proposed optimal charging strategy. A comparison study between uncoordinated and coordinated charging schemes in terms of daily load curve and EV operating costs is carried out to investigate the effectiveness of the proposed coordinated charging. Three case studies are analysed for coordinated charging based on different charging periods. EV charging rate is varied in order to determine the minimum operational costs. The results show that coordinated charging ensures stable grid operation within constraints limit and produce lower EV operational cost compares to uncoordinated charging.

Keywords: *Charging Coordination; Cost Minimisation; Electric Vehicle; Evolutionary Programming*

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Introduction

Electric vehicles can be considered as one of the evolving technologies in recent years. EVs invention is an alternative to achieve environmental conservation by reducing carbon emission. Compared to conventional internal combustion engine (ICE) transportation [1], EVs are expected to be accepted and popular among vehicle users in the near future. Famous brands that are already involved in EV manufacturing include Tesla, Honda, Nissan, Renault, and BMW.

There are several types of EVs and the most commonly available types are the Battery Electric Vehicle (BEV) [2], Hybrid Electric Vehicle (HEV) [3], Plug-in Electric Vehicle (PEV) [4], and Fuel cell Electric Vehicle (FEV) [3]. Each type of EV has its characteristics and configurations, for example, BEV utilises the propulsion of electric motors, while PEV utilises an electric motor at low speed and an internal combustion engine at high speed. An EV is a type of vehicle that is battery-powered and rechargeable; therefore, whenever the electrical energy stored in the battery is depleted or almost used up, it can be recharged using a charger. Charging can take place at any charging station, as well as at home.

Most EVs can travel 80 to 100 kilometers with 10 kWh of battery storage [5], but new EVs, such as the Tesla X and S models can store approximately 100 kWh [6]. Meanwhile, the electricity usage of an average home is approximately 25 kWh per day. This means that electricity grids will need to support an increase of four times the current load. Malaysia has set a target to support 200,000 EVs by 2020 [7]. The growing number of EVs increases the numbers of load in the network system, thus will significantly affect the power grid [8, 9]. High EV penetration comes with the risk of degrading the reliability and distribution performance of the power grid [10]. Simultaneous charging of EVs, especially at residential nodes will impose a serious impact on peak demand and increases power transmission loss [11]. Thus, it may increases the operational costs, in terms of replacing new equipment and maintenance [12].

Numerous studies on EV smart charging coordination strategies were introduced using various optimisation techniques to reduce EV penetration impacts and operational costs. Two heuristic-based approaches, namely, hybrid fuzzy genetic algorithm (FGA) and hybrid fuzzy discrete particle swarm optimisation (FDPSO) were proposed in [13] to minimize operational costs associated with energy generation and grid losses. In [14], the ant colony optimisation approach was applied to find the optimal charging station with minimum charging time, travel time, and charging cost based on dynamic price variations. Similarly, a centralised and decentralised scheme of EV charging based on the dynamic pricing model was proposed in [15].

The charging costs of an EV fleet in distribution grids was successfully optimized in [16] by considering load and price forecasting, and power demand from EVs. Forecast variables were applied in [17] to ensure minimum costs based on the rolling optimisation method, whereby inputs are updated from time to time.

The growing EV trend will not necessarily require utility operators to add new generation capacity or make extreme infrastructure upgrades. A new modern power grid, known as the smart grid, is the key to EV smart charging management. With intelligent computer-based control and the ability to perform bi-directional communications between the grid and consumers, utility operators can mitigate EV load impacts effectively [18]. Cost is one of the important factors that need to be considered in this structure. The cost of energy consumption during peak hours is much higher than off-peak hours. Therefore, EVs' charging time must be well managed to achieve minimum charging costs.

This study aims to coordinate EV charging using Evolutionary Programming (EP) optimisation technique. The algorithm considered a 24 hours electricity price data, and varied EV users' charging rate and time in order to achieve the minimum operational cost. This method considers the grid operation to be within the normal voltage and power limit, especially during peak hours. The uncoordinated and coordinated charging results of three case studies are compared and discussed.

System Modelling

An analysis is performed on a residential distribution system by considering a 24-hour load profile and energy market pricing. An EV is modelled as an additional load demand in the system.

