# Active power loss minimization in the Santa Cruz and Baltra hybrid energy system using particle swarm optimization

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***Abstract*.- Appropriate operating conditions allow to take advantage of the resources more efficiently, in particular, in electrical systems whose thermal generator fleet may affect the ecosystem. Within this context, a Particle Swarm Optimization in DIgSILENT software is proposed to determine appropriate settings for the elements to control the reactive power. This algorithm reduce the active losses which implying a saving of fossil fuels on the Hybrid Santa Cruz and Baltra Island System (SHGEE) located in the Galápagos Islands whose grid is characterized by conventional generation like thermal power plants and unconventional generation such as wind, solar and battery energy storage systems to supply its demand.**

***Index Terms*—Losses, reactive power, PSO, modified-PSO.**

## I. INTRODUCTION

The work referenced by this article, is a study the hybrid-electric system of Santa Cruz and Baltra (islands of Galapagos) that is currently supplied by thermal generation, wind generation and photovoltaic generation. The analysis of this special system allows to improve its operational conditions, minimizing the losses of active power and improving the environmental conditions.

In recent years, there have been significant efforts to replace thermal generation that has traditionally been used to supply the electrical demand of the Santa Cruz Island and Baltra Island, by incorporating unconventional sources that help decrease the consumption of fossil fuels (diesel), a key objective in environmental conservation of this natural heritage [1].

The active power loss minimization is an important criterion considered in power systems operation, as it involves costs of active power generation. In this paper, a classic meta-heuristic algorithm, Particle Swarm Optimization, (PSO) is implemented and a modified version of PSO is proposed with the finally to address mixed integer nonlinear problems. Such algorithms are implemented in DIgSILENT and permit to achieve a quasi-optimal solution by adding constraints on an optimization process that considers the management of mixed variables.

We chose this type of optimization method due to the non-linearity of the electric power systems modeling, and because it works with continuous and discrete variables.

The rest of the paper is organized as follows. Section II introduces the formulation of the loss minimization problem, as well as, the theoretical background of the compared algorithms. Section III demonstrates and discusses the results obtained from IEEE 14 bus test system and the hybrid-electric system of Galapagos. The conclusions drawn from this study are provided in Section IV.

## II. PROBLEM FORMULATION

### A. General Formulation

In general, a non-linear problem is formulated as follows:

$$\begin{aligned} &\min\ f(x, \mathrm{y}) \\ &s.t. \\ &h(x, y) = 0 \\ &g(x, y) \le 0 \end{aligned} \tag{1}$$

Where $x$ and $y$ represent the vector of optimization variables (continuous and discrete), while $f(x, y)$, $h(x, y)$ and $g(x, y)$ denotes the objective function and constraints of equality and inequality, respectively. Traditionally, mathematical programming techniques, such as linear, non-linear, integer-mixed, among others, have been applied to solve approximate formulations and ensure the global optimum of the problems; however, in certain cases, the complexities of the model limited the definition and calculation of the analytical expression with classical optimization methods [2].

As an alternative to solving non-linear and non-convex problems, arises the meta-heuristic techniques that allow to reach a good solution, although not necessarily optimal.

Is known that the time it takes a conventional method to find an optimal solution to a difficult problem is lower than the time it takes a meta-heuristic method, however, the latter returns an acceptable solution within a reasonable time and

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with an important saving in mathematical modeling development.

*B. Loss minimization*

According to the guidelines set forth in [3], the optimization problem is a non-linear mixed-integer. Mathematically, this problem has the following format:

$$\min\left\{ f(x,y) := \sum_{n}\sum_{m} G_{nm}\left[V_n^2 + V_m^2 - 2V_nV_m\cos(\theta_{nm})\right]\right\} \quad (2)$$

s. t.

$$Pg_i - Pd_i - P_{nm}(V_n, \theta_{nm}) = 0 \quad \forall i \in n \quad (3)$$

$$Qg_i - Qd_i - Q_n(V_n, \theta_{nm}) = 0 \quad \forall i \in n \quad (4)$$

$$S_{nm} \le S_{nm}^{\max} \quad \forall m \in n \quad (5)$$

$$Pg_i^{\min} \le Pg_i \le Pg_i^{\max} \quad \forall i \in n \quad (6)$$

$$Qg_i^{\min} \le Qg_i \le Qg_i^{\max} \quad \forall i \in n \quad (7)$$

$$T_k^{\min} \le T_k \le T_k^{\max} \quad \forall k \in (n,m), \forall T \in \Xi \quad (8)$$

$$Qc_j^{\min} \le Qc_j \le Qc_j^{\max} \quad \forall j \in n \; \forall Qc \in \Phi \quad (9)$$

$$V_n^{\min} \le V_n \le V_n^{\max} \quad (10)$$

Where:

