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CSOA-Based Residential Energy Management System in Smart Grid Considering DGs for Demand Response

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***Abstract*— The increase in energy consumption in the residential sector due to overpopulation has adverse effects on the power system. The traditional power grid is unable to handle a sustainable supply of energy for consumers. The adoption of smart grid and distributed generation sources (DGs) can play a vital role to cope with this challenge of a constant supply of energy retainment. In this paper, DGs like photovoltaic (PV) and battery storage system (BSS) are considered with home to grid (H2G) mutual exchange for residential consumers energy cost reduction based upon real time price signal (RTP). The Crow Search Optimization Algorithm (CSOA) has been applied for energy management controller (EMC) in home energy management (HEM) system to schedule home appliances optimally. It is evident from the analysis that DGs and H2G are important in minimizing consumption cost by an effective HEM system. The results attained from the CSOA proves that the approach is useful for residential consumers. The energy consumption cost is minimized in the proposed scheme taking consumers priorities into consideration. The results are helpful to initiate different demand response programs in the context of both consumers and power system operator.**

Keywords—Demand response, distributed generations, Battery storage system, home energy management, Crow search optimization, optimal scheduling, photovoltaic.

I. INTRODUCTION

Due to the increase in population over the last few decades, energy utilization has also been greatly increased. Now, it has become very important to solve the problems related to both energy generation and its optimal utilization. Newly developed tools based on modern techniques and bidirectional flow of power can solve these problems. Today, we have smart grid stations that can work properly with these devices. They not only enhance the efficiency of the system but also improve system security [1]. The reliability, efficiency, security, and flexibility of the power systems can be increased if smart grids replace old conventional grids. The already present traditional grids cannot solve these problems [2]. Demand-side management (DSM) techniques can be developed to run these smart grids that can benefit both consumers by limiting their utility bills and suppliers by reducing different power losses [3].

There is a great contribution of demand-side flexibility and DSM towards optimum energy management in these newly developed smart grids [4, 5]. The main objective is to flatten the demand curve as more as possible. As in smart grid systems, there is the dual flow of power from user to grid and grid to the user; therefore, the efficient use of power on the consumer's side with proper implementation of DSM techniques make it easier to achieve this. If some factors like peak demand factor and load factor are properly controlled, it becomes easier to implement other techniques related to DSM [6]. Distributed transformers are also an important part of smart power systems. The objectives like peak clipping, improved efficiency, and optimal load shifting can be achieved by properly using distributed transformers with the DSM technique [7, 8].

One of the main objectives of the DSM technique implemented by using the smart tariff method can be achieved by realizing consumers the benefits of optimal power usage [9-11]. If somehow bidirectional power optimization is achieved, then it should flat the demand curve. More than one technique can be adopted at a time to make power system efficiency and reduce consumer's bill costs. Some of the newly developed optimization techniques use the best possible available time for scheduling loads. On the other hand, some are based on different algorithms. Generally, to take care of these optimization problems, and energy management controller (EMC) is used at the consumer's end. It automatically and optimally schedules the loads depending upon the power at which they operate [12, 13].

An IoT-based technique with EMC has been used in [14] to schedule the consumers' load optimally. DSM method with EMC to reduce electricity bill costs through load optimization has been proposed in [15]. The authors of [16] have used a similar model to limit peak-to-average ratio (PAR) by managing consumer's load optimally. A model known as Bender microgrid has been used in [17] to find optimal scheduling time of multi-load at different levels. In [18], the authors have implemented different cost-efficient power optimization techniques with EMC to control the bidirectional flow of power. This control enables the user to limit his/her energy utilization expenses. A more modern optimization algorithm-based technique has been discussed in [19] that uses power generated by the batteries in electric vehicles to flow towards the grid when available in excess. The model also shifts the load to off-peak hours so that bill cost can be reduced.