Network model

An IEEE 33-bus with a 415 V distribution system, as shown in Figure 1, was used as a test case network in this study. All buses are connected to a residential feeder populated with two EV loads per bus. The system modelling, Newton-Raphson load flow, and optimisation programming are developed using MATLAB software.

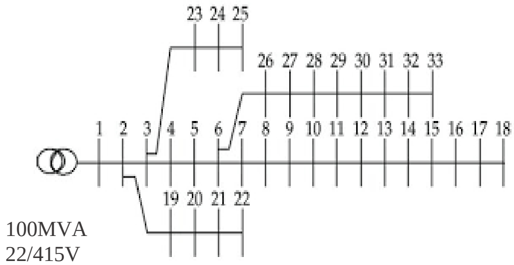

Figure 1: Test case network of 33-bus, 415 V distribution system.

Load profiles and EV charging assumptions

In this study, EV charging is assumed to occur at home and not at the charging station. EV users are assumed to be using their EV as their daily transport that they can use for a short distance, such as go to work, send their kids to school, or go to shopping malls for groceries. After returning home from their respective activities, users can directly charge their EV overnight. A typical residential daily load curve without EV charging load, as shown in Figure 2, was used to model the domestic load variations within 24 hours. This curve was plotted based on real data captured from a distribution transformer [12].

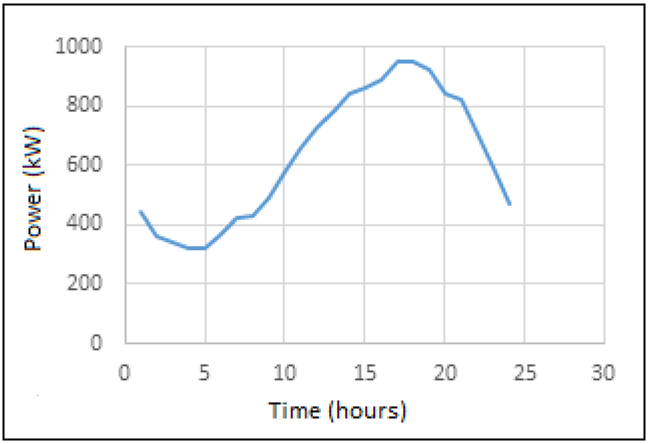

Figure 2: 24 hours residential load demand.

The maximum power output of a standard single phase 240 V outlet is 4.6 kW [12]. Therefore, domestic EV chargers are assumed to be rated at 4 kW per hour. This is the highest charging rate that can be used for a regular outlet at home without having to change the socket wiring [19]. Battery capacity is important to determine reasonable charging profiles for all EVs. In this study, all EVs are assumed to have a maximum battery storage capacity of 16 kWh, with state of charge (SOC) from 0 percent to 100 percent [20]. Therefore, 4 hours would be needed for all EVs to be completely charged. The batteries can only be charged since vehicle-to-grid is not considered in this study.

Problem Formulation

This study develops an optimal EV charging schedule by varying the charging rate to minimise the operational costs of EV home charging based on 24 hours market price data [21]. In order to achieve system stability, some technical operational constraints are considered in the optimisation phase. This study considered three charging zones of different EV parking times with the possibility of two EV loads per bus.

The minimum cost function is shown in Equation (1), where the cost function is the summation of charging hour price. The EV charging load in MW of the system per hour is obtained when P_{ev_t} is multiplied by the $Price_{t,i}$ of the energy, where i is the time to indicate the price of the energy in the algorithm. The variation of the price is important in the algorithm as the aim is to minimise the cost. Therefore, the algorithm will choose the best time for charging with minimal cost.

$$F_{cost} = \sum_{t=1}^{t=24} \left[P_{ev\_t} * Price_{t,i} \right] \tag{1}$$

P_{ev_t} is formulated in Equation (2), whereby EV charging load, P_{ev} is multiplied by the EV charging rate. The charging rate is optimised in the algorithm to choose when the EV will need to charge at a full rate and lower rate.

$$P_{ev\_t} = P_{ev} * C_{rate_t} \tag{2}$$

The charging rate of EV varies depending on the total hours the EV is set to charge.