- $n$: number of busbars.
- $V_n$: voltage of busbar $n$.
- $\theta_{nm}$: angular difference between $n$ y $m$.
- $G_{nm}$: conductances of lines.
- $Pg_i$: active power produced by generator $i$.
- $Qg_i$: reactive power produced by generator $i$.
- $Pd_i$: active power demanded by busbar $i$.
- $Qd_i$: reactive power demanded by busbar $i$.
- $P_{nm}$: active power flow in link $nm$.
- $Q_{nm}$: reactive power flow in link $nm$.
- $S_{nm}$: power flow in link $nm$.
- $T_k$: tap position of transformer $k$ (link $nm$).
- $Qc_j$: static compensator connected to busbar $j$.
- $\Gamma$: set of generators with AVR (automatic voltage regulator).
- $\Xi$: set of transformers with tap changer.
- $\Phi$: set of static compensator.

The optimization problem variables are $x=\{V_i, \forall i \epsilon \Gamma\}$ and $y=\{T_k, \forall T \epsilon \Xi; Qcj, \forall Q_c \epsilon \Phi\}$, emphasizing that $x$ are continuous variables and $y$ are discrete variables.

Objective function (2) expresses the identification of suitable combinations of continuous and discrete variables in order to minimize losses of the electrical system. The equality constraints equations (3) and (4) represent the nodal power balances. The inequality constraints equations, (5) to (10), set technical limits of the equipment. The constraint (5) set power flow limits of the lines, while the constraints (6) and (7) set capability limits of generators and constraints (8) and (9) model increases/decreases of tap changers of transformers and power output of static compensators, respectively. Finally, inequality (10) sets the limits of voltage at each node.

*C. Modified-PSO algorithm*

The particle swarm optimization is a very efficient evolutionary computational technique that was developed by James Kennedy and Rusell Eberhart. This algorithm emulates the behavior of flocks of birds in two-dimensional space [4]. In essence, the PSO is an optimization algorithm based on population behavior. This population is known as *swarm* and every individual entity as *particle* [4] [5].

Although different variants of PSO have been proposed, as shown in [5], its practical implementation has been scarce. Hence, this study implements the algorithm using DPL DIgSILENT for analyzing a real hybrid-electric system.

Under this premise, and considering that the optimization problem is nonlinear mixed integer, in this paper, a modified-PSO is implemented according to the criteria defined in [6] [7].

Fig. 1 illustrates the steps of the proposed algorithm, wherein the following formulas are used. Readers wishing to cover the theory and fundamentals of PSO can go to [8]

*1) Update speed.*

$$V_i^{k+1} = wV^k + c_1r_1\left(pbest_i^k - X_i\right) + c_2r_2\left(gbest_i^k - X_i\right) \quad (11)$$

Where $V_i^{k+1}$ is the speed in the current iteration and $V_i^k$ is the speed in the previous iteration. $w$ is the inertia factor and can be calculated as follows:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter\max} iter \quad (12)$$

Being $w_{max}$ and $w_{min}$ the maximum and minimum weights of $w$, respectively. The current iteration is represented by *iter* and the maximum number of iterations through *itermax*.

The factors $c_1$ and $c_2$ are denominated weights and typically are fixed between 1 and 2. In this study case $c_2$ is fixed in 0.5 while $c_1$ is changed in each iteration through the equation (13), where $c_{max}$ is equal to 0.6 and $c_{min}$ take a value of 0.1.

$$c_1 = c_{\max} - \frac{c_{\max} - c_{\min}}{iter\max} iter \quad (13)$$

The values of $r_1$ and $r_2$ are random numbers between 0 and 1. $X_i$ is the *i-th* particle at iteration $k$, $pbest_i^k$ is the best position of the *i-th* particle at iteration $k$ and $gbest_i^k$ is the highest among all the swarm, characterizing the PSO as a global version [6].

