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Review on Optimal sizing of Battery energy storage for grid-tied Residential PV system

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***Abstract*—**Grid connected PV systems are proving to be worth considering in the adoption of renewable energy technologies. Among other renewable energies, grid connected PV systems continue to attract investors and electricity customers all over the world. Due to interconnection with the utility grid, the system can glean some benefits such as selling PV electricity surplus to the utility grid or purchasing electricity from grid for battery system charging at off peak hours either for self-consumption or selling back to the grid during peak hours. Significant research and development of various optimization methods have been conducted to improve cost, efficiency and system reliability of ES storage to reach a certain maturity in relation to their rise in electric grid. This paper review some of the pertaining works in the area and identifies relevant gaps.

***Keywords*——**Battery, electricity surplus, Grid connected PV, Residential, sizing.

I. INTRODUCTION

For most of the history of electric power systems, generation has been derived from large central-station plants due to economies-of-scale. Fossil-fuel plants have comprised the majority of this power generation[1].The need to reduce greenhouse gas emissions due to fossil fuels and the liberalization of the electricity market have led to large scale development of renewable energy generators in electric grids[2].Among renewable energy technologies such as hydroelectric, photovoltaic (PV), wind, geothermal, biomass, and tidal systems, grid-connected solar PV continued to be the fastest growing power generation technology, with a 70% increase in existing capacity to 13GW in 2008[3].

In many developing countries, reliable access to electricity is still a big challenge. Grids are sometimes characterized by insufficient power supply and frequent interruptions. Due to this fact, [4]some users who especially use classical grid-connected photovoltaic systems are unable to profit from their installations considering the intermittent nature of the solar. The requirement of an energy storage to a grid connected PV system is proving to be a prominent option. Grid-connected PV systems can produce higher energy than actually needed, especially during the summer. This extra energy is either stored in ESSs or fed back to the grid[5]. The aim of a battery energy storage incorporated in a PV system is to supply the load when PV generation is not sufficient or not available at all (rainy days or night). Despite the various benefits resulting from the adoption and integration of RES, studies have pointed that there are a number of challenges that need to be considered and handled. One of the practical and effective solutions to some of the issues is the deployment of energy storage systems. In [6], among all feasible types of energy storage technologies, a battery based energy storage system can be considered as widely used and fairly developed.

Limited supply, increasing costs and climate change concerns made it mandatory to increase the percentage of electricity generated by renewable energy sources[7]. The main drawbacks related to these sources are their dependence on weather, leading to undesirable fluctuations. Researchers are underway in the growth of technologies for optimum utilization of these resources to extract maximum output energy. Several studies have been carried out to find an optimum size of PV-Battery systems but mostly focuses of stand-alone configurations. This paper reviews some of the optimization techniques applied and investigate for possible gaps in knowledge which open new questions for further studies.

II. GRID-CONNECTED PV SYSTEMS

Grid connected PV systems can either be with or without Energy Storage Systems. The two systems can further be categorized into small, medium and large scale systems. Despite a great deal of benefits that comes out of these grid connected system, the generated power from PV systems varies greatly due to weather conditions, and consequently lead to unpredictable and intermittent power generation.

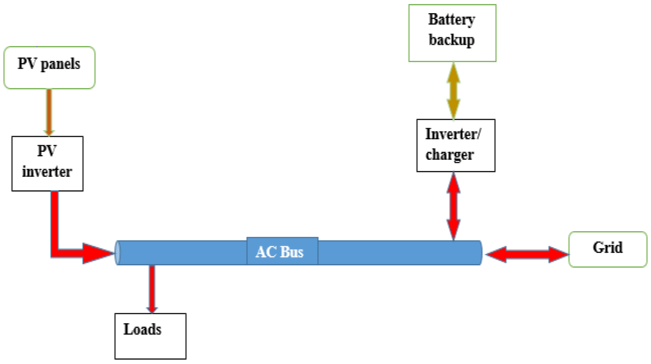

Fig. 1 Basic Topology of the Grid Connected PV System with BESS

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PV systems as well as other RES can in [8] be strategically integrated in power systems for grid reinforcement, reducing power losses and on-peak operating costs, improving voltage profiles and load factors, and improving system integrity, reliability, and efficiency. In a grid connected PV systems electricity is delivered all the way from panels straight to the households and to the utility grid through an inverter. PV panels generate electricity with higher amount of power during daytime of sunny days. During the night time and rainy or cloudy days, the utility grid or the battery storage supply the electricity to the loads. When the PV system production is higher than the demand, the surplus can be benefited from by selling it to the utility grid.