Methodology

EP algorithm works on a population of candidate lists. The initial population is normally selected at random. Each selected trial schedule can influence the figure of merit to produce an offspring, which is then generated in a similar method as its parent. Offspring are generated by selecting a process that is running on a current machine and then, reassigning that process through multiple random mutations. After all schedules have been calculated, the process to select the best schedule is conducted, in which each schedule is associated with a randomly selected subset of the population. In each comparison, the schedule receives a "win" if it is at least as efficient as the schedule from the randomly selected subset. After all schedules have been completed, the parents of the next generation are selected based on the number of wins attained, and the process is iterated. Finally, the new generation of the population is created using the ranking selection of the individuals from the parental and mutated populations. The rationale for using this technique is as follows:

i. Operating with reduced information, in which some of the values may be unavailable.
ii. Simple and easy to manage.
iii. Discovering uncontrolled scheduling cases that may cause difficulties to the algorithms.
iv. Develops the most effective and cost-effective configurations of machines for a specific set of tasks.
v. Creates a combination of ranks based on conditions set in the equation, whether to minimise or maximise.

Figure 3 shows a flowchart of the optimisation technique used in this study based on the EP algorithm. The EV charging schedule optimisation starts by initialising different parameters, such as the number of EVs and charging rate. A random number that represents the charging rate is varied from 0 to 1. The charging rate is generated while maintaining the power limit and minimum voltage of the system. If the total load meets the constraints, the process continues to fitness 1. The data will then go through a mutation process and new data will be generated (parents/offspring) for fitness 2. In order to proceed to the selection process of best data, both new data of parents and offspring will be combined. The final result is observed for convergence. If it is not converged, the process will go through fitness 1 again and the cycle is repeated until convergence is achieved, which will end the algorithm.

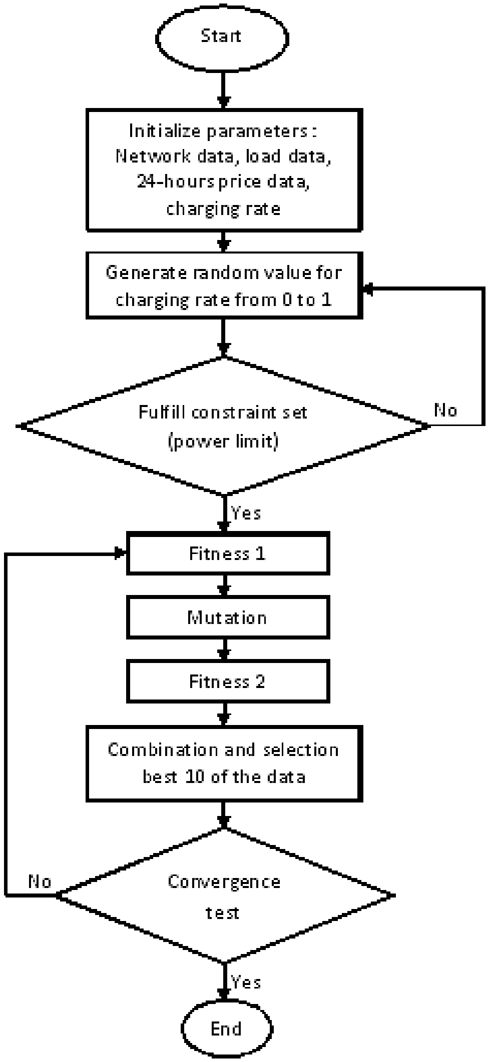

Figure 3: Optimisation flowchart using evolutionary programming.

Results and Discussion

The effect of uncoordinated and coordinated charging schemes on daily residential load curve and EV operational cost are investigated considering 24 hours residential load demand [12] and 24 hours electricity price of open market [8]. Table 1 shows EV charging schemes and charging hours set for uncoordinated and coordinated charging schemes. In the coordinated charging scheme, three case studies are considered which involve three different EV charging periods of 10, 11, and 13 hours. This condition is set up to study how the EV charging time affects the load curve and influences the cost. In order to obtain minimal operation cost, optimization of charging rate is also considered in the coordinated charging scheme.

