Microgrid economic operation considering electric vehicles integration

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Abstract— In this report, an economic dispatch model for a microgrid was developed. The power supply in microgrid normally consists of renewable energy power plants including wind and solar power plants and conventional power plants while using grid as backup power source. Recent years, with the increasing need of Blade Electric Vehicles(BEV), it is necessary to consider the influence of BEV on integrated microgrid. Due to the vehicle-to-grid(V2G) method, the charging load of BEV is also considered as the power consumer, which has significant impact on energy sources in microgrid. This report will present the individual model of each components of microgrid and use the Particle swarm optimization algorithm for economic dispatch when BEV was included and excluded. The simulation results showed that BEV with V2G method added in the microgrid could increase aggregator profits and improve the reliability and stability of the system.

Index Terms: economic dispatch, microgrid, V2G, PSO, EV.

I. Introduction

With the increasing concerns of environmental issue and trend in transportation electrification, electric vehicles technology has been developed rapidly in recent years. EV technology provides more opportunities to power grid and offers many benefits over internal combustion conventional engine in terms of impact on environment. However, a great amount of charging of EVs can cause stability issue to power system [1]. To alleviate the problem, [2] addressed the solution called technology of Vehicle to Grid(V2G). The power flow is bidirectional to EVs, which means the EVs are not only charging loads but also having potential roles to play as possible backup power resources. This technology brings many opportunities to grid. Quick-response of V2G can smooth fluctuations in both generation and demand sides such as load balancing by valley filling, peak load shaving. Ancillary benefits including frequency control and spinning reserves are also provided [3]. Meanwhile, the EV owners cost less with electricity subsidy from government by providing power back to grid. This report will present the benefits of using EV and V2G method in terms of economical dispatch. Mathematical model of conventional power plants, renewable energy source including wind and solar, battery and EV model will be shown first. Then, mathematical model to minimize the cost of power generations of the micro-grid will be established in the case study based on statistical data. Next, PSO algorithm is used to solve the economical dispatch problem with EV and without EV. The results of two situations will be compared to obtain the results that integrated microgrid with EV is more economical. In the end, further study and limitation of this project will be discussed.

II. Modelling

Wind

Wind and solar are most common sources widely used in microgrid. Different from the conventional power plants, the output power is not stable due to the uncertainties of energy sources. In wind power generation, the most important parameter is wind speed. Hence, it is essential to predict wind speed when considering the wind power generation. [4] addressed the four wind speed component combination wind speed mathematical model. In [5], wind speed distribution is assumed to be Rayleigh and Monte Carlo simulation is used to simulate the wind speed. In this report, Monte Carlo simulation based on Weibull Distribution (WD) is used to predict wind speed. The wind simulation is shown in the appendix. The general form of the Weibull distribution function, which is a two-parameter function, for wind speed is given as

$$f(v,k,c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-(v/c)^k} \tag{1}$$

$$k = \left(\frac{\sigma}{\mu}\right)^{-1.086} \tag{2}$$

$$c = \frac{\mu}{\tau(1+1/k)} \tag{3}$$

where $\tau(1+1/k)$ is the gamma function of (1+1/k); μ is the average value of recorded wind speed ; σ is the variance of sampled wind speed. Therefore, the two Weibull parameters of the wind speed distribution function, the shape parameter k(dimensionless) and the scale parameter c (ms) are related to the mean value of the wind speed. In the case study, k and c were computed from the wind speed data [10], which equal to 6.78 and 1.94.

The physical reality of power versus wind speed is that the power will vary with the cube of the velocity. Figure1 in the appendix shows the operation regions of wind turbine under different wind speed. The turbine starts at cut in speed and increases as wind speed increases until reaches the rated value. Then, turbine works in constant power region. Once the wind speed is higher than cut out wind speed, the turbine will be forced to stop for safety.

