1 Cost Optimization Formulation

A. Problem Description

The market prices are obtained from the Energy Market according to which, the EV scheduling is done so as to minimize the cost for charging an EV. The user can set the expected departure time of an EV when is connected to the grid through the charger. To protect the battery from being damaged in charging process, the maximum charging power can be also set artificially. The charger with embedded market price module can now intelligently formulate optimized charging scheme in consideration of the SOC curve and the maximum charging power(from Grid,PV and battery) set by controller in a phase of a 3 phase system, the aim of which is to minimize the cost.

B. Objective Function

Take the cost that EV users need to pay to charge once as objection function

$$min \rightarrow C = \int_{t_0}^{t_0+T} P(t)C(t)\ dt + D(t)C_D \tag{1}$$

In (1), P(t) is the power from the grid and PV and/or battery, C(t) is the market price at time t, D(t) is the Delay time and C_D is the Delay cost respectively.

$$P_{Storage} = E_{Storage,0} + \int_{t_0}^{t_0+T} P_{Bat,t}\ dt + e \tag{2}$$

In (2), $E_{Storage,0}$ is the initial energy state of the storage battery, $P_{Bat,t}$ is the is the charging/discharging power of EV battery at t and e is the error due to charging/discharging imbalance.

$$P_{rr} = \sum_{t=1}^{T} P_{pv}(t) \tag{3}$$

In (3),P_{rr} is the total renewable resource output till time t+T and $P_{pv}(t)$ is the energy generated by PV at time t. Therefore, P(t) in (1) is calculated as follows,

$$P(t) = P_{Grid}(t) + P_{rr} + P_{Storage} \tag{4}$$

In (4), is the total power at t.

C. Constraints

From the power expression $P = VI$, the charging power of EV battery should not exceed a certain limited value. The charging power is constrained by (5)

$$-P_{max} \leq P_{Bat,t} \leq P_{max} \tag{5}$$

where $-P_{max}$ and P_{max} are the upper and lower power limitation during the battery charging/discharging process respectively. $P_{Bat,t}$ is the charging/discharging power of EV battery at t.

The initial SOC of various EV batteries are different as the driving mode and charging habits of different EV users are not the same. The energy demand of EV user with initial SOC considered is stated as below

$$\int_{t_0}^{t_0+T} P(t)\ dt = (SOC_{dep} - SOC_{int})B_r \tag{6}$$

In (6), SOC_{dep} is the required SOC level provided by the user at the time of departure,SOC_{int} is the initial SOC value and B_r is the rated capacity of EV battery.

The main constraint used in this thesis is to charge the EV in a single phase out of a three phase system, In order to find that single phase the following is done,

$$P_{EV_{(i)}}(t) = \sum_{j=1}^{3} \alpha_{ij} P_{ij}(t) \tag{7}$$

such that, $\sum_{j=1}^{3} \alpha_{ij} = 1$, where j is the number of phases.

Grid constraints are specified as follows,

$$P_G(t) = \sum_{i=0}^{n} P_{EV_{(i)}}(t) \tag{8}$$

On substituting (7) in (8) we get (9),

$$P_{Gj}(t) = \sum_{i=0}^{n} \sum_{j=1}^{3} \alpha_{ij} P_{ij}(t) \tag{9}$$

The grid current and voltage imbalance is given by the following equations,

1. Current Imbalance:

$$I_{im} = \frac{(I_m - I_A)(I_m - I_B)(I_m - I_C)}{I_m} \times 100\% \tag{10}$$

where,

$$I_{im} = \frac{(I_A)(I_B)(I_C)}{3}$$

2. Voltage Imbalance:

$$V_{im} = \frac{(V_m - V_A)(V_m - V_B)(V_m - V_C)}{V_m} \times 100\% \tag{10}$$

where,

$$V_{im} = \frac{(V_A)(V_B)(V_C)}{3}$$

2 Smart Grid Architecture Model (SGAM)

SGAM is the best approach for the modeling of use cases in a structured manner. The purpose of developing SGAM was to provide an easiest and simplest way to illustrates or visualize the smart grid related functionalities. The SGAM represents how the three-dimensional (zone plane, domain plane, and interoperability layers) architecture is used to describe the use case and sub functionalities of the use case in pictorial form.

SGAM is represented as follows,

1. SGAM domain (one dimensional smart grid plane) shows the stages involved in transmission of power of electrical energy from generation to customers.

2. SGAM zone shows that how the power system management is divided in hierarchical way into six zones, namely; process, field, station, operation, enterprise, and market.

3. The interoperability layers represent that how the devices, communication and IT technologies are integrated that belongs to different layers of interoperability.