In spite of grid connected PV systems being in different sizes, the main components basically include PV panels, inverters, utility grid, net metering.

The PV module includes several PV cells, which are arranged in series and parallel to meet the energy requirements[9]. Harnessing the maximum output power from a PV source is a big challenge especially in the case of repetitive partial shading. PV array basically consists of n parallel-connected strings and m series-connected modules per string, i.e. an array with a dimension of (m × n).

Elserougi *et al* in [10] presented a switched PV approach in which each string can be reconfigured to form two parallel strings of m/2 modules per string resulting in a new array with a dimension of (m/2 × 2n)+

A PV array can be different in sizes with the amount of PV modules attached to the array. The major purpose of the PV array is to convert the power of the sun rays into DC power.

An ideal PV cell is generally characterized by a single diode [11] or double diode model. The basic equation that mathematically expresses the I-V characteristic of the ideal PV cell is:

$$I = Isc - I_0\left(e^{\frac{vq}{KT}} - 1\right) = I_{sc} - I_d \qquad (1)$$

Where I_{sc} is Photocurrent, I_0 is Reverse saturated current of the diode, q is the Charge of the electron, K is the Boltzmann constant and T is the Operating temperature in Kelvin.

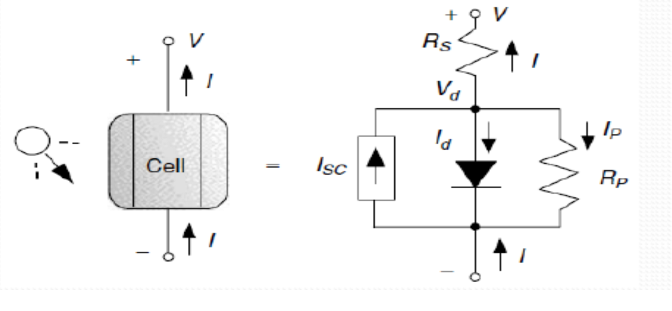


Fig. 2 Identical circuit of a practical PV device

For practical implementation of PV array several PV cells need to be connected in series or parallel and it requires additional parameters to be considered in the basic equation. The basic equation for current and voltage is therefore written as:

$$I = I_{sc} - I_0\left[e^{\frac{(V+IRs}{aVt}} - 1\right] - \frac{V+IRs}{R_p} \qquad (2)$$

Where I$_0$ is the saturation current, I_{sc} is the photovoltaic current, V$_t$ = NskT/q is the thermal voltage of the array Rs and Rp are the equivalent series and parallel resistance of the array respectively.

III. OPTIMIZATION PROBLEM FORMULATION

In any optimization process, researchers basically seek to find an optimal solution of an objective function given some constraints and variables that need to either be maximized or minimized. In a grid-connected PV-Battery configuration, the variables to be optimized are essentially different costs associated with the operation of the entire system. In order to account for these different variables in the optimization problem, researchers try to take into account the impact of each component of the system, ranging from PV modules to different inverters. The most common usually taken into account include :PV generation, Grid electricity, Battery storages, Loads, inverters etc [2][12][13].

a. Grid Energy

In a grid-connected PV system, electricity can either be purchased from or sold to the grid. Grid tariffs are usually defined as a function of time because they vary dynamically depending on different parameters such as: the amount of power demanded by the local loads, fuel prices, available generation and equipment outages. The grid energy costs are basically expressed as power from/to grid multiplied by the electricity price:

$$C_{grid}(t) = E_{Price}(t) * P_{grid}(t) \qquad (3)$$

Where $C_{grid}(t)$ is the cost of grid energy, $E_{Price}(t)$electricity price and $P_{grid}(t)$ amount of energy imported from the grid.

b. PV energy

With the rapid advancement of technology in Renewable Energy Resources, a wide range of data is now available online at any location. The radiation reaching the earth's surface is decomposed into different components and can be accessed. Global Horizontal Irradiance (GHI) is of particular interest for PV installation and it includes both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) and each contributes to the total apparent energy incident on the PV modules.