The mathematical model is shown in equation.[4]

$$P_w = \begin{cases} 0, v < v_i or v \geq v_o \\ P_n \dfrac{v^3 - v_i^3}{v_n^3 - v_i^3}, v_i \leq v \leq v_n \\ P_n, v_n \leq v < v_o \end{cases} \tag{4}$$

Solar

Similarly, solar power is dependent on radiation from the sun, and power generation from photovoltaic (PV) is directly related to this parameter. In [7] e Iqbal model and ASHRAE model are investigated and compared. Semi-sinusoidal model is used in this project.

$$Q(t) = A\sin\left(\frac{t-a}{b-a}\pi\right) \tag{5}$$

$$A = \frac{\pi}{2(b-a)} Q_a \tag{6}$$

where $Q(t)$ is the function of radiation with respect to time; a is the time of sunrise; b is the time of sunset.; A is the maximum value of the solar radiation of the day; Q_a is the total amount of radiation.

Output power of solar panel with respect to the Q is shown in the following equation:

$$Ps = \begin{cases} 0, Q = 0 \\ \eta P_{\max} Q / Q_n \quad ,0 < Q < Q_n \\ \eta P_{\max}, Q \geq Q_n \end{cases} \tag{7}$$

Where Q is the solar radiation intensity; Q_n is the radiation intensity measured in the standard environment. $P_{\max}$ is the maximum output power obtained in the standard environment; η is the battery efficiency (including the losses of converter, solar radiation losses, etc.)

Gas turbine

In microgrid, gas turbines are normally used as regular generation unit to ensure the stability of the system. Besides, it has low operating pressure and oil cost. The model is shown below [8].

$$C_r = \sum_0^T \rho B(t) \tag{8}$$

$$B(t) = (Q_r(t) + 3600 P_r(t)) / (\eta Q_{dw}) \tag{9}$$

$$Q_r(t) = \lambda P_r(t) \tag{10}$$

where C_r is the total cost of natural gas per gas turbine; ρ is the price of the natural gas; $B(t)$ is the amount (volumn) of gas needed at time t; $Q_r(t)$ is the heat produced by gas turbine; $P_r(t)$ is the output power; Q_{dw} is the calorific value; λ is the heat to power ratio of gas turbine; T is the total time.

Battery

In microgrid, power balance is impossible to achieve due to fundamental uncertainties inherent of the renewable energy unit. And combination with electrical energy storage could enable microgrid operate separately from electrical grid in a reliable and secure manner. Because of the lowest-cost of lead-acid batteries, in this paper, they are picked as backup power in microgrid model.

Many different battery models are discussed in [9]. For simplification, charging and discharging are approximated to be linear. Energy of the battery depends on the energy discharged from the battery and the charge energy put into the battery. The charging and discharging relationship are shown in the following equation.

$$E(t) = E(t-1) + (E_G(t) - E_L(t))\eta \tag{11}$$

$$E(t) = E(t-1) - (E_L(t) - E_G(t)) \tag{12}$$

where E is the battery energy; $EG(t)$ is the charging energy and $EL(t)$ is the discharging energy of the battery; η is the charging efficiency that is 0.793 in this mode, while the discharging efficiency is assumed to be 1.

EV

Vehicle to Grid, or V2G, technology of electric vehicles is an important method to solve this problem. EVs can both be used as power load absorbing excess energy when demand is low and be as power supply returning some energy when demand is high. Electric vehicles include Blade Electric Vehicles—BEV,Hybrid electric vehicle—HEV, Fuel cell electric vehicle—FCEV. In this paper, only BEV that only consumes electricity is taken into account.

when EV is charging:

$$E_{BV}(t) = E_{BV}(t-1) + \Delta P \eta \tag{13}$$

$$\Delta P = E_{\max} \frac{\Delta t}{t_a} \tag{14}$$

when EV is discharging:

$$E_{BV}(t) = E_{BV}(t-1) - \Delta P \tag{15}$$

$$\Delta P = E_{\max} \frac{\Delta t}{t_a} \tag{16}$$

where, $E_{BV}(t)$ is the state of charge at time t; $E\max$ is the maximum state of charge: ΔP is the change during time period Δt; t_a is the time for charging to full capacity; η is charge/discharge efficiency. In this paper, the assumption was made that the efficiency for discharging is 1 and the charging and discharging process of EVs is a linear function.

