CHAPTER 5
CODES-MM: COST OPTIMIZATION OF DISTRIBUTIVE ENERGY SYSTEM USING MARKOV MODEL

5.1 Preamble

This chapter discusses the cost estimation process followed by minimization process considering the smart appliances being exposed to a renewable resource. The chapter also introduces a mathematical model in order to elaborate the scheme of controlling the cost of power utilization with a sufficient balance of service quality.

5.2 Introduction

The caution of global warming and the growing demand for electricity in the current world has motivated the generation of power in an eco-friendly way. Thus, the research attention is increased with smart grid-based power generation with reduced carbon emission globally. The management and the distribution of electricity within the intelligent grids are evolved with up-gradation by bringing advanced information and communication mechanisms for efficiency improvement, reliability improvement and safety improvement with the combination of widespread DPG. In smart grid, the idea of Smart Appliances (SA) has out formed as significant one which enables both the commercial as well as residential devices to adjust automatically with respect to their power usage patterns: minimizing power usage or postponing the operation time during peak demand as per the real-time price of electricity.

The prime significance of the SA mechanisms is twofold, i.e., from the consumer perspective and provider perspective. As per the consumer perspective, the electricity usage cost will be minimized, and from the electricity provider perspective the peak demand can be reduced and hence the cost and risk factor to the grid can be decreased. In order to favour the functionalities of the smart antennas, the micro-grid must act as the better infrastructure and is the central unit of the power distribution system exists at the tail of distribution sub-station. In the Figure 5.1, the flow model of the micro-grid system is depicted which includes local Electricity Provider (EP) who forwards the real-time price of electricity to the micro-grid. In general perspective, a distributed energy resources such as DPG (through wind turbines or
solar panels), distributed energy storage and micro gas turbines are existed to minimize the overall peak load and its fluctuations in the micro-grid.

![Figure 5.1 Flow Model of the Micro-Grid System](image)

The distributed energy storage (DES) has emerged as a more exciting concept in the power domain in the recent decade. The existing researchers have explored DES functionalities to relieve the non-linearity of the renewable resources based power system. But, there is a lack of investigation towards micro-grid that how the DES can help to reduce SA users financial cost. However, managing DES resources in the real-time scenario of electrical price are must and also for SAs and DES characteristics. In this chapter, an efficient and structured power grid is presented which optimizes the electricity cost of SAs. The overall chapter is organized with various units like an architectural model of CODES-MM, algorithm implementation, results in the analysis and summary of the chapter.

5.3 Architectural Model For CODES-MM

This section gives the systematic design of proposed CODES-MM model that aims to minimize the electricity cost of SA. The proposed model uses the Markov
Decision Process for token allocation policy under DES scenario. The architectural model of CODES-MM is represented in Figure 5.2 with five blocks –
(i) Operations (ii) Power (iii) Problem (iv) CODES-MM and (v) Performance analysis.

The architectural model of CODES-MM initiates a set of operations like Micro Grid Controller (MCG), SA operations, DES power pricing and allocation policy. The framework uses the MGC module and is integrated with SAs and distributed information network which can be a neighbourhood area or building area network. The MGC networked model can be composed of different decision sets and action phases.

The functional flow of the CODES-MM can be composed of different operations which can help to minimize the financial costs of each smart appliance (as shown in Figure 5.3).

![Figure 5.2 Architectural Model of CODES-MM](image)

![Figure 5.3 Functional Flow of CODES-MM](image)
The CODES-MM incorporates with the principle of energy usage schemes which can bring down the cost of the smart appliance. Both the MGC and the SAs are connected with the power system distribution. The time frame of the MGC controller is divided for scheduling of minimum units from one to infinity. The pricing of electricity in real-time exists for all the SAs at the start of each frame. Further, the user can set some rule to receive (R) or limits (L) the price. The charging (C), discharging (D) or be the idle process of SAs can be performed by MGC for a particular frame. The micro-grid exhibits certain distributed power resources which can be considered as negative and non-deferrable power demands in the CODES-MM. Each element of the CODES-MM is described as below.