TABLE I
PRICES OF SOLAR PANEL SYSTEMS IN THE MARKET

PV size	Price Range	Price per KW
3KW	\$5,000 - \$6,500	\$1,667/KW - \$2,167/KW
4KW	\$6,500 - \$7,500	\$1,625/KW - \$1,875/KW
5KW	\$7,500 - \$8,500	\$1,500/KW - \$1,700/KW
10KW	\$13,000 - \$16,000	\$1,300/KW - \$1,600/KW

Once the insolation, incident on a PV panel, is known, its output power (P_{pv}) can easily be estimated by the following equation:

$$P_{pv} = R * \cos(\theta) * n_m * A_p * n_{pv} \tag{4}$$

Where R is solar radiation (w/m^2), θ is the angle of incident, n_m is efficiency of the MPPT, A_p area of the PV panel and n_{pv} is efficiency of the PV panel. Table I shows the prices of the fully installed solar panel system with different sizes in the market[14]

c. Battery storage

There are three main types of lead acid battery generally used in RE, namely flooded type, gelled electrolyte sealed and AGM battery. Flooded type batteries are considered to be the most economical and widely used in PV systems. However, they need continuous maintenance and must be used in ventilated location. Both gelled electrolyte and AGM type are suitable for closed type system because they are sealed types and do not require maintenance or ventilation [2][15].

The battery dynamic behavior need to be considered and it is expressed in the following dynamic equation[2]

$$\frac{dE_B(t)}{dt} = P_B(t) \tag{5}$$

Where $E_B(t)$ the amount of energy is stored in the battery at time t and $P_B(t)$ is the charging/discharging rate at time t

IV. METHODS AND OPTIMIZATION TECHNIQUES FOR BATTERY SIZING

Various methods and techniques have been developed for optimal sizing of both REs and storages in recent years. Some of these techniques include multi-objective function usually focusing on smoothing output fluctuations and cost of the systems. This part of the paper summarizes some of the optimization techniques used for battery sizing in either on grid or off grid PV systems. Existence of optimization methods can be traced to the days of Newton, Lagrange, and Cauchy.

High-speed digital computers made implementation of the complex optimization procedures possible and stimulated further research on newer methods. The desire to optimize more than one objective or a goal while satisfying the physical limitations led to the development of multi-objective programming methods. Artificial intelligent methods are the most commonly used techniques in optimization due to their execution speed, accuracy and guarantee for global optima.

Many conventional optimization techniques have been designed to solve a wide range of optimization problems, such as LP, NL P, DP or CO. However according to Gavrilas *et al* [16], some of the existing conventional optimization techniques applied to real world problems suffer from a marked sensitivity with respect to problems such as: difficulties in passing over local optimal solutions; risk of divergence; difficulties in handling constraints or numerical difficulties related to computing first or second order derivatives. To overcome these problems, several heuristic and metaheuristic techniques have evolved in the last decades.

TABLE II
PSEUDOCODE FOR GENETIC ALGORITHM

```
• Data: population size N, crossover rate $\eta_c$ and mutation $\eta_m$
• Initialization: create initial population $P = \{P_i\}, i = 1 \dots N$, and initialize the best solution $\mathbf{Best} \longleftarrow \mathbf{void}$.
• WHILE {stopping criterion not met}
    • Evaluate P and update the best solution Best
    • Initialize offspring population $R \longleftarrow \mathbf{void}$.
    • Create offsprings:
        FOR k = 1 TO N/2 DO
            • Select stage: select parents $Q_1$ and $Q_2$ from P, based on fitness values.
            • Crossover stage: use crossover rate $\eta_c$ and parents $(Q_1;Q_2)$ to create offsprings $(S_1;S_2)$.
            • Mutation state: use mutation rate $\eta_m$ to apply stochastic changes to $S_1$ and $S_2$ and create mutated offsprings $T_1$ and $T_2$.
            • Add $T_1$ and $T_2$ to offspring population:
                $R \longleftarrow R \cup \{T_1 \text{ and } T_2\}$.
    • replace current population P with offspring population R: $P \longleftarrow R$.
    • elitism: replace the poorest solution in P with the best solution stored in Best
```

There is quite a number of these methods and even though they work differently, research shows that all of them can optimize same problems.