When EVs are integrated into microgrid, there are limits for state of charge(SOC) of EVs'battery. In this paper, the limit of SOC is 20%-90% of whole capacity. Meanwhile, for regular usage for EVs' owners like commuting, the SOC should not below 33% of the whole capacity.

III. PSO

The the PSO method was motivated by social behavior of organisms such as fish schooling and bird flocking. The basic idea about PSO is by comparing the fitness value during search process or iteration, each particle changes its position and speed until the optimal solution is found. Then the best previous position of the i-th particle $pbest_i$ and best particle among all the particles in the group $gbest_d$ could be obtained.

Let x and v denote a particle's position and its corresponding flight speed (velocity) in a search space, respectively. The modified velocity and position of each particle can be calculated using the current velocity and the distance from $pbest_{id}$ to $gbest_d$ as shown in the following formulas:

$$\begin{aligned} v_{id}^{(t+1)} &= w\, v_{id}^{(t)} + c1 * rand() * (pbest_{id} - x_{id}^{(t)}) \\ &+ c2 * Rand() * (gbest_d - x_{id}^{(t)}), \end{aligned} \tag{17}$$

$$\begin{aligned} x_{id}^{(t+1)} &= x_{id}^{(t)} + v_{id}^{(t+1)}, i = 1,2,...,n, \\ d &= 1,2,...,m \end{aligned} \tag{18}$$

Where, n is the number of particles in a group; m is number of members in a particle; t is number of iterations (generations); w is inertia weight factor; c_1, c_2 are acceleration constant; rand(), Rand() are uniform random value in the range [0,1]; $v_i^{(t)}$ is velocity of i-th particle at t-th iteration; $x_i^{(t)}$ is current position of i-th particle at t-th iteration. Particles' velocities on each dimension are clamped to a maximum velocity $V_{\max}$ which determines the resolution, or fitness. If $V_{\max}$ is too high, particles might fly past good solutions. If $V_{\max}$ is too small, particles may not explore sufficiently beyond local solutions. If the sum of accelerations would cause the velocity to exceed $V_{\max}$, then the velocity is limited to $V_{\max}$. In many experiences with PSO, $V_{\max}$ was often set at 10–20% of the dynamic range of the variable on each dimension.

The constants c_1 and c_2 represent the weighting of the stochastic acceleration terms that pull each particle toward the $pbest$ and $gbest$ positions which represent particles' realization of its own status and society environment. Low values allow particles to deviate far from the targeted regions before being pull back. And high values result in quick movement toward targeted regions while may push the particle past it at the same time. Hence, the acceleration constants are often set to be 2.0 according to past experiences.

Suitable selection of inertia weight provides a balance between global and local explorations, thus requiring less iteration on average to find a sufficiently optimal solution. This parameter is often set to be 0.8.

Steps:

1.Initialize the position and the velocity for each particle;
2.For each particle, calculate fitness value. And if the fitness value is better than the previous best fitness value, then set current value as the new $pbest$,and choose the particle with the best fitness value of all the particles as the $gbest$.
3.Update the position and the velocity for each particle according to equation (17) and (18).
4.While maximum iterations or minimum error criteria is attained, iteration terminates.

Penalty method

Penalty function was used in this paper to change constrained optimization problems into unconstrained problems. The solution of the latter converges to that of the original constrained problem.

The original problem is like following:

$$\begin{aligned} &\min f(x) \\ &g_i(x) \geq 0, i = 1,...,n \\ &h_j(x) = 0, j = 1,...,m \end{aligned} \tag{19}$$

where, $f(x)$、$g_i(x)$ and $h_j(x)$ are continuous; f(x)is objective function; gi(x)and $h_j(x)$ are constraints. Constraints are transferred to be part of objective function as following:

$$\begin{aligned} F(x) &= f(x) + f_1(x) + f_2(x) \\ f_1(x) &= C_1 \sum_{j=1}^{m} h_j^2(x) \\ f_2(x) &= C_2 \sum_{i=1}^{n} (\min(0, g_i(x)))^2 \end{aligned} \tag{20}$$

where, $f_1(x) and f_2(x)$ are penalty function. C1,C2are penalty parameters. Only when the constraints are not satisfied, the value of penalty function is nonzero.