To flat demand curve and reduce power losses, a modern version of particle swarm optimization (PSO) has been used [20]. To optimally schedule load through home energy management controller (HEMC), the authors of [21] have used different optimization algorithms like ant colony optimization (ACO), binary PSO, and genetic algorithm (GA). In [22], a grey wolf optimizer (GWO) has been used to reduce bill costs. The authors of [23] have suggested using the HEMS-based model to control the bidirectional flow of power optimally. In [24], the earthworm optimization (EWO) algorithm is used crossover operators to give an optimal solution to the peak off-load shifting problem. The use of EWO gives two outputs. The 1st output gives a male or female offspring while, in the 2nd more than one offspring is obtained. To shift load from peak-on to peak-off hours, a very famous population optimization algorithm, polar bear optimization (PBO), has been used by different authors [25].

Research work mentioned above motives us towards smart energy management system consisting of H2G, BSS, and PV. CSOA technique has been used in this paper to solve efficient energy management problems. Remaining sections of paper are: HEM mathematical model has been discussed in section II, problem formulation and its solution using CSOA have been described in Section III and IV, results and different cases have been discussed in Section V, and finally Section VII gives the conclusion of this paper.

II. MATHEMATICAL MODELLING OF HEM SYSTEM

HEM system components include different types of appliances that are required daily in homes; a smart meter; DGs, including PV, BSS with the main power grid. The main component of HEM system is EMC. IoT based wireless communication scheme is employed so that it links wirelessly with different components. RTP signal to EMC is applied so that it performs consumers preferences based flexible home appliances planning. The whole framework is shown in Fig. 1.

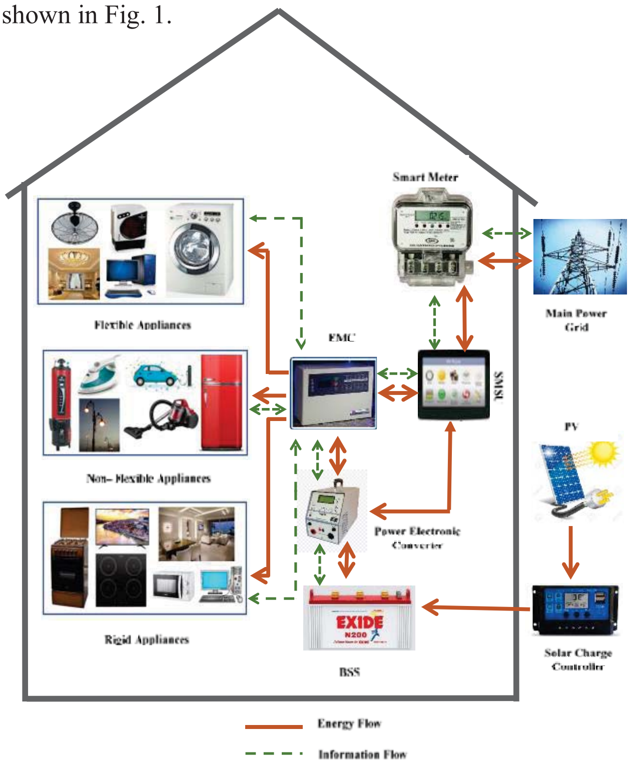

Fig.1. Framework for the Proposed CSOA based HEM system

For a smart home, every energy consuming appliance belongs to flexible and non-flexible categories. The flexible appliances have their operation interruptible and will scheduled later at any time when energy is enough. These appliances take part in CSOA computations. While non-flexible appliances and rigid appliances do not take part in home appliances scheduling. Rigid appliances follow the following time constraints as explored in [26].

$$\sum_{S_A}^{E_A} C_{\mathrm{A}}(H) = U_{\mathrm{A}} \tag{1}$$

The limits of S_A and E_A are

$$1 \leq S_{\mathrm{A}} \leq H - R_{\mathrm{A}} + 1 \tag{2}$$
$$R_{\mathrm{A}} \leq E_{\mathrm{A}} \leq H \tag{3}$$

where *'H'* is total time for appliances (A) are scheduling along with PV and BSS. Per half hour slots are used then 24 hours becomes 48 half hours slots *(H),* i.e., *h=1,2,3, ...,48.* The supplied power for every appliance is symbolized by D_A. $[S_A, E_A]$ is each appliance operational time. U_A is the duration in which each appliance completes its action. $C_A(H)$ shows the current ON or OFF states of appliances. ON indicates that state is 1 while OFF represents that state is a 0.