5.3.1 MGC Operations

The Micro-grid controller implements on frame by frame basis with scheduling mechanism. Figure 5.4 indicates the frame formation of MGC that receives line information and decides at decision stage of \((k_{th})\) frame. The received information may have the present price of electricity, the present stage of each smart antenna and the DES stage.

![Figure 5.4 Frame Formation of MGC](image)

The stage of decision involves both action and power allocation policies. The decision stage can be followed with process stage in which the decision may take effect. In the process stage the decision taken in the decision stage is processed and implemented. During MGC operation, the scheduling can be done to optimize the cost of SA in a long-term process.

5.3.2 SA Operations

Multiple deferrable SAs can be registered within the MGC database during SA’s operation. Later an assumption is made that the each SAs will have continuous power rating during the interesting period.
Apart from the power rating, the user can preset some other parameter value of SA such as the desired price threshold and delay threshold in operation. Hence, if the electricity price crosses the threshold price, then SA may not take power from the utility grid. In case the operational delay of SA touches threshold then SA will operate much quickly. Under some scenario, the energy demand of SA may be in ON or OFF position i.e. ON means operation of SA for particular operation delay threshold by user interaction while OFF position indicates the idle state of SA.

The SA may have deadline state in ON or OFF position. The OFF position indicates the deferred operation time of SA while ON state represents the operation deadline which is reaching the delay threshold and hence the operation time of SA cannot be deferred any more. Thus the multiple successive ON state of energy demand indicates the one operation of SA needs multiple time frames. Therefore the operation of SA can't begin until the previous process gets completed.

5.3.3 DES Operations

The DES is battery that can be deployed in the micro-grid system owned by the consumer. Multiple numbers of DES can be grouped into a cluster of single DES. Generally, in DES, the batteries are lithium-ion battery, lead acid battery which exhibits the capacity effect that is the available battery capacity with a higher discharging rate. Thus, energy need for charging of battery increases with charging rate. In order to avoid the impact of DES at overlarge capacity offset, it can be assumed that the rate of DES charging is low and fixed and rate of discharging may have multiple levels in discharging threshold rate.

Also, the state of the charging/discharging of DES ($S_C$) can be given by equation 5.1 as:

$$S_C = \frac{Available\,Energy}{DES\,capacity} = \frac{A_e}{D_e}$$  \hspace{1cm} (5.1)

The state of DES charging and discharging ($S_C$) can be assumed of the finite state which helps to perform a proper analysis. The action of DES at a different rate can be obtained by using MGC at discharging or charging or idle state.

During charging, DES can have the charging rate given by equation 5.2 as:

Charging rate = Traditional load + power rating  \hspace{1cm} (5.2)
During discharging, the DES can have generator property with the rate of discharging equal to the capacity. Finally, both the DES capacity and $S_C$ can be stored in the MGC model.

### 5.3.4 Pricing policy of DES

The power given by the distributed energy storage is not free of cost, but it provides a cheaper alternative of energy generated by the conventional power grid. In this, DES purchase energy from the conventional power systems for some price which can be considered as "base price of" DES power. Thus, the initial investment for renting or deploying the DES within the micro-grid is cost effective because the manufacturing, maintaining and recycling of rechargeable battery needs higher cost. Hence, the pricing of DES is considered as the battery cost and the power pricing of DES follows the fixed rule, and it doesn't require any real-time scheduling.

### 5.3.5 Power allocation policy of DES power

In order to explain the allocation policy of DES, power for the SAs an auxiliary element known as the token is introduced.

\[
T_n = S_{A_{\text{max}}} \tag{5.3}
\]

where,

\[
T_n = \text{No. of tokens} \quad S_{A_{\text{max}}} = \text{Maximum number of SAs}
\]

Thus, $T_n$ can be afforded by determining the DES output power and SAs power ratings. If an SA is indicated with $T_n$ in the decision stage, then it uses power from DES while in action stage SA will pay DES power price instead of grid power price. The MGC must decide for token allocation policy.