IV. Economical dispatch strategy

without EV

In this part of report, system model not considering EV will be discussed. Renewable sources of energy are highly dependent on the weather conditions and geographic locations. Due to the unstable nature, renewable sources are not dispatchable. Wind and solar energy are consumed first, then gas turbines provide energy. Batteries storage system are used for the reliability of microgrid system, and the grid is used as a backup source when generation unit and battery storage could not meet the remaining load demand.

Objective function

The goal is to minimize the total generation cost. While generation cost functions are modeled with the inclusion of investment cost of equipment, maintenance cost of resources, cost of fuel in one dispatch period and energy transaction costs. Objective functions are shown in the equation

$$C_{total} = C_{\cos t} + \sum_{t=1}^{T}(C_{fuel}(t) + C_{buy}(t) - C_{sell}(t)) \quad (21)$$

$$C_{\cos t} = C_{\cos t}' / 365 \quad (22)$$

$$C_{\cos t}' = \sum_{i=1}^{n} M_i (C_{capital.i} \frac{r(1+r)^{N_i}}{(1+r)^{N_i} - 1} + C_{OM.i}) \quad (23)$$

The heat is provided by the gas turbine and fuel in this case is natural gas that costs 0.5 $\$ / m^3$. Bank rate r equals to 6%. C_{total} is total generation cost of the whole microgrid system. $C_{\cos t}'$ is investment cost. $C_{fuel}(t)$ is the cost of natural gas. $C_{buy}(t)$ is the cost of buying electricity from grid. $C_{sell}(t)$ is the profit of selling electricity to grid. T is one dispatch period. M_i is the number of generator unit. $C_{OM.i}$ is the maintenance cost. n is the number of distributed batteries in the microgrid.

equality constraints

$$\sum_{i=1}^{n1} P_{w.i}(t) + \sum_{i=1}^{n2} P_{s.i}(t) + \sum_{i=1}^{n3} P_{r.i}(t) + \sum_{i=1}^{n4} P_{bt.i}(t) + P_{Grid}(t) = P_{load}(t) \quad (24)$$

thermal balance

$$\sum_{i=1}^{n3} Q_{r.i} = Q_{load} \quad (25)$$

where $P_{w.i}(t)$ is the output power of wind turbine, $P_{s.i}(t)$ is the output power of PV, $P_{r.i}(t)$ is the output power of gas turbine, $P_{bt.i}(t)$ is the output discharging power of battery and negative value indicating that the battery is charging. $P_{Grid}(t)$ is the exchange power between microgrid and power grid. $P_{load}(t)$ is the load demand at time t. $n1, n2, n3, n4$ are number of corresponding generation unit.

inequality constraints

$$P_{wi.\min} \le P_{wi}(t) \le P_{wi.\max} \quad (26)$$

$$P_{si.\min} \le P_{si}(t) \le P_{si.\max} \quad (27)$$

$$P_{ri.\min} \le P_{ri}(t) \le P_{ri.\max} \quad (28)$$

$$E_{bti.\min} \le E_{bti}(t) \le E_{bti.\max} \quad (29)$$

where , $P_{wi.\min}$, $P_{si.\min}$, $P_{ri.\min}$ are minimum power output of each generation unit, while $P_{wi.\max}$, $P_{si.\max}$, $P_{ri.\max}$ are maximum power output of each generation unit ; $E_{bti.\min}$ is the lower limit of battery charge and $E_{bti.\max}$ is the upper limit of battery charge.