Jiaming [14] suggested a GA algorithm to jointly optimally size the PV and battery systems by adjusting the battery charge and discharge cycles according to the availability of solar resource and a time-of-use tariff structure for electricity. In his work, the optimization took into account both PV and Battery sizing simultaneously for a household.

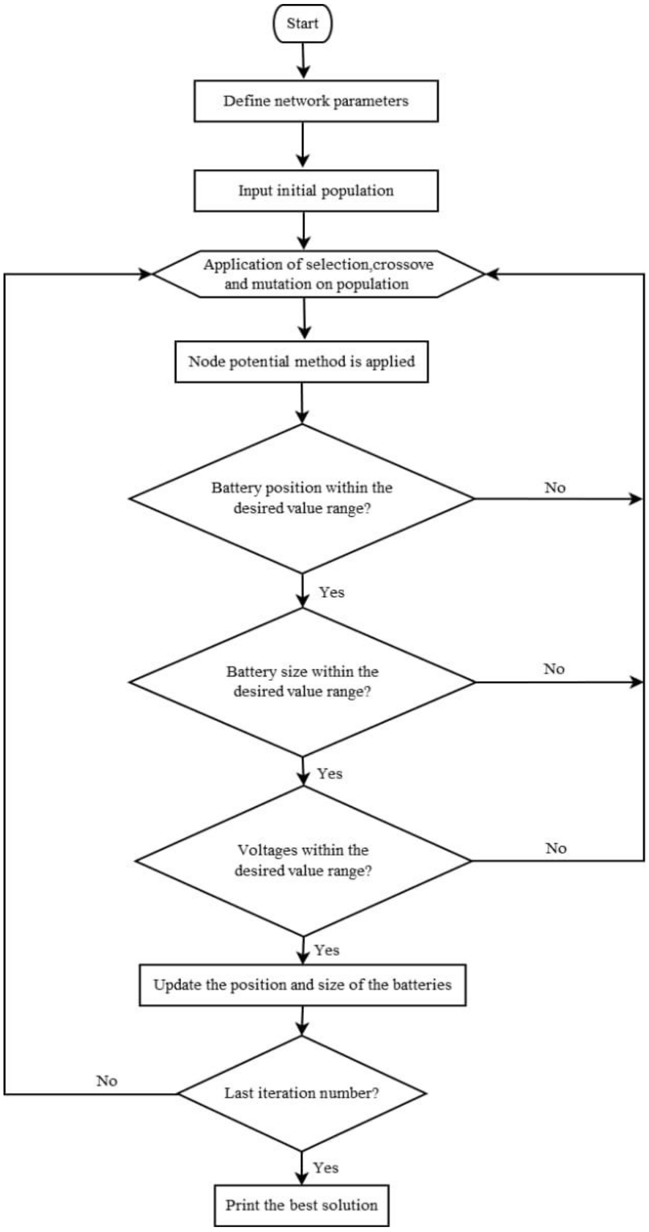


Fig.3 Flow chart of the Genetic Algorithm

The goal of Genetic Algorithm in his work was to find optimal battery size (C_{mx}) and solar size panel M. that could maximize the fitness function. The cost of battery per day and solar panel cost measurements per day were defined in Eq (6) and Eq (7) respectively.

The cost of battery per day ρ is expressed as:

$$\rho = \frac{N*B*\beta*E}{365*Y_B} \tag{6}$$

Where N is the number of battery needed, B is β is unitary price of battery, E cost of battery accessories and Y_B is battery warranty.

The cost of solar panel per day is also expressed as:

$$\Psi = \frac{\alpha*M*\Phi}{365*Y_S} \tag{7}$$

Where α is the solar panel cost ($/KW), $M$is the size of solar panel, Y_S is warranty of solar panel.

The total house energy related cost that needs to be minimized is

$$\zeta_i = S*B*\beta*\rho*\Psi*F \tag{8}$$

Where S is the cost of electricity supply for the house, B is the cost of electricity supply for charging battery, and F is the electricity service fee.

The proposed technique was tested and the optimal solutions were obtained to achieve energy cost saving. In order to evaluate the quality of the proposed method, two scenarios were investigated. Individual PV generation and storage of each house as well as group house optimization were performed. Results showed that although individual optimal batteries can significantly reduce energy cost, a group battery offers more value for cost saving, especially for groups with sufficient diversity in their demand profiles.