To represent the model flow of proposed CODES-MM system, consider the decision stage of one frame where the micro-grid controller collects the real-time pricing of electricity, power demand stated and deadline state of all the SAs operation, $S_C$ state of DES. In such a case, the electricity pricing will be quite high for the current frame. In case the operation delay of SAs achieves threshold value of
operation delay then SAs will operate at higher financial cost. MGC takes the decision to perform discharging of DES power at the low price if the energy exists in DES.

Hence, the SAs may exhibit another preference to get the energy at the lowest financial cost. However, the DES actions in the current frame can have the impact on actions and results on desired frames which are needed to be appropriately decided. The following assumption is made with respect to DES,

- If more than two energy demand states are adjusted, then various power rating levels indicate with each SA.
- In this research, the logical term is used to represent the assignment of SA with a token which in general does not consume the electrical power from the distributed energy storage, because the power from the main power system and DES is not distinguished by the SA.

5.4 Problem Formulation

The cost optimization problem for the distributed system with respect to communication overhead, action and decision set is represented below.

5.4.1 Communication overhead in power network

From the conceptual explanation of Figure 5.2, the MGC is considered as servers while the smart antennas (SAs) & DES as clients that exchanges the power through the power network. In this, N- the number of SAs was deployed over the area, the real-time pricing level (x) of local power system with different action preferences (y) like charging, discharging, idle with three rates. Considered a frame length of "t" minutes. Hence, the downlink overheads of the communication are composed of \(\log_2(x)\) bit/frame with "x" price levels, \(\log_2(y)\) bit/frame for "y" DES action preferences and \(T_n\) allocation policy of N bits/frame with N number of SAs. The demand states of uplink overhead and operation deadline states require N bits/frames for N number of SAs. From this, it can be said that the communication overhead at more number of SAs is limited for a power network. Further, for improvement of the power network even at transmission errors, a re-transmission mechanism is incorporated.
5.4.2 Information Set

A following mathematical equation is derived-

\[ \beta(k) = \{p(k), d(k), m(k), l(k)\} \]  

(5.4)

In the above equation (5.4):

- \( p(k) \) represents electricity price per unit of energy
- \( d(k) \) gives the demand states of energy it can be defined as,
  \[ d(k) = [d_1(k), d_2(k), \ldots, d_M(k)]^T \in \mathbb{B}^M \text{ where } \mathbb{B} = \{0,1\} \]

Where index with respect to SAs and Microgrid are denoted as \( M \).

ii) Decision and Action Set

The decision set for energy storage can be derived in terms of below mathematical expression (5.5).

\[ \eta(k) = \{a(k), t(k)\} \]  

(5.5)

Similarly, the action set can be defined as (5.6):

\[
a(k) = \begin{cases} 
1 \\
0 \\
-i 
\end{cases} \]  

(5.6)

For action set value of 1 is selected if storage is in charging state while the value of 0 represents an idle state and \(-i\) indicates its discharging state where a value of \( i = \{1, 2, 3\} \). The objective function for the purpose of an optimization process is mathematically derived from reducing the financial cost of the system and an optimization process is employed and is represented in (5.7).

\[
\lim_{L \to \infty} \text{Min} \ (\eta(k), \eta(k)) 
\]  

(5.7)

The DES actions can be estimated at the end of the \( k^{th} \) frame; it can be taken as:

\[ l(k+1) = l(k) + a(k) \in \beta \]  

(5.8)

To analyse \( h(k) \in \mathbb{B} \) is introduced which represents the state of the electricity price in which 0 is for a low price while 1 is for a high price.

\[ \text{i.e., } \ p(k) = p_{LOW} + (p_{HIGH} - p_{LOW}) \times h(k) \]  

(5.9)