With EV

When EVs are integrated in the microgrid, they are potential energy storage unit as well. When all the other power generator could not meet load demand, battery and EVs could discharge to satisfy the load and power grid is still acting as backup. However, the discharging time of EVs should be regulated to ensure the demands of owners. There are four states of charge of EVs, the conditions should be satisfied anytime that the charge of the EVs should be within the bound of charging limits when are charged. In addition, the charge of EVs should be enough to meet owners needs after discharging to mircrogrid. The detailed constraints will be shown. C_{buy} should contain the part of money that is paid to the EVs' owner when the EVs discharge to microgrid.

equality constraints

$$\sum_{i=1}^{n1} P_{w.i}(t) + \sum_{i=1}^{n2} P_{s.i}(t) + \sum_{i=1}^{n3} P_{r.i}(t) + \sum_{i=1}^{n4} P_{bt.i}(t) + \sum_{i=1}^{n5} P_{ev.i}(t) + P_{Grid}(t) = P_{load}(t) \quad (30)$$

Thermal balance

$$\sum_{i=1}^{n3} Q_{r.i} = Q_{load} \quad (31)$$

where $P_{ev.i}(t)$ is the output discharging power from EV, while negative value indicates charging.

Inequality constraints

$$P_{wi.\min} \le P_{wi}(t) \le P_{wi.\max} \quad (32)$$

$$P_{si.\min} \le P_{si}(t) \le P_{si.\max} \quad (33)$$

$$P_{ri.\min} \le P_{ri}(t) \le P_{ri.\max} \quad (34)$$

$$E_{bti.\min} \le E_{bti}(t) \le E_{bti.\max} \quad (35)$$

$$\begin{cases} E_{evi.\min} \le E_{ev}(t) \le E_{evi.\max}; 20:00-6:00 \\ E_{ev}(t) > E_{\min}; 8:00-18:00 \end{cases} \quad (36)$$

where, $E_{evi.\min}$ is the minimum charge of EV when charging ; $E_{evi.\max}$ is maximum charge of EV when charging ; $E_{\min}$ is the minimum charge of EV when discharging ; $E_{ev}(t)$ is the maximum charge of EV when discharging

V. Case study

The case study was based on the microgrid system providing electricity and heat power to a building. The parameters of the corresponding distributed generations and load information are showed in table1 and figure 1. The heat is provided by the gas turbine and fuel in this case is natural gas that costs $0.5\$/m^3$. Bank rate r=6%.

Table 1. Parameters of distributed generation

<table>
<tr><th>Type</th><th colspan="2">Rated power /kW</th><th>Investment /cost($/ea)</th><th>Maintenance /fee($·)</th><th>Life time/years</th><th>Numbers</th></tr>
<tr><td>WT</td><td colspan="2">60</td><td>25,000</td><td>1,250</td><td>15</td><td>9</td></tr>
<tr><td>PV</td><td colspan="2">100</td><td>20,000</td><td>1,000</td><td>15</td><td>5</td></tr>
<tr><td>BT</td><td colspan="2">12</td><td>1,000</td><td>50</td><td>15</td><td>20</td></tr>
<tr><td>EV</td><td colspan="2">20</td><td></td><td></td><td></td><td>30</td></tr>
<tr><td rowspan="2">GT</td><td>Min /kW</td><td>Max /kW</td><td rowspan="2">25,000</td><td rowspan="2">1,500</td><td rowspan="2">15</td><td rowspan="2">6</td></tr>
<tr><td>10</td><td>65</td></tr>
</table>

WT-wind turbine; PV- Photovoltaic ; BT-battery; EV-electric vehicle; GT-gas turbine

