International Conference on Renewable Energies and Power Quality (ICREPQ'14)
Cordoba (Spain), 8th to 10th April, 2014
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, No.12, April 2014

Multi-objective Optimization applied to Photovoltaic Street Lighting Systems

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Abstract. This paper proposes a new method of optimization that minimizes energy consumption in street lighting with the aim of using minimal infrastructure in photovoltaic installations. In an attempt to reduce our energy dependency from the outside, the world of science not only is searching and developing new energy sources, but it is also implementing new methods of design of installations that consume less, while they maintain the highest standards of quality. In this work we continue with that idea, it provide an alternative method to achieve that lighting installations consume less and at the same time take advantage of the qualities of renewable energies. To do this, in this study two variables are chosen to optimize the installation of public lighting; energy consumption and global uniformity. The first is intended to minimize the number and cost of photovoltaic elements and the second to ensure the quality of the lighting.

As a practical example, any city of the South of Spain was chosen, therefore the choice of solar photovoltaic is justified because there are large number of hours of sunshine per year.

Keywords

Street lighting, energy saving, stand-alone solar PV, Pareto optimality.

1. Introduction

The idea of this project within the field of renewable energy sources is based on the need to provide answers to the energy problems of today's society. Society has become aware that energy is a valuable and scarce resource, therefore we are in a dilemma in which, on the one hand our consumption continues to grow, and on the other hand, our model is based on limited resources, mainly fossil fuels, like oil and coal. This situation makes that energy costs increase every year, and therefore the expenditure by the public administration in public lighting is excessive.

Currently, in Spain, the budget dedicated to the lighting round the 1000 million euro, and spending has doubled over the last 5 years [1]. Administrations could see reduced both operating costs and maintenance, betting on models based on alternative energy sources and with longer service life (in the case of LED).

These two elements are the basis that motivates this work, however there is another positive aspect: the improvement of the quality of the light, to replace traditional discharge lamps (e.g. sodium vapor lamp) with others with a more natural color reproduction. However, not only the replacement of the traditional lights by the luminaires with LED technology is sufficient, as we have seen repeatedly in the municipalities where the lighting systems have been renovated, in addition an adjustment in the distribution of luminaires is required. Obviously, if the luminaires are not redistributed, although new light sources will consume less energy, the quality of the installation is aggravated because it does not provide adequate levels of uniformity or lighting.

Currently, there are countless lines of research seeking alternative and durable solutions to the problem of energy in all areas of technology. In the present work we offer an alternative method to others [2, 3] that can find the optimum distribution of the luminaire to minimize energy consumption and therefore to minimize the use of infrastructure in photovoltaic systems.

2. Lighting of Roads

The main objective of the road lighting is to reproduce lighting conditions that provide a safe and comfortable environment for the driver and pedestrians during the hours of night. Effective use of the road lighting on streets helps protect drivers/pedestrians and improving traffic, also provides economic benefits, streamlined the levels of lighting. When levels are optimal, the system provides enough illumination to minimize the number of accidents, maintaining at the same time minimum energy consumption.

Road lighting installations are characterized by geometrical parameters as well as by the light distribution of the luminaires and their light sources. The requirements for the performance of such installations have been specified by the CIE [4], where the performance level is calculated according to the values of certain criteria known as light technical parameters. In our case, light technical parameters are illuminance-based (where the illuminance is the luminous flux received per unit of surface).

The first parameter is the overall illuminance uniformity, which is directly related to the quality of the roads illumination because low uniformity ratios imply frequent changes of contrasting high and low–lit road segments and it causes enormous eye discomfort, leading to stress and tiredness and therefore jeopardizing road safety. The illuminance uniformity is defined by (1):

$$U_0 = \frac{E_{\min}}{E_{av}} \tag{1}$$

where E_{min} is the minimum illuminance value calculated for all units between the next two lighting fittings; and E_{av} is the average illuminance. The energy consumption per unit time to each luminaire is:

$$e = \frac{P}{S} \tag{2}$$

where P is the electrical energy or power and S is the surface associated to a individual luminaire (see Figure 1)

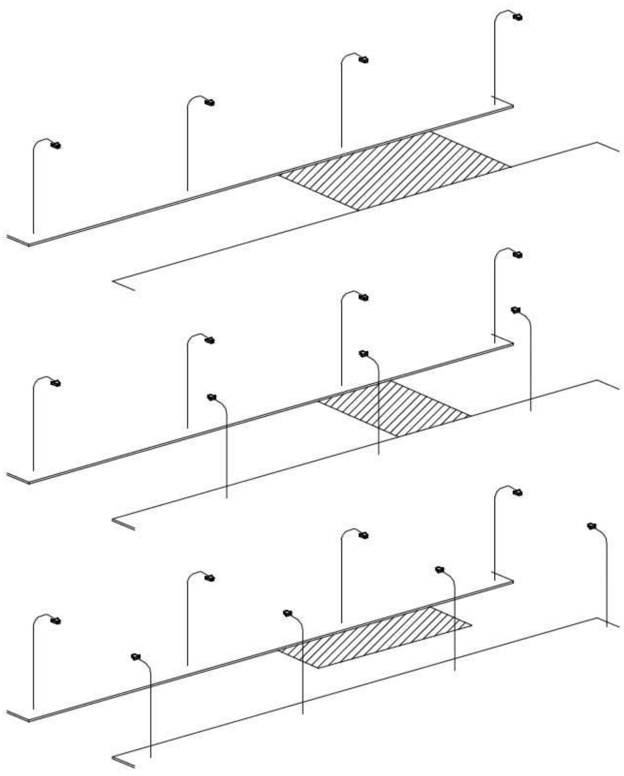

Fig. 1. One-sided, and two-sided (staggered and coupled) installations with the surface corresponding to individual luminaire.