*2) Position update*

Using (14) the position of each particle is updated. Because the problem is mixed integer, the particles contain values for continuous and discrete variables. Therefore, are considered, according to the aforementioned variables, discrete and continuous numbers in (11) and (14) [8].

$$X_i^{k+1} = X_i + V_i^{k+1} \quad (14)$$

*3) Calculation of adaptive function*

Once defined the particles, power flow is simulated, respecting as an input parameter the values allocated to each generator according to a previously defined economic dispatch. Then the adaptive function, $F_i(x,y)$, which considers the losses of the electrical system, objective function $f_i(x,y)$, and the penalties, $k_cf_c(z)$, which arise due to the violation of the estimated restrictions (5)-(10) [9], is calculated. In (15) is presented the adaptive function.

$$\mathrm{F}_i\left(x,y\right):=f_i\left(x,y\right)+\sum_{c\in Z}k_c f_c\left(z\right) \tag{15}$$

It should be noted that penalties are activated as defined in (16).

$$f_c\left(z\right)=\begin{cases}0 & si\; z_{\min}\le z\le z_{\max}\\ \left(z-z_{\max}\right)^2 & si\; z>z_{\max}\\ \left(z_{\min}-z\right)^2 & si\; z<z_{\min}\end{cases} \tag{16}$$

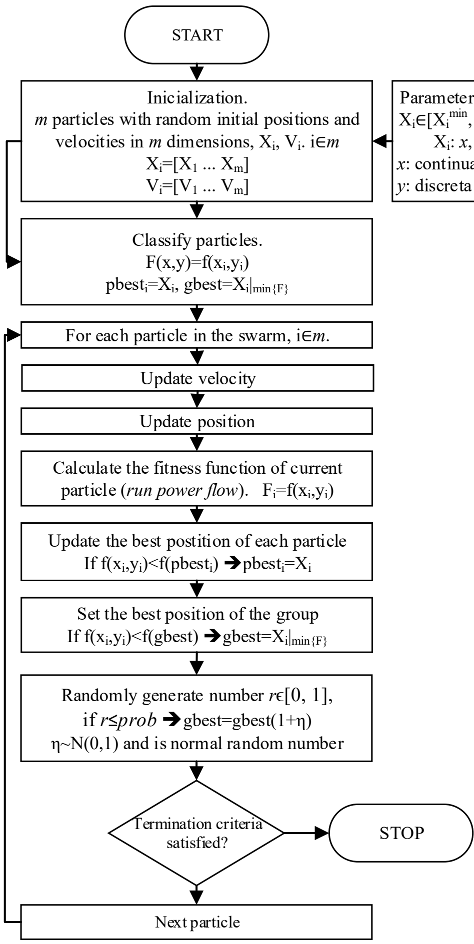


Fig. 1. Search procedure of modified PSO

### 4) *Calculating the probability of mutation*

In [6] is possible appreciate a detailed discussion of the procedure for calculating the mutation operator, which in the opinion of the authors, is successful when the global optimum knew in advance, for the present study case the minimum system losses. For practical purposes of this paper and in order to prevent that the algorithm becomes trapped in a local optimum, a disturbance in $g_{best}$ (see Eq. (17)) is applied to achieve significantly improve the ability of global convergence.

$$\text{gbest}=\text{gbest}\left(1+\eta\right) \tag{17}$$

Where η is a random number that underlay in a normal distribution: η~N(0,1).

## III. Illustrative Example and Case Study

To probe the effectiveness of the proposed algorithm, diverse algorithms are implemented in DPL (DIgSILENT Programming Language). The simulations were carried out in DIgSILENT 15.2.5 (for Education) in a desktop with AMD FX (tm) -8350 Eight-Core Processor running at 4.00GHz and 8GB of RAM.

### *A. IEEE 14 bus test system*

Prior to the practical application for the model outlined in the previous section, the effectiveness of the modified-PSO is validated by the IEEE14 bus test system. Data IEEE14 network topology can be found in [10]. The present study deals with the topology network included in the library of examples of DIgSILENT. Fig. 2. shows the aforementioned network.

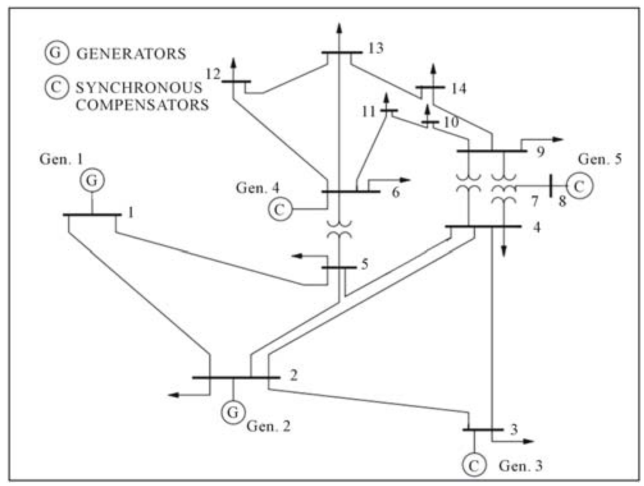


Fig. 2. IEEE 14-bus test system.