In the above equation, \( p_{LOW} \) indicates the off-peak price while \( p_{HIGH} \) indicates on-peak price hence \( p(k) \approx h(k) \). Defining a vector for power consumption \( v(k) \)
\[ v(k) = [v_1(k), v_2(k), ..., v_n(k)]^T \in B^m \] (5.10)

Where \( v_n(k) \) indicates that whether \( n^{th} \) SA utilizes the power from the main power grid. The \( v(k) \) value gives the state of SA operation reaching to its delay threshold. The \( n^{th} \) SA collects \( v_n(k) \) and stores in a memory. In order to obtain \( v(k) \) in MGC following computation method is followed. Remaining energy demand is defined as \( \theta_n(k) \), which includes un-served units of demands of demand in \( n^{th} \) SA at \( k^{th} \) frame starting. Similarly, \( \theta_n(1)=d_n(1) \) demand with grid vector \( v_n(k) \) at the \( k^{th} \) frame can be computed by MGC and is represented in (5.11):

\[
v_n(k) = \begin{cases} 
\max \left\{ \frac{1}{\theta_n(k)}, m_n(k) \right\} & h(k) = 0 \\
m_n(k)(1-t_m(k)) & h(k) = 1 
\end{cases}
\] (5.11)

In (5.11), the value of function \( 1_{\bullet} \)'s equal to 1 if the statement in \( \bullet \) is true otherwise, it will be zero. Similarly, the token vector is indicated as \( t_n \).

Hence,

\[ \theta_n(k + 1) = \theta_n(k) + d_n(k + 1) - v_n(k) - t_n(k), \quad k = 1, 2, ... \] (5.12)

Later, define a delay counter \( g_n(k) \) to represent the nearing degree of operational delay threshold of an \( n^{th} \) smart antenna at the \( k^{th} \) frame starting, which is stored in the same antenna memory. Hence, \( g_n(1)=G_n \), later, an updating function is developed to operate the deadline state vector by using the following algorithm.

**Algorithm: Deadline state operation vector**

| Inputs: m, \( \theta_n(k) \), \( v_n(k) \), \( g_n(k) \) |
| Output: Update of deadline state operation vector |

**Start**

1. for all \( n \in \sigma \) do
2. if \( \theta_n(k + 1) > 0 \)
3. if \( v_n(k) + t_n(k) = 0 \) and \( \theta_n(k) > 0 \)
4. \( g_n(k + 1) = g_n(k) - 1 \)
5. else,
6. \( g_n(k + 1) = g_n(k) \)
7. \( \text{endif} \)
8. \( \text{if } g_n(k + 1) \leq 0 \)
9. \( m_n(k + 1) = 1 \)
10. \( \text{else,} \)
11. \( m_n(k + 1) = 0 \)
12. \( \text{else if} \)
13. \( \text{else} \)
14. \( g_n(k + 1) = G_n \)
15. \( m_n(k + 1) = 0 \)
16. \( \text{endif} \)
17. \( \text{end for} \)

**End**

The proposed CODES-MM model is expressed through the following algorithm and design flow model. The algorithm begins with the deployment of the distributive power system (Dp) model (line-1) which consists of DES unit, and smart appliances. Once the deployment of Dp is done then the input parameters are needed to be defined (line-2), i.e., DES capacity (\( \chi \)) and DES constraints (\( \kappa \)). Then the highest price state (\( \Gamma \)) value needs to be provided in USD (Line-3). Later, the different methods for analysis are considered (Line-4) separately with existing methods, E1, E2, E3 and proposed method P. Then number of frames (\( \zeta \)) are defined (Line-5). Once the above process is completed then, simulation is performed (Line-6) and analysed for \( \chi \), \( \kappa \) and \( \Gamma \) against financial cost (\( Z \)) (Line-7). Finally, the financial cost \( Z \) is obtained (Line-9).