The proposed model is only for rigid appliances. In next section, there is discussion about modelling of flexible appliances. Flexible appliances comprise interruptible and non- interruptible devices. Flexible appliances operation can be altered at any time. Its model is as follows.

$$C_{\mathrm{A}}(H) = (0,1), \mathrm{t} \in [S_{\mathrm{A}}, E_{\mathrm{A}}] \tag{4}$$
$$\sum_{S_{\mathrm{A}}}^{E_A} C_{\mathrm{A}}(H) \times D_{\mathrm{A}} = E_{\mathrm{A}} \tag{5}$$

The operation of non-flexible appliances cannot be interfered until its operation is ended. Its model is discussed in [27] and can be given as

$$\sum_{h=m+1}^{m+D_{\mathrm{A}}} P_{\mathrm{A}}(H) \geq n_{\mathrm{A}} \left[C_{\mathrm{A}}(m+1) - C_{\mathrm{A}}(m)\right] \tag{6}$$

The range of *'m'* is

$$m \in [S_{\mathrm{A}} - 1, E_{\mathrm{A}} - U_{\mathrm{A}}] \tag{7}$$

n_{A} is the uninterrupted total operational time which is necessary for non-flexible appliances take to complete their action. It is probable that operation of appliances is disrupted due to high consumption cost or unobtainability of energy during that time. So, at this time, BSS will supply energy to appliances to finish their process. The model of battery is described as follows.

The charging and discharging of BSS will be done according to RTP and consumers preferences. Normally charging of BSS will take place during low RTP. The model is depicted as follows.

$$D_{\mathrm{BSS}}^{ch}(h) = \frac{D_{\mathrm{BSS}}^{ch}(h)}{\eta_{\mathrm{ch}}} . C_{\mathrm{BSS}}(H) \tag{8}$$
$$D_{\mathrm{BSS}}^{ch}(h) = D_{\mathrm{BSS}}^{\mathrm{dch}}(h) . \eta_{\mathrm{dch}} \left(1 - C_{\mathrm{BSS}}(h)\right) \tag{9}$$
$$D_{\mathrm{BSS}}(h) = D_{\mathrm{BSS}}^{\mathrm{ch}}(h) - D_{\mathrm{BSS}}^{\mathrm{dch}}(h) \tag{10}$$

The range of $\frac{D_{\mathrm{BSS}}^{ch}(h)}{\eta_{\mathrm{ch}}}$ and $D_{\mathrm{BSS}}^{ch}(h) . \eta_{\mathrm{dch}}$ are

$$0 \leq \frac{D_{\mathrm{BSS}}^{ch}(h)}{\eta_{\mathrm{ch}}} \leq D_{\mathrm{ch}}^{\max} . C_{\mathrm{BSS}}(H) \tag{11}$$

$$0 \leq D_{\mathrm{BSS}}^{\mathrm{dch}}(h).\eta_{\mathrm{dch}} \leq D_{\mathrm{dch}}^{\max}.(1-C_{\mathrm{BSS}}(H)) \quad (12)$$

where $D_{\mathrm{BSS}}(h)$ shows total power supplied by BSS. If it has positive value, then it signifies charging and negative value indicates discharging. Maximum charge and discharge are represented by $D_{\mathrm{ch}}^{\max}$ and $D_{\mathrm{dch}}^{\max}$. The state of charge $S(h)$ associated with BSS is described as follows.

$$S(h+1) = S(h) + \frac{(D_{\mathrm{BSS}}^{ch}(h) - D_{\mathrm{BSS}}^{\mathrm{dch}}(h)).h}{D_{\mathrm{BSS}}} \quad (13)$$

$$S^{minmum} < S(t) < S^{maximum} \quad (14)$$

III. PROBLEM FORMULATION

The proposed mathematical model suggests an optimal home appliance scheduling along with PV, BSSS and H2G framework. The minimization of objective function will be done in ter ms of low c ost. W hen R TP is low, the ho me appliances from main power grid. Otherwise, they will try to fulfil energy demand from PV and BSS. At each per half hour slot, the total power consumed is given as:

$$D_{\mathrm{T}}(h) = \sum_{p+q}^{p+q} C_{\mathrm{A}}(H) \times D_{\mathrm{A}} + D_{\mathrm{rigid}}(h) \pm D_{\mathrm{BSS}}(h) - D_{\mathrm{PV}}(h) \quad (15)$$