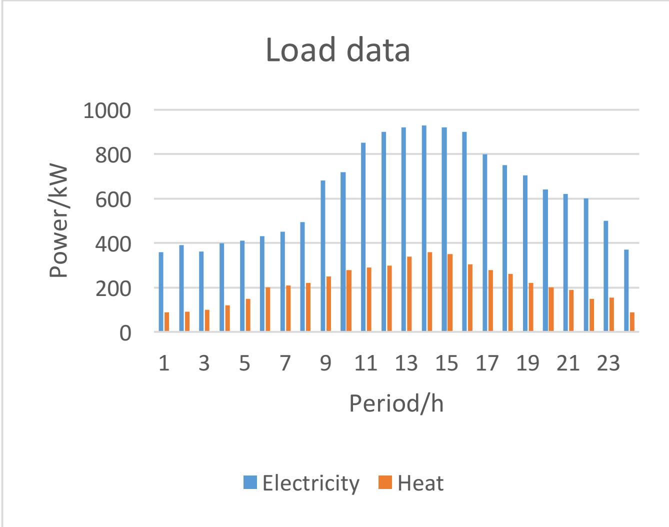

Fig1. Load

Without EV

The strategy without EV is following: when the generation is greater than load, extra power will charge battery first and sell power to grid if there is some left. When the generation is less than the load, battery will provide power first then buy power from grid if load demands are still not satisfied. The results showed that the cost for 24 hours without EV is 613$.

With EV

For the simplification, the assumption was made that the EV has 73% of the maximum charge when owners arrive the destination. While there will be 33% of the maximum charge left when the owners leave from work. Results showed that with EV participate as potential battery to the microgrid, the cost reduced to 487$.

The following figures show the matching of the load and generations. Without EV, there are large difference between total generation of microgrid and load, which means with the limited gas turbine, large amount of the power should be bought from grid or increase the equipment investment, both of which increase the cost. Also, the generation of heat are larger than demand when strategy satisfy electricity load first. While, with EV in the microgrid, EV providing electricity leads to less generation from gas turbine and grid, also reduce the waste of heat power. As a result, the total cost decreased.

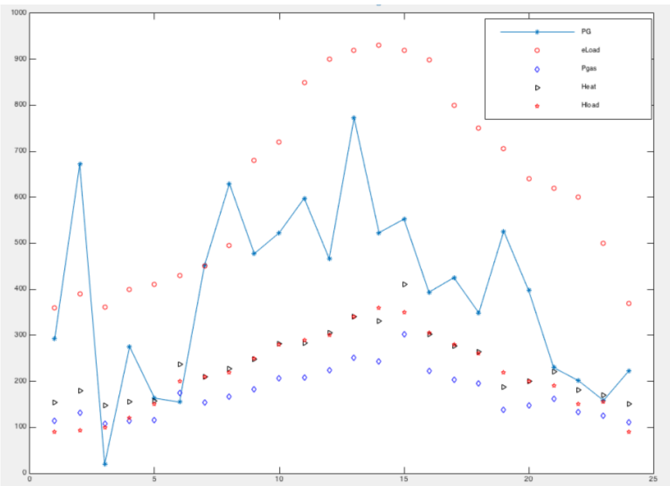

Fig2. Power generation without EV integrated

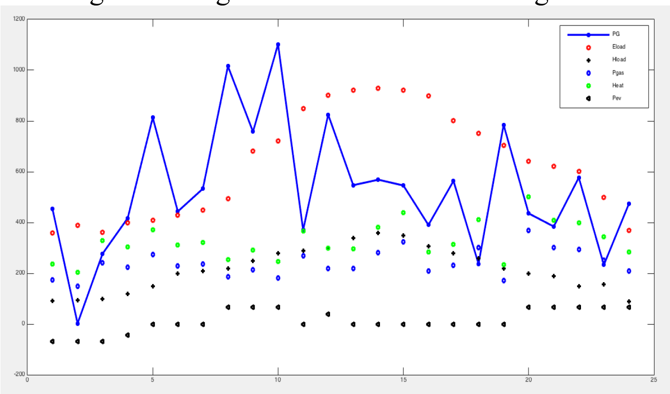

Fig3. Power generation with EV integrated

The profits made from adding EV to the microgrid comes from the fact that the electricity provided from EV is cheaper than the one from grid. In addition, EV owners also could gain profits from selling electricity to grid, which is a win-win situation.

VI. Conclusion

In conclusion, with the help of V2G technology, EV load could be a reliable power source in microgrid, which decreases the cost of the operation of microgrid and compensates the instability of renewable energy generation. In this report, pso algorithm was used to analyze the cost comparison between microgrid with EV and without EV. When load demand is high, microgrid buys electricity from EV owner with lower price instead of grid which reduces cost. The results showed that addition of EV increases the reliability and stability of microgrid. Meanwhile, total cost of operation and extra heat from gas turbine are decreased.