**Algorithm: Overall system model and analysis**

**Input:** Dp model  
**Output:** \( \mathfrak{R} \)

**Start**
1. Deploy \( \rightarrow \) Dp model
2. Define \( \rightarrow \) \( \chi \), \( \kappa \)
3. Set \( \rightarrow \) \( \Gamma \)
4. Choose $\rightarrow$ E1, E2, E3 and P
5. Define $\rightarrow$ $\zeta$
6. Perform $\rightarrow$ simulation
7. Analyse $\rightarrow$ $\chi$, $\kappa$, $\Gamma$ Vs $\Re$
8. Obtain $\rightarrow$ $Z$

End

The following section explains the results analysis of the proposed method.

5.5 Result Analysis

MATLAB software is used for programming and execution of the proposed CODES MM approach by considering the financial cost as a parameter to be minimized for the smart grid.

First, in the execution process, the power system model is deployed over an area and is shown in Figure 5.5. In this, the MGC is considered as servers while the smart antennas (SAs) & DES as clients that exchanges the power through the power network. In this, ten SAs were deployed over the area, the real-time pricing level of local power system with different action preferences like charging, discharging, idle with three rates. In this, the minute frame length is considered. Thus, the communication overhead at downlink consists of price level for preferences of DES actions while 10bits frame of token allocation policy. Similarly, for demand state of uplink overhead and operation deadline state, the SAs exhibit bits/frame demand.

On analysing this, it is found that the communication overhead for the power network is limited for more number of SAs. Also, the re-transmission method can be substituted for the data packet which improves the power network robustness at transmission errors. Once the power system model is deployed the input parameters like delay constraints values are defined between values of 1 to 6 (for experimentation given as 1), the capacity of DES is defined between the values of 5 to 20 (take the value of 6) with high price state in USD of 0.07. Later, three different methods like Yue et al. [120], Spiliotis et al. [121], and Arikiez et al. [122] are selected to perform the performance analysis of the proposed CODES-MM model with a selected number of frames as 50. During the execution, considering delay constraints, energy storage capacity (of value ranging from 5 to 20) and high price state (in USD) as design parameters with 50 number of frames. The results obtained from the simulation
environment shows that the proposed optimal framework can significantly reduce the financial cost of electrical appliances in the smart grid.

![Deployment of Power System Model](image)

**Figure 5.5 Deployment of Power System Model**

In Figure 5.6, financial costs of smart antenna with different methods at a variable peak price are shown. The price varies from $7 \times 10^{-2}$ to $1 \times 10^{-1}$ USD/kWh. It has been observed that the annual financial cost will increase with on-peak electricity price. On analysing Figure 5.6, it is observed that the different methods have variable performance gap or higher with respect to the on-peak price of electricity. Hence, the proposed model is more significant in minimizing the electricity price even at on-peak and off-peak price with variable/higher performance gap.

![Analysis of Financial Cost Vs. Electricity Price](image)

**Figure 5.6 Analysis of Financial Cost Vs. Electricity Price**
The simulation outcome of the different approaches like Yue et al. [120], Spiliotis et al. [121], and Arikiez et al. [122] and proposed CODES-MM model are represented in Figure 5.7 with respect to annual cost and average operational threshold. With clear observation of the Figure 5.7, it can be said that the proposed method achieved significant and optimized financial cost than other approaches [120], [121] and [122].

On the clear view of the plot representing annual cost Vs. DES capacity (in Figure 5.8), it has been found that the approaches of Yue et al. [120], Spiliotis et al. [121], and Arikiez et al. [122] are compared with proposed CODES MM approach. In this, the performance of the proposed model is improved by integrating the pricing policy and distributed energy storage power allocation using a Markov decision process to
achieve a significant allocation of power distribution over a network. Observing Figure 5.8 it is found that the proposed model reduces the financial cost for the same DES capacity than other methods.

5.6 Summary

The proposed model of CODES-MM was designed by aiming financial cost minimization in smart grids. The designed framework considers delay constraints, energy storage capacity (of value ranging from 5 to 20) and high price state (in USD) as design parameters. The model takes 50 numbers of frames. Finally, the outcomes suggest that the model achieves a significant reduction in financial cost in the smart grid.