The power utilized by all typ es of ap pliances will be equal to sum of all operational appliances at a ny tim e interval. Therefore, the objective function becomes

$$\boldsymbol{min} \sum_{x=1}^{48} [D_{\mathrm{T}}(h).\delta h).RTP] \quad (16)$$

subject to:

$$D_{\mathrm{T}}(h) \leq D_{\mathrm{L}}(h) \quad (17)$$

$$\sum_{x=1}^{48} \sum_{A=1}^{p+q} C_A(h) = \sum_{A=1}^{p+q} U_A \quad (18)$$

where $D_{\mathrm{L}}(h)$ is maximum demand limit. The whole power consumed in smart home m ust be less than a threshol d value durin g scheduling. Flexible ap pliances are denoted by p whole non-flexible appliances are represented by q.

IV. PROPOSED CSOA ALOGRITHM FOR HEM

CSOA is a heu ristic algorithm based upon intellectual food seeking act of crows. The flack of crows remembers the initial position durin g f ood search ing p rocess in this algorithm. The new position during f ood search ing procedure of crows will be assessed by fitness estimation. The meth od is repetitive until the best possible status is obtained [21]. In this approach parameters, I_{max}, N_V, P_s, F_C, and P_C are initially ad justed. I_{max} is the total number of iterations while N_V and P_s indicates the quantity of variables and crows, respectively . P_C an d F_C are and awaren ess probability of crows flying and flight length, respectively. Besides, x_c specifies the initial position of crows. Firstly, a random number is generated and equated to P_C, and if the P_C is greater than the random number then the crow moves arbitrarily in the search sp ace. Otherwise, the crow (C_m) randomly chooses any crow am ong flack (C_n) an d the n tracks C_n to deter mine the po sition of its secret diet. The newest position for the crow (C_m) can be concluded as:

$$C^{m+1, I_n+1} = C^{m, I_n} + r_i \times F_C{}^{i, I_n} \times (C^{n, I_n} - C^{m, I_n}) \quad (19)$$

where r and I_n characterize a random number and iteration, respectively. This process will be rep eated for N_V. The pseudocode of CSOA for HEM system is presented as follows.

Proposed CSOA Algorithm for HEM

```
Generate the population of crows Xn (n=1, 2, ..., q)
Calculate the fitness of each crow
Initialize the memory of crows
while ( In < Imax )
 for each crow
     Define Ps (Probability of awareness)
     Generate r (Random number)
       if r ≥ Ps
        Update position of crow by equation (19)
      else
        Generate random position of crow
       end if
 end for
     Probability of new crows positions assessment
     Fitness assessment of all crows
     Update the memory of all crows
In = In + 1
end while
return the best crow
```

V. RESULTS AND DISCUSSION

The appliances consumption data, RTP signal an d PV generation information are taken from [28] for this stud y. Fig.2 gives the c onsumer dai ly load , PV, a nd RTP. Five different scena rios are i nvestigated in this pap er as demonstrated i n Tab le I i n this study. Simu lations are executed on a PC with MATLAB software on W indows platform. T he computational time tak en by the CSOA based HEMC in HEM system is 30-35 seconds.