The meta-heuristics algorithms implemented in DIgSILENT, along the lines indicated in [11] [12] [13] [14], are: Genetic Algorithm (GA), classical PSO, Mean-Variance Optimization Mapping (MVMO) and modified-PSO. The simulations consider 30 entities and 300 iterations. In the case of GA, a mutation rate of 1% and a probability of 60% are parametrized and the MVMO requires prior configuration of the scaling factor (fs_factor = 1), asymmetry factor (AF = 2.5) and initial value of shape factor (SD = 25). Classical PSO considers $c_1$=$c_2$=1.5 y $w_{max}$=0.9 y $w_{min}$=0.4 and modified PSO uses the same weights with $c_2$=0.25; $c_{max}$=0.6 and $c_{min}$=0.1.

The TABLE I. show the results obtained. Note that the classic PSO produces better solutions but it is the slower than the modified-PSO, followed by MVMO and GA.

In Fig. 3. evolutions of the convergence of the above algorithms are presented, showing that all meta-heuristic stabilize (find a good solution) from 150 iterations. Note that the convergence of the modified-PSO is faster than the others, i.e. before iteration 100.

TABLE I. EXPERIMENT RESULT OF IEEE 14 BUS

| Algorithm | Losses (MW) | Time (s) |
|---|---|---|
| PSO | 11.37 | 10.68 |
| PSO-M | 11.53 | 10.50 |
| GA | 11.65 | 11.54 |
| MVMO | 11.55 | 11.05 |

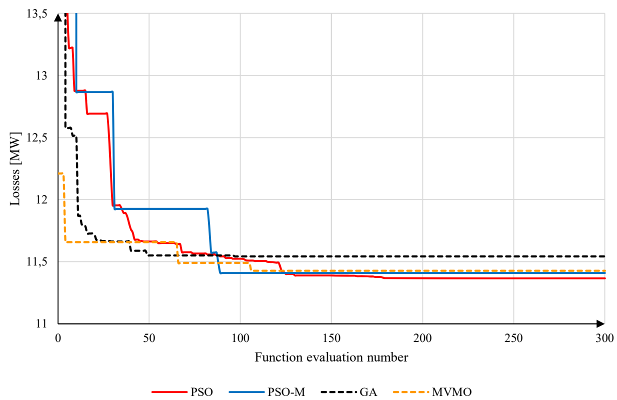


Fig. 3. Objective function convergence

Based on the results, and considering that experiences with mixed-integer non-linear problems show the ease of setting parameters for classical PSO and modified PSO [5] [7], the implementation in the hybrid-electric system considers only those algorithms.

*B. Hybrid system of the Galapagos Islands [15].*

Annex 1 contains the one-line diagram of the Galapagos power system that includes nine conventional synchronous machines with exciter IEEE avr_ESAC8B. Unconventional generation of the Galapagos Islands is made up of a wind farm and a photovoltaic plant in Baltra, a photovoltaic plant in Santa Cruz, a battery bank for regulating fluctuations wind/irradiation (lithium-ion batteries) and a bank batteries for energy storage (lead-acid batteries).

The Baltra Wind Farm consists of three wind turbines of 750 kW rated power each one, with AC/DC/AC full converter (Fully Rated Wind Turbine Generator Converter, FRCWTG).

The wind turbines are connected in a scheme "Daisy Chain" through a cable to 13.8 kV, which terminates in the fourth coupling to the network. The Santa Cruz photovoltaic park has a rated power of 1500 kW and the Baltra photovoltaic park has a rated power of 200 kW. In the Baltra Island are also installed two batteries banks in a solar farm associated with different purposes: a batteries bank of lithium-ion for regulating fluctuations in renewable-energy sources and a batteries bank of lead acid for storage and re-use of renewable energy not used. The lithium-ion bank of batteries has an inverter with a rated capacity of 500kVA, and a storage of 400kWh.

The Baltra-Santa Cruz transmission system has two voltage levels (34.5kV and 13.8 kV). The Baltra-Santa Cruz transmission line at 34.5kV consists of different sections: the first one, with air conductor 250 MCM, a segment with submarine cable of section 95 mm² crossing the channel between Baltra and Santa Cruz Islands and the final segment of underground cable 120 mm².