VII. Further study

Due to the simplification made in the model. The results could be more accurate. For example, the EV model could consider the more realistic situation about the time duration the owners use the vehicles and the actual charge in the battery. In addition, the more sophisticated charging and discharging strategies could be investigated to lower total cost. The model of wind and solar also could be improved be more realistic.

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Appendix

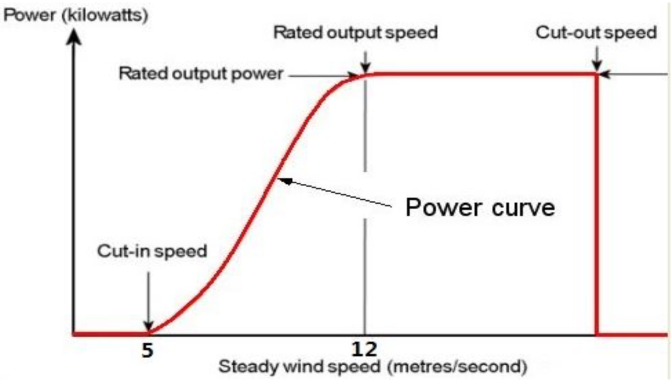

Figure1 . wind power curve against wind speed

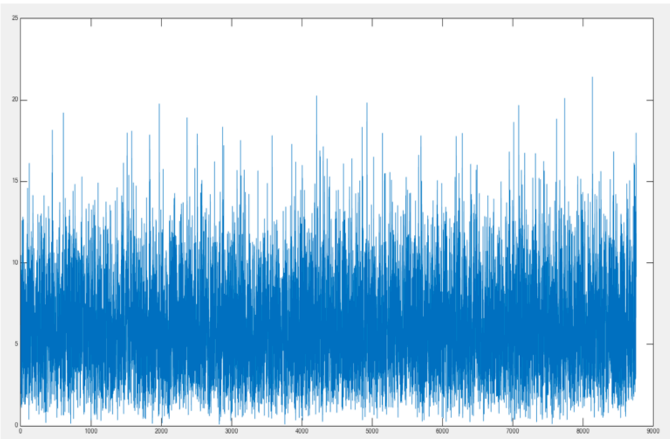

Figure2 . Wind speed simulation of whole year

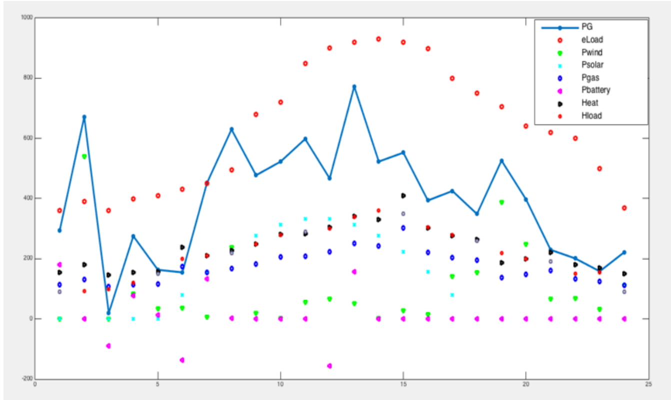

Figure3. Power generation without EV

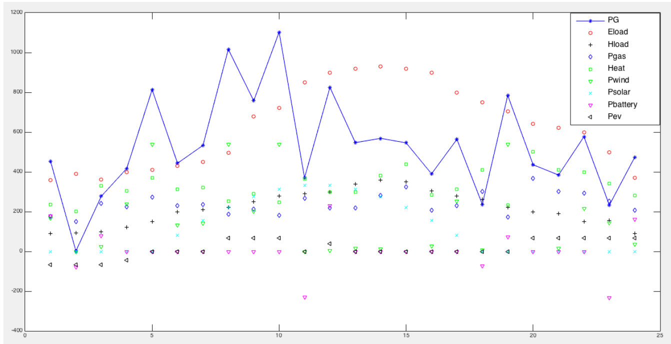

Figure4. Power generation with EV integrated