TABLE I. DIFFERENT SCENARIOS

H2G	Scenario	PV	ESS
Without H2G	A	No	No
	B	Yes	No
	C	Yes	Yes
With H2G	D	Yes	No
	E	Yes	Yes

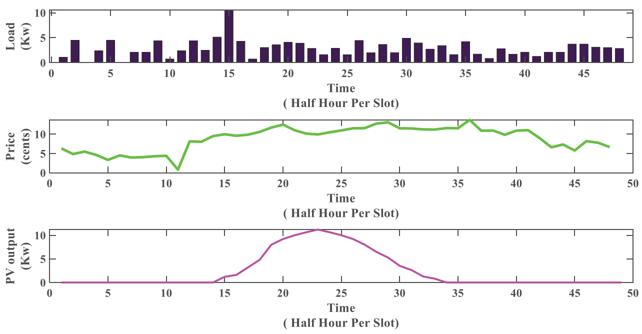

Fig.2. (a) Consumer half-hourly based load, (b) RTP signal and (c) PV data

In scenario (a), the main power grid only accomplishes the e lectrical r equirements of consumers. Fig. 3 an d 4 illustrates the load an d elect ricity co nsumption co st per day. T he electricity co nsumption co st o f sc enario (a) is 312.26 cents as shown in Fig. 5. In scenario (b), consumer installs P V. Both PV and main power grid satisfy the consumer’s energy dem and. The load requirem ents are accomplished by the PV on a sunny day. During low PV output, the main power grid satisfies the energy requirements of consumer. The daily half hour-based load in kW and cost in cents of this scenario are mentioned in Fig. 3 and 4 respectively. The operational cost of scenario (b) is 279.53 cents as shown in Fig. 5.

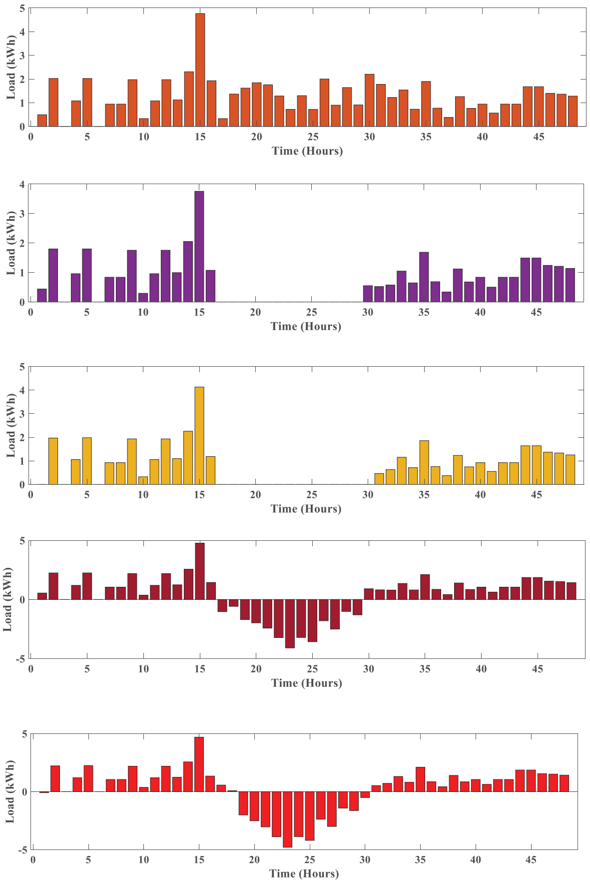

Fig.3. End-user daily load for scenerios (a)-(e)

In scenario (c), the system comprises PV, ESS, main power grid without H2G. The precedence energy source is PV i.e., cost-effective as compared to importing energy from the main power grid. The energy is also imported during the high demand periods from the main utility grid and when PV output is not adequate. Fig. 3 and 4 portrays the load and electricity consumption cost, respectively. In this case, cost is observed by 261.93 cents. The electricity consumption cost shown in Fig. 5 that is lesser than the cost in scenario (a) and scenario (b). In scenario (d), the H2G exchange is also permissible. The PV is the significant energy resource during the day to fulfil the load necessities. Fig. 3 and 4 shows the half-hourly based appliances load accompanied by the electricity consumption cost, respectively. The total electricity consumption cost during this scenario is 249.34 cents that are depicted in Fig. 5.

For scenario (e), the ESS is integrated with the PV and main power grid. At First, all energy demand is accomplished through ESS and PV. Also, the excess energy from ESS and PV are directed back to the main power generation source to reduce the electricity consumption cost and power grid resilience. Fig. 3 and 4 shows values of half hourly based load and electricity consumption cost, respectively. The electricity consumption cost observed, in this scenario, is 158.67 cents, that is the minimum consumption cost in comparison to other situations as shown in Fig. 5.