In [17], Wong *et al* proposed a Firefly- based method in mitigating the voltage rise by optimally locating and sizing the Battery energy storage system in PVDG integrated distribution network. The FA is normally presented based on three assumptions that are:

- All fireflies are of the same sex and consequently the attraction between each firefly is independent;
- The brightness of fireflies are different and the attraction between changes proportionally;
- The brightness of a firefly is decided by the objective function.

There are two main components consisted in FA namely, variation of light intensity and the formulation of attractiveness.

In this paper he proposed two optimization processes to obtain the optimal battery size. In the first optimization process, an enhanced opposition-based firefly algorithm (EOFA) was developed to get the optimal average hourly Battery Energy Storage System active output power for the PVDG integrated system. This optimization was used satisfy the system constraint that required the voltage deviation of the PVDG buses to remain within the range of 0.95 p.u. to 1.05 p.u.

A BESS state of charge (SOC) was considered and calculated each sample time as:

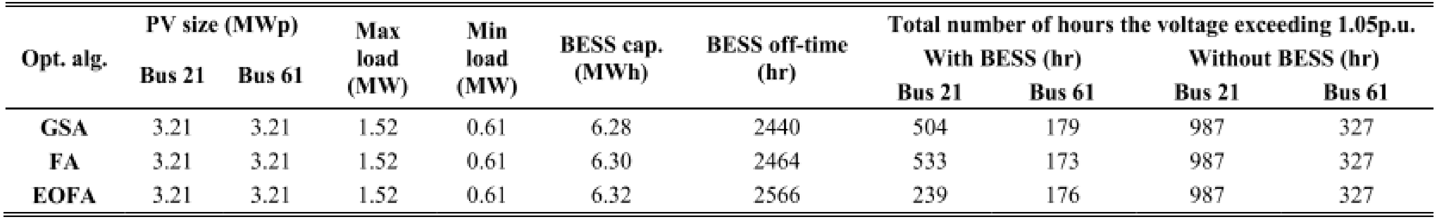
$$SOC = 100\left(1 - \frac{\int I_{bs}dt}{Q}\right) \tag{9}$$

Where $I_{bs}$the Battery current, t is the time instant and Q is the Battery capacity (Ah).

According to Ref [17], The EOFA is an improved version of FA with the integration of opposition-based learning and inertia weight function. The opposition-based theorem in this technique is used in the initialization process and the firefly location updating process.

TABLE III

COMPARISON OF PERFORMANCE FOR GSA, FA AND EOFA IN BATTERY SIZING FOR TWO PVDG INSTALLED POWER SYSTEM WITH SINGLE BESS



Opt. alg.	PV size (MWp)		Max load (MW)	Min load (MW)	BESS cap. (MWh)	BESS off-time (hr)	Total number of hours the voltage exceeding 1.05p.u.			
							With BESS (hr)		Without BESS (hr)	
	Bus 21	Bus 61					Bus 21	Bus 61	Bus 21	Bus 61
GSA	3.21	3.21	1.52	0.61	6.28	2440	504	179	987	327
FA	3.21	3.21	1.52	0.61	6.30	2464	533	173	987	327
EOFA	3.21	3.21	1.52	0.61	6.32	2566	239	176	987	327