Figure 1: Smart Grid Architecture Model

Interoperability layers: The various interoperability layers as described in the below table (Table 1.1)

Layer	**Description**
Business	This layer maps the use case into SGAM to realize the effect/involvement/role of regulatory and economic markets, policies, and business models.
Function	This layer presents the functions for the use cases in pictorial form as well as the services related to the use case.
Information	This layer describes the exchange of information for function, services and components. This layer represents the information object and canonical data model.
Communication	This layer provides the communication media, protocols and mechanisms for data transmission from the component layer to the process and function layer.
Component	This layer presents the physical components used in SGAM for the use case,which includes power system equipment, communication network infrastructure and computers used for applications.

Table 1: Interoperability layers

SGAM Domains: The various domains used in SGAM are as described in the below table (Table 1.2)

Domain	**Description**
(Bulk) Generation	This layer represents the generation of electricity in bulk quantity. The generators are connected to the transmission system, Examples of generation are power plants (nuclear, hydro, solar power plants) and wind farms.
Transmission	The transmission layer represents the transportation of electricity from Generation to Distribution over long distance.
Distribution	This layer represents the infrastructure for the distribution of electricity to customers.
DER	The DER represent the distributed electricity resources connected at the small scale at homes/hospitals or at industries.These resources may be controlled by DSO or a customer itself.
Customer	It holds the both consumers and prosumers of electricity.

Table 2: SGAM Domains

SGAM Zones: The various zones used in SGAM are as described in the below table (Table 1.3)

Zone	**Description**
Process	The process shows the transform of energy (electricity, solar, wind, water, heat). The physical components that are involved in process are Generators, transformers, cables, electrical loads, sensors and actuators.
Field	The field consists of the equipment (IEDs) for monitoring and controlling and provides the protection of a process of the power system.
Station	The station is used for data collection, supervision, and substation automation functionalities.
Operation	Hosting power system control operation in respective domains, the operations include monitoring, supervision, estate estimation, controlling and management of electricity production, transmission, distribution, storage and consumption.
Enterprise	It holds the both consumers and prosumers of electricity.It provides commercial and organizational process, services and infrastructure for enterprises(utilities, service providers, energy traders) eg. Asset management, staff training, billing and procurement.
Market	Reflecting the market operations possible along the energy conversion chain. Examples Energy trading, mass market, retail market, etc.,

Table 3: SGAM Zones

The interoperability layers are modeled in the following section based on the use case for the thesis i.e to charge an EV efficiently in a single phase under specified grid constraints by coupling the photo-voltaic panels and the energy storage device (battery).

3 SGAM use case modelling

3.1 Component Layer :

The component layer shows the physical devices, components and communication media used for the use cases. The components used in the component layer are,

Short name	**Extended name**	**Domain**	**Zone**	**Reason**
C	Controller	Customer	Operation	The controller is placed in the Operation zone in tomer domain because it provides monitoring controlling of entities and provides asset man ment.
M	Market	Transmission	Market	Reflects the energy market prices.
SM	Smart Meter	Customer	Field	Monitors the electricity usage of a household.
DSO	Distribution System Operator	Distribution	Operation	Power system control in the Distribution domai
EV	Electric vehicle	Customer	Process	Customers energy transformation
PV	Photo-voltaic Panels	Customer	Process	Customers physical energy conversion(solar)
B	Batteries	Customer	Process	Customers energy transformation
U	User	Customer	Field	Monitors Arrival/ Departure time of EV
F	Forecast	Customer	Enterprise	Distribution of load profiles from utility

Table 4: SGAM Component layer

Figure 2: Smart Grid Architecture Model

3.2 Business Layer :

The business layer defines the business actors and business goals of use cases. The benefits that can be achieved by efficient EV charging use cases are:

1. Cost Optimization by charging EV's during off peak times or by using PV and batteries .
2. Efficient EV charging at 7kw in one phase of a 3-phase system.

3. Scheduling of EV's based on earliest deadline.

Figure 3: Smart Grid Architecture Model

The Business layer intends to host the business processes, business objectives, economic and regulatory constraints underlying the use case.

The business layer shows the area affected by the use case and is influenced by its underlying business objectives.

The main objective is to Efficiently charge the EV in a single phase out of 3 phases with the grid constraints.

3.3 Information Layer :

The task of the information layer is to generate object models with identification of supporting standards for data objects for data transmission between different actors. The information layer presents,

• Business context view (what information is exchanged between actors and enterprise).

3.3.1 Business context view

The business context view presents that what information is exchanged between actors and systems.

Figure 4: Smart Grid Architecture Model

Information flow from	**Information flow into**	**Information transfered**
Smart Meter	Controller	U,I
Forecast	Controller	Load profiles
Controller	EV,PV,B	P,Q and charging/discharging of power to grid
Distribution System Operator	Controller	Grid Constraints (U and I)
Electric vehicle	Controller	U,I
Photo-voltaic Panels	Controller and Forecast	U,I and load profile
Batteries	Controller	P,Q
User	Controller	Arrival/Departure time and SOC level
Market	Controller	Price list
Household	Forecast and Smart Meter	U,I and load profile

Table 5: SGAM Information layer

3.4 Function layer :

The function layer describes the function of each entity/device/ application used in use cases. The goal or focus of the function layer is to support the IT related functionalities, which are used to support the functions of the business layer. The function layer illustrates that how the information is processed and utilized by different actors.