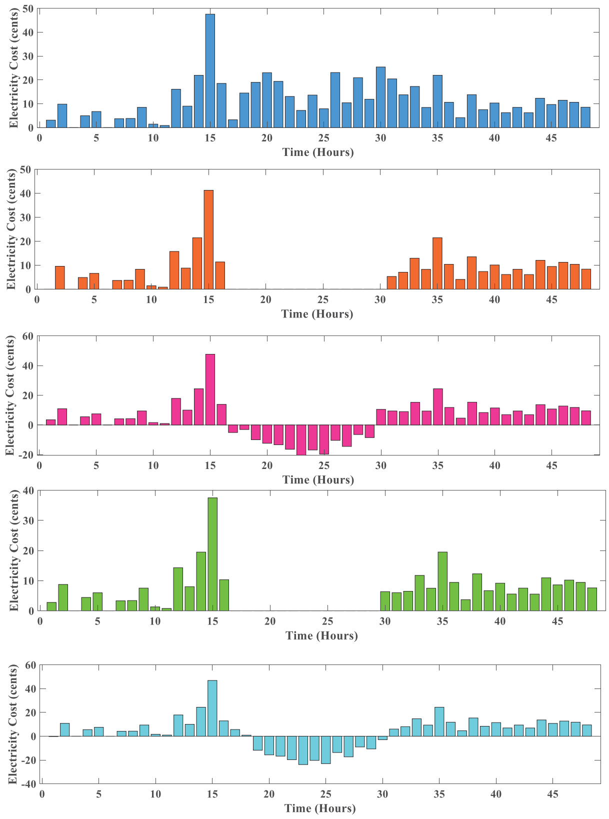

Fig.4. End-user daily consumption cost for scenerios (a)-(e)

The comparison of daily electricity consumption cost among different scenarios can be visualized from Fig. 5. Furthermore, the comparison of consumption cost results by different approaches for scenario (e) has been presented in Table II. It can be observed that the proposed CSOA gives better results of 158.67 cents as compared to all other approaches. GWO gives value of about 169.67 cents that is better as compared to PSO, GO and EWO that gives results of about 219.03, 241.45, and 199.32, respectively.

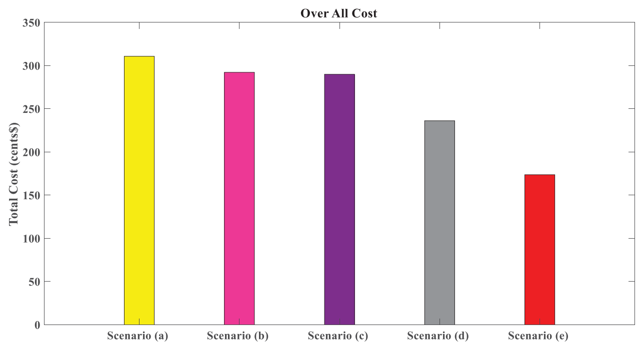

Fig.5. Comparison of day-based electrical consumption cost among all scenarios

TABLE II. COMPARISON OF CONSUMPTION COST WITH OTHER APPROACHES FOR SCENARIO WITH H2G, PV AND ESS

Approach	GA [21]	PSO [21]	GWO [27]	EWO [24]	Proposed CSOA
Consumption Cost (cents)	241.45	219.03	169.67	199.32	158.67

VI. CONCLUSION

This study presents an optimal HEMC incorporated with CSOA for the HEM system. The optimal scheduling is performed in the presence of both ESS and PV with H2G exchange environment. A dual-energy flow environment is generated in a smart home with a proposed HEM system framework by using RTP. ESS store energy under sunlight and supply excess energy to the grid when vital to minimize consumer electricity consumption costs while home appliances are also operated at the same time. The appliances taking supply from the main power grid are transferred to low-cost intervals. In this way, an intelligent HEM system is exploited to comfort electricity consumers. CSOA based HEMC gives the lower cost of 158.67 cents as compared to other approaches in the scenario with PV, ESS, main power grid with H2G exchange environment.

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