Table 1: EV charging schemes and case studies

Case no.	Charging scheme/time
	Uncoordinated charging
	5:00 pm - 9:00 pm (4 hours)
	Coordinated charging
1	5:00 pm - 3:00 am (10 hours)
2	5:00 pm - 4:00 am (11 hours)
3	5:00 pm - 6:00 am (13 hours)

Uncoordinated charging

Malaysian working hours are typically from 8:00 am to 5:00 pm. In the uncoordinated charging scheme, all EVs are expected to start charging immediately once users return home from work, which is during peak hours [13]. It is assumed that the battery is charged at a full rate of 4 kW per hour and all EVs are expected to be fully charged within 4 hours.

Figure 4 shows the 24-hours load curve with uncoordinated charging of EVs. Compared to baseload, the load curve for uncoordinated charging shows that a sudden increase in power consumption occurs between 1700 h to 2100 h, which exceeds the power limit of the system set at 0.95 MW. This situation can lead to many problems to the electrical power grid, such as power failures due to overloading, as well as degradation of components, such as transformers and cables. This will also involve large costs in terms of maintenance and also EV operation or charging costs.

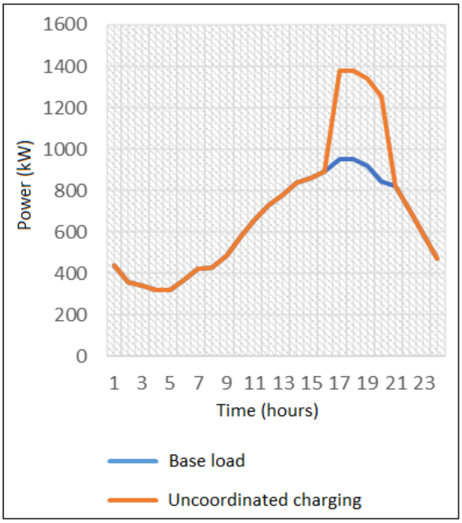

Figure 4: Daily load curve with uncoordinated charging.

Coordinated charging

The coordinated charging scheme is expected to distribute EVs charging over the designated charging period while achieving minimal EV operational cost. The stability and safety of the grid are ensured by following the operational constraints of the maximum allowable power limit and voltage limit that has been set in the algorithm. The basis of this coordination is to smartly distribute the load from EVs during peak hours to off-peak hours.

This coordinated charging scheme is simulated using three case studies consisting of different charging periods. The daily load curve results for each case study are shown in Figures 5-7. All EVs are set to initialize charging at 1700 h. With reference to the baseload curve, the duration between 1700 h and 2100 h is peak hours. The coordinated charging will lead the load from EVs to be shifted from peak hours to off-peak hours. This is evident when it is observed that the charging process starts at 2200 h in all case studies. Based on the predetermined charging periods, it is observed that case studies 1-3 will complete charging within 5, 6, and 8 hours, respectively. All three case studies show good performance in terms of load demand control by successfully maintaining the system power limit below 0.95 W. Differences in the charging period for each case study will affect the optimization of total EV operational cost.

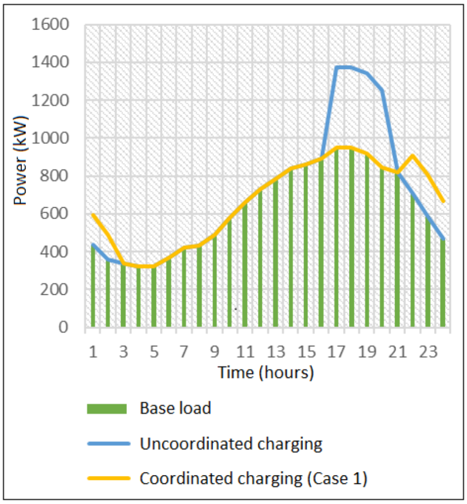

Figure 5: Daily load curve with coordinated charging (Case study 1).

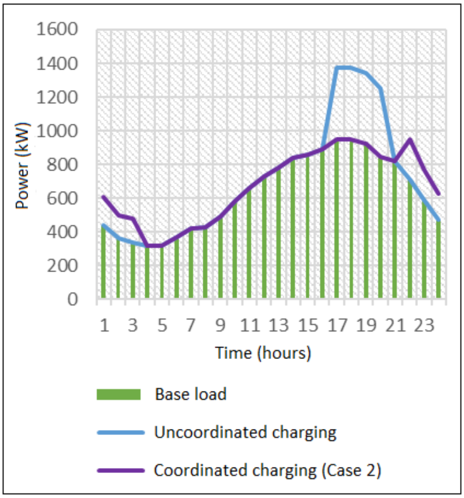

Figure 6: Daily load curve with coordinated charging (Case study 2).