4 Particle Swarm Optimization Algorithm:

Particle Swarm Optimization (PSO) is a computational method that optimizes a problem by iteratively trying to improve a candidate solution. It solves a problem by having a population of candidate solutions (i.e particles) and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. Each particle's movement is influenced by its local best known position, but is also guided toward the global best known positions in the search-space.

Our task is to prove that the search space is convex in nature. Below is the description on how the search space is defined with certain constraints.

Search space condition:

$$\{x \in \mathbb{R}^n | constraints\}$$

Above condition refers to determining a multi dimensional real valued search space with a set of constraints.

The search space is defined as follows,

$$\{(A_i, B_i, C_i, P_i)\}_t$$

where, $1 \leq i \leq M$, $1 \leq t \leq T$, $P \in [-P_{max}, P_{max}] \subseteq \mathbb{R}$ and A,B,C are the 3 phases

The parameters in the search space(A_i, B_i, C_i, P_i) are the phase and power of i^{th} EV's, M is the maximum number of EV's and T is the endding time.

Hence the dimension of the search space becomes :

$$\mathbb{R}^{MT}$$

The following are the constraints based on which the boundaries for the search space is defined,

1. Phase Constraints:
   Only one phase is chosen out of the 3 phases A,B and C For the tuple (A_i, B_i, C_i, P_i) the constraint is as follows,

   $$A_i + B_i + C_i = 1$$

   where $(A_i, B_i, C_i) \in \{0, 1\}$

2. Grid constraints:
   The grid constraints are defined in such a way that the power consumption should not exceed 4.6KW

   $$I(t) = f\left(P_A(t), P_B(t), P_C(t)\right)$$

where,
$\forall t \in [1, T] : I(t) \leq 4.6$ KW

$P_A(t) = \sum_{i=1}^{M} A_i \cdot P_i(t)$

$P_B(t) = \sum_{i=1}^{M} B_i \cdot P_i(t)$

$P_C(t) = \sum_{i=1}^{M} C_i \cdot P_i(t)$

$f(P_A(t), P_B(t), P_C(t)) : max\,\{|P_A(t) - P_B(t)|, |P_B(t) - P_C(t)|, |P_C(t) - P_A(t)|\} \leq 4.6$

This can be further linearized as follows,

$|P_A(t) - P_B(t)| \leq 4.6 \implies -4.6 \leq P_A(t) - P_B(t) \leq 4.6$

$|P_B(t) - P_C(t)| \leq 4.6 \implies -4.6 \leq P_B(t) - P_C(t) \leq 4.6$

$|P_C(t) - P_A(t)| \leq 4.6 \implies -4.6 \leq P_C(t) - P_A(t) \leq 4.6$

3. SOC constraints:

   General constraint:

   The constraint is that the energy consumed and/or produced (E_i^t) by an EV must be greater than 0 and must be less than the maximum battery capacity (E_{max}).

$$\forall t_x \in [T_S, T_D] : \qquad E_i^t = \sum_{t=T_S}^{t_x} t \cdot P_i(t) \cdot \epsilon$$

   where, $E_i^t \geq 0$,$E_i^t \leq E_{max}$ and $\epsilon = 0.95$ is the efficiency value which provides the losses when charging and discharging.

   User constraint:

   The constraint is set so that the energy consumed and/or produced by an EV must be equal to (E_{req}).

$$E_{int} + \sum_{t=T_S}^{T_D} t \cdot P_i(t) \cdot \epsilon = E_{req}$$

   With an assumption that the initial value of the energy level of an EV battery (E_{int}) is provided by user.

4. Power consumed at t $\notin [T_S, T_D]$:

   This constraint defines that the power drawn is set to 0 during the time when the EV is not plugged in the charging station.

$$\forall t \in [1, T_S] \cup [T_D, T] : \qquad P_i(t) = 0$$

The total cost is calculated as follows,

The time duration is discretized with a fixed time slot duration and the time slot is enumerated with $1 \leq t \leq T$

$C = \sum_{i=1}^{M} C_i$

$C_i = \sum_{t=T_S}^{T_D} C_i(t)$ where $C_i(t) = E_i^t \cdot c(t)$ and $E_i^t = t \cdot P_i(t) \cdot \epsilon$

where, c(t) is the cost from market in ct/kwh, E_i^t is the energy of i^{th} EV at time t in kwh and $C_i(t)$ is the cost of i^{th} EV at time t in ct (euro cent).

Finally the particle swarm optimization algorithm is used to minimize the total cost.

i.e $min \rightarrow C$