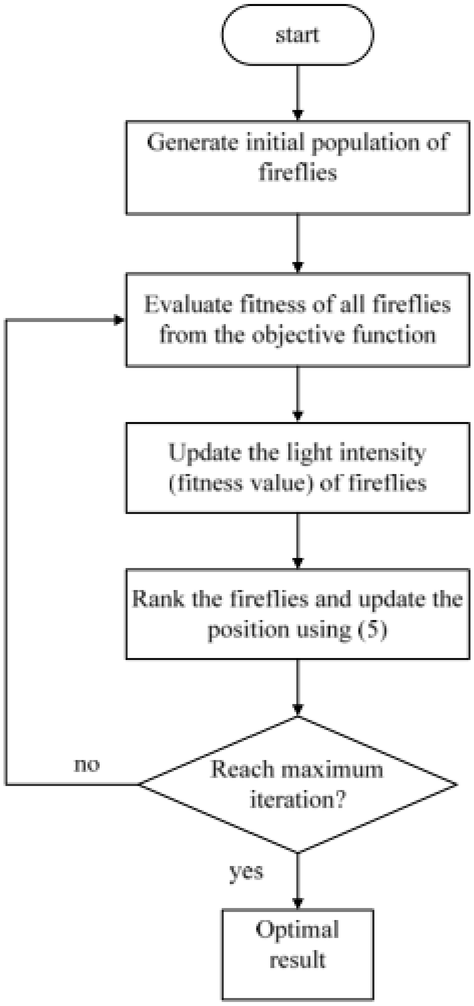


Fig. 4 Basic flow chart for Firefly Algorithm

The quantum Inspired Binary Firefly Algorithm (QBFA) which is also an improved discrete version of Firefly algorithm was used in Wong's paper to find the optimal location for the Battery Energy Storage System. It basically provides binary output of either '1' or '0'. Fig. 3 shows a basic flow chart for Firefly optimization method. The two optimization algorithms, QBFA and EOFA, have been applied in order to obtain the optimal BESS location and capacity respectively.

The techniques were tested on IEEE 69-Radial Bus system for the both the location and sizing to the BESS and the results were compared with GSA and the original firefly algorithm and the proposed algorithm proved to perform better as shown in table below.

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In Ref. [13] a Fuzzy Clustering Method (FCM) is used to determine battery capacity in a grid-connected PV/storage system with respect to optimal scheduling of the battery. The main goal of this paper was to provide an optimization method that helps electricity consumers equipped with PV system to make decisions to install economically sized battery storage system.

Fuzzy Clustering Method normally try todissimilarity from any given data point to a cluster center multiplied by membership grade of that data point. It is calculated on the base of the degree of memberships assigned to cluster center of each group.

TABLE IV

PSEUDOCODE FOR PARTICLE SWARM OPTIMIZATION

```
• Data: population size $\mathbf{N}$, personal-best weight $\boldsymbol{\alpha}$, local-best weight $\boldsymbol{\beta}$, global-best weight $\boldsymbol{\gamma}$, correction facto r$\boldsymbol{\varepsilon}$.
• Initialization: create initial population $\mathbf{P}$.
• WHILE {stopping criterion not met}
    • Select the best solution from the current P: Best
    • Select global-best solution for all particles: $\mathbf{B^G}$.
    • Apply swarming:
      FOR k = 1 TO N DO
          • Select personal-best solution for particle $\mathbf{X_i}$: $\mathbf{B_i^P}$.
          • Select local-best solution for particle $\mathbf{X_i}$: $\mathbf{B_i^L}$.
          • Compute velocity for particle $\mathbf{X_i}$:
            FOR j = 1 TO DIM DO
                • Generate correction coefficients: $\mathbf{a} = \boldsymbol{\alpha}$.
                  rand(); $\mathbf{b} = \boldsymbol{\beta} \cdot$ rand(); $\mathbf{c} = \boldsymbol{\gamma} \cdot$ rand().
                • Update velocity of particle $\mathbf{X_i}$ along dimension $\mathbf{j}$:
                  $\mathbf{V_{ij}} = \mathbf{V_{ij}} + \mathbf{a} \cdot (\mathbf{B_{ij}^P} - \mathbf{X_{ij}}) + \mathbf{b} \cdot (\mathbf{B_{ij}^L} - \mathbf{X_{ij}}) + \mathbf{c} \cdot (\mathbf{B_j^G} - \mathbf{X_{ij}})$
          • Update position od particle $X_i$: $X_i = X_i + \varepsilon \cdot V_i$
```

The objective function of the Fuzzy Clustering Methods was formulated in work as in eq (10).

$$F(X;U;V) = \sum_{j=i}^{c}\sum_{k=1}^{N}(u_{jk})^m \left\|X_k - V_j\right\|_{NI}^2 \tag{10}$$

Where $X = [X_k]$ is a vector of data points, $U = [u_{jk}]$ and $V = [V_j]$ are vectors of the resulting degrees of membership and prototypes for clusters respectively, and NI is the norm.

The objective function in this paper was a function of Battery capacity and the later is a function of battery charging/discharging rate. For all combinations of batterey capacities ranging from 3 to 30 KWh and maximum allowed peak demand ranging from 800 to 1800W, optimization problem for each of the typical days is solved to find the best combination which minimizes the operation cost of the system during all the studied days.