With the objective to present results of implementation of algorithms, we selected the cases corresponding to hot weather and maximum day demand. For this, the cases combine different wind, solar and radiation conditions. We defined different cases, which are summarized in TABLE II. This cases not consider contingencies in the network. Note that the numbers in brackets of the column of wind power and thermal power of this table represent the units of generation considered.

TABLE II. LEVEL OF PRODUCTION FOR EACH CASE

| CASES | Wind power (MW) | PV power (MW) | Thermal Power (MW) | Shunt reactor (Mvar) |
|---|---|---|---|---|
| 1 | 2.25 (3) | 0.204 | 3.16 (4) | - |
| 2 | 2.25 (3) | 0.108 | 3.66 (5) | - |
| 3 | 1.32 (3) | 0.108 | 3.66 (5) | - |
| 4 | 1.32 (3) | 0.108 | 3.66 (5) | - |
| 5 | - | 0.204 | 4.79 (6) | 0.75 |
| 6 | - | 0.108 | 5.47 (7) | 0.75 |

The demand values assigned to each load that model the distribution feeders, vary from case to consider. However, in order to make a diagnosis at critical supply conditions, we considered a maximum demand of 4.79 MW.

The control variables in the optimization process using the PSO algorithm are 17: 7 AVRs, 9 transformers with tap changer each one and 1 capacitor banks. The $c_j$ weighting coefficients of the velocity equation are established in 1.2 for the classical PSO and the modified PSO uses the following factors: $c_2$=0.25, $c_{max}$=0.6 and $c_{min}$=0.1. The initial weight $w_{max}$ and the final weight $w_{min}$ are parameterized in 0.9 and 0.4 respectively. The penalty constant $k_c$ parameterize to $1x10^7$. The loading limit of the links is set to 80% of its thermal limit. The number of particles is set to 10 and the maximum number of iterations at 100, whose setting parameters are drawn from the results obtained in the analysis of IEEE 14 bus test system.

*1) Results Analysis*

The results obtained from the minimization of active power losses are presented as follows:

TABLE III. RESULTS ALGORITHMS APPLICATION

| CASE | Losses without PSO (MW) | Losses with classical PSO (MW) | Losses with modified PSO (MW) | Simulation Time PSO (s) | Simulation Time PSO-M (s) |
|---|---|---|---|---|---|
| 1 | 0.1370 | 0.1261 | 0.1261 | 7.58 | 8.26 |
| 2 | 0.1266 | 0.1173 | 0.1168 | 7.92 | 7.64 |
| 3 | 0.0792 | 0.0731 | 0.0730 | 7.97 | 7.62 |
| 4 | 0.0707 | 0.0654 | 0.0654 | 7.41 | 7.82 |
| 5 | 0.0518 | 0.0439 | 0.0439 | 7.03 | 7.18 |
| 6 | 0.0463 | 0.0393 | 0.0393 | 7.31 | 7.21 |

In the cases that the energy from the wind farm is considered available, it shows that there is a decrease in losses ranging between 7% and 8%.

In the cases considered unavailability of wind, it is necessary to place a reactive compensation of 0.75 Mvar in the busbar13.8kV from the S/E Baltra. This compensation becomes necessary for successful convergence of the algorithm when you do not have the contribution of wind generation. Considering compensation one can notice that the power loss reduction achieved 15%.

The evolution of the search process takes 7-8 seconds, acceptable time in power systems operational processes under study and therefore, the optimization algorithms are valuable tools that contribute to the power systems operation.

Among the most relevant results, it can be seen that a loss reduction is achieved during operating conditions based upon the obtained results by the PSO algorithms. Additionally, it can be noticed that there is a positive environmental impact because of reduction on the fossil fuel (diesel) consumption in conventional thermal units that supply energy to the loads in the Galapagos Islands.

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## IV. CONCLUSIONS

The application of a substantial improvement in the classical PSO has been implemented and validated successfully in the software DIgSILENT, establishing a tool about loss minimization that compared with other meta-heuristics algorithms turns out to be attractive from a practical viewpoint.

With the implementation of the classical PSO and modified PSO in the simulation cases raised for SHGEE Islands Santa Cruz and Baltra, positioning values of the elements of reactive power control (AVR, taps, steps of inductors/capacitors) are determined such as operating conditions that minimize the power losses, which translates into savings in operating costs, which helps in the reduction of CO2 emissions that produced by burning diesel.

As future works, and since both the classical PSO and modified PSO are easy to implement in DIgSILENT, other types of non-linear and non-convex problems could be solved in reasonable computation time.

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**Annex 1**: Galapagos electrical system modeling in DIgSILENT