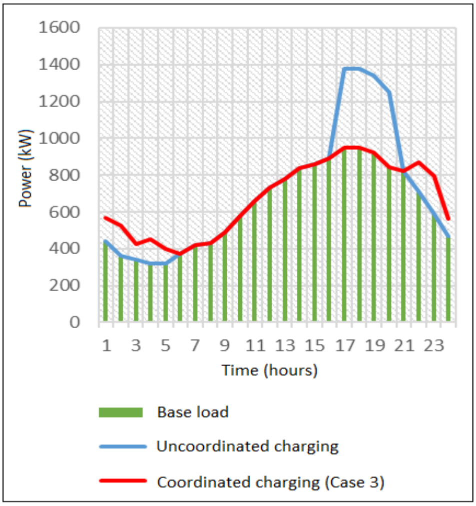

Figure 7: Daily load curve with coordinated charging (Case study 3).

Operation cost minimisation

The charging rates are also optimised in the coordinated charging scheme in order to minimise the operational cost of EVs. Charging rates are expressed in values of 0 to 1 in the algorithm which represents the minimum and maximum charging rate values, respectively. The total cost is calculated based on the hourly electricity price of the open market, as shown in Table 2 [8]. Results of optimal charging rates and total costs are summarised in Table 3 for both uncoordinated and coordinated charging schemes. The collected data indicated that the cost for every hour is inconsistent in all case studies.

The cost of uncoordinated charging is the highest compared to the other three case studies in the coordinated charging scheme. This is because the price of electricity is not considered during uncoordinated EV's charging. The charging rate is also not optimized in this scheme and set to 1 during all charging hours. In the coordinated charging scheme, it can be observed that EV charging rates are varied in all case studies. Based on the hourly electricity price, the proposed algorithm optimizes the charging rates in order to obtain the minimum EV operational cost. The total EVs operational cost obtained in case studies 1-3 are $44.21, $43.79, and $38.45, respectively. Among the three case studies, case study 3 with 13 hours of charging time resulted in the lowest cost. It is observed that a longer charging time will reduce the EV operational cost. This is because the algorithm has more options to optimise the combination of optimal charging rates based on the electricity price in order to produce a minimum total cost.

Table 2: Hourly electricity price of open market

Time	1	2	3	4	5	6
$/kWh	0.033	0.027	0.020	0.017	0.017	0.029
Time	7	8	9	10	11	12
$/kWh	0.033	0.054	0.215	0.572	0.572	0.572
Time	13	14	15	16	17	18
$/kWh	0.215	0.572	0.286	0.279	0.086	0.059
Time	19	20	21	22	23	24
$/kWh	0.050	0.061	0.181	0.077	0.043	0.037

Table 3: A summary of results showing EV charging hours, charging cost per hour, charging rate, and total cost for each case study

	Uncoordinated charging		Coordinated charging					
			Case 1		Case 2		Case 3	
Time (h)	Cost ($)	Rate	Cost ($)	Rate	Cost ($)	Rate	Cost ($)	Rate
1			5.08	0.7	5.52	0.3	4.21	0.3
2			3.44	0.9	3.72	0.8	4.50	0.3
3					2.74	1.0	1.69	0.8
4							2.27	1.0
5							1.37	0.4
17	28.00	1.0						
18	19.21	1.0						
19	13.45	1.0						
20	12.67	1.0						
22			17.29	0.5	17.25	0.2	11.55	0.2
23			9.86	0.9	7.72	1.0	8.86	0.3
24			8.55	1.0	6.84	0.7	4.00	0.7
Total cost	$73.33		$44.21		$43.79		$38.45	

Conclusion

This paper proposed the EV charging coordination for an IEEE 33-bus residential distribution system to minimise the operational costs using the EP algorithm. The simulation results were presented and compared with the uncoordinated and coordinated charging schemes. All case studies in coordinated charging had performed good performance of maintaining the load demand below the maximum power limit of the test distribution network. The charging rates of EVs were optimised throughout the programming process in order to achieve minimum total operational cost. The proposed algorithm has successfully achieved the objective of minimising the operational costs of EV without violating network conditions.

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