Two time-varying pricing structures, a time-of-use rate without specifying demand charge and a time-of-use rate with demand charge were considered in this study.

Optimal sizes of battery storages for a typical residential customer with PV system under both of the tariffs were determined. The results illustrated that, sizing optimization for Battery used in PV/storage system highly depends on electricity rates and battery aging cost.

M. Badawy *et al* [12]proposed a two layers optimization procedure using PSO technique to optimize the battery size of grid-tied PV system. Inner and outer optimization layer. In the inner layer, the optimization is carried out to obtain optimal SOC scheduling for an evaluated time period such that the running cost of the whole system can be minimized. On the other hand, the outer optimization is performed to determine the optimal battery size taking the dynamics of the considered system into account. He developed and implanted a PSO algorithm in both optimization layers to find the optimal battery size at the minimum operating cost.

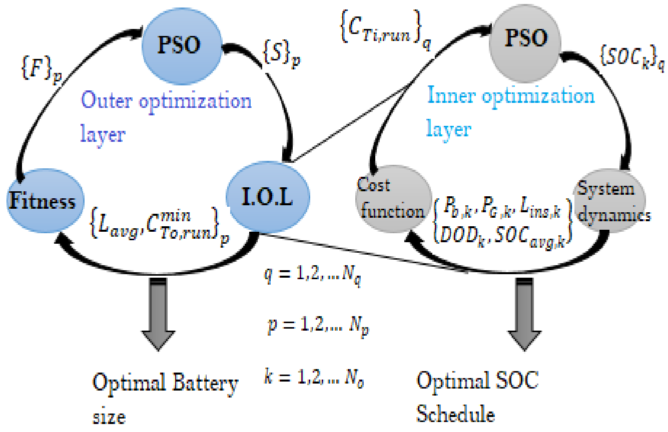

Fig. 5 Proposed optimization procedure for battery sizing

During the optimization stage, the PSO starts the computation with randomly selected particles, whose positions are updated for the next iteration based on their associated fitness function values

The results are analyzed and the optimal battery capacity along with its associated annual cost are presented in the paper.A case study is presented using a PV/battery powered energy system as an application. Different scenarios are applied to the studied system resulting in different sizing and power flow results.The case study results proved the system effectiveness in determining the optimal battery sizing under different operating scenarios.

V. DISCUSSION

In this review, we have realized that the amount of publications in the area of sizing energy storage, it is very clear that the current literature pertaining to this area of research has flourished. Significant approaches towards associating ESS with grid connected Renewables have been achieved. Regarding grid connected PV systems with battery energy storage, most researches have been considering high penetration of PV and focusing on smoothing out its output fluctuation fed into the grid. Recent important studies and development have been conducted to improve cost, efficiency and reliability of the ES. However a limited amount of literature have considered the impact of both oversizing and undersizing of the energy storage on the overall operation cost of the system. Residential PV systems connected to the utility grid through an export/import meter are attracting both utility owners and customers. In this review, we can also observe that in a residential PV-Battery system, for a battery of a given nominal capacity, the following can be noticed:

- If the battery is rarely used, then the cost due to the battery capacity loss is low. But the cost due to the power purchase from the grid is high.
- If the battery is oftenly used, the cost due to the power purchase from the grid is low whereas then the cost due to the battery capacity loss is high.

So there is a trade off on the use of battery and an optimal control policy of the charging/discharging rate need to be carefully calculated.

We have also seen that different optimization techniques have been developed and implemented in order to find an optimal solution of an objective function given some constraints and variables that need to either be maximized or minimized. There is quite a number of these methods and even though they work differently, research shows that all of them can optimize same problems. To the general question

VI. RECOMMENDATIONS

Despite a significant amount of research done in the area of grid-connected Renewable energy systems, either on the utility level or residential level, there is still more research to be done. The identified gaps in this review are:

- Most researches have been considering high penetration of PV and focusing on smoothing out its output fluctuation fed into the grid. There is a need to consider small scale grid-tied PV and cost minimization.
- In many optimization methodologies for optimal battery sizing, DOC, and Average SOC are assumed constants. These assumptions may lead to imprecise lifetime calculations.
- Limited amount of literature have considered the impact of oversized/undersized ES on the overall operation cost.

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