3. Optimization Method

The optimization methods used were two; the Multi-objective Evolutionary Algorithm knows as Non-dominated Sorting Genetic Algorithm II (NSGA-II) [5] and the interval arithmetic or "interval finite element method [6]". The first one was used to study the overall uniformity and the energy consumption of a street lighting installation, which are the two optimization variables. Non-dominated sorting in genetic algorithms is a popular non-domination based genetic algorithm for multi-objective optimization [7]. In this paper, the new version, NSGA-II has been applied. This algorithm is similar to a conventional genetic algorithm involving the following steps: population initialization, fitness evaluation, reproduction, simulated binary recombination crossover [8], and mutation. The main difference between NSGA and NSGA-II is the inclusion of the non-dominated sort classification and crowding distance.

Overall uniformity and energy saving are contradictory objectives because if the uniformity increases then spacing between poles decrease and therefore increases the number of luminaires installed. Consequently, the bi-objective optimization outcomes are a solution set that is a compromise between these two objectives. The genetic algorithm parameters used for the different optimizations are shown in Table I.

Table I. – NSGA-II parameters used for the optimization

Parameter	Value
Number of generations (Ngen)	150
Number of individuals per generation	100
Crossing probability	90%
Mutation probability	10%

In this case, the street width and lamp type are the input parameters. Our objective was to evaluate the influence of the location and characteristics of the luminaires on the performance of the roadway lighting systems.

The second method is the simplest method, which represents a range of possibilities. The target is similar to previous one; study the overall uniformity and the energy consumption of a street lighting installation. The disadvantage of this method is the computational cost although it is the most robust. The results of both methods have been overlapping in order to check that both are coherent.

A free software frequently used for lighting calculations called DIALux [9] has been used to obtain all possible solutions in the interval finite element method. The procedure can be understood by means of an example.

We suppose a 7.5 meter width road for motor vehicles driving at a very limited speed or a suburban residential street with sidewalks on both sides of the road. Based on the CIE recommended values, this is lighting class *P*, whose lighting requirements are summarized in Table II. Our case is *P1* lighting class where $E_{av} \geq 15$ lux is the minimum average illuminance and $U_0 \geq 0.2$.

Applying the interval finite element method, the range of spacing between poles goes from 10 to 50 meters and the mounting height range goes from 6 to 10 meters, therefore, the only element in the optimization process is the choice of the type of lamp. Obviously, in order to achieve minimum energy consumption (and maintaining reduced), LED technology would be chosen.

Table II. – Lighting requirements for conflict areas

LIGHTING CLASS	Average Illuminance (Minimum)	Uniformity of illuminance (Minimum)
P1	15	0.20
P2	10	
P3	7,5	
P4	5	

Taking into account the street width, boundary conditions (e.g. spacing between poles) and the average illuminance, theoretically, the light source must emit a luminous flux ranging from 1100 to 5500 lumens, therefore a randomly selected lamp with these range luminous flux is shown in Figure 2.

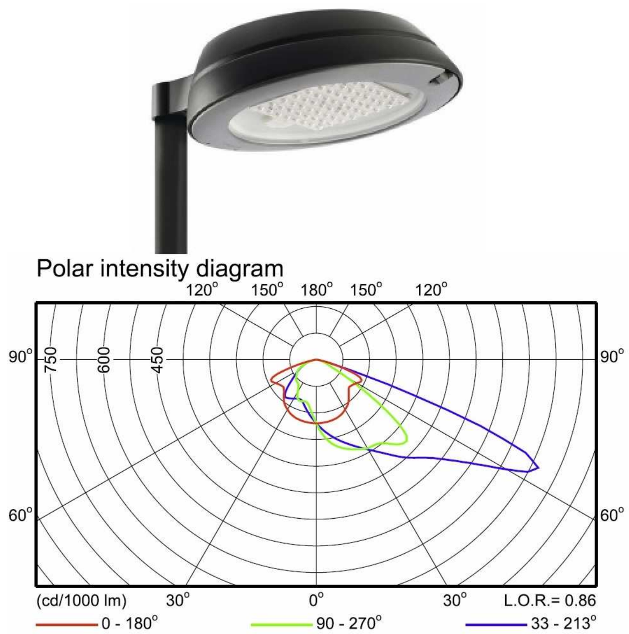

Fig. 2. The randomly selected lamp with its polar intensity diagram. The luminous flux of the system is 2890 lm and the power is 36W.

Using the luminaire shown in Figure 2, have been calculated all the configurations and they have been represented in Figure 3 (red points) as scatter plots in terms of energy consumption and uniformity (parameters to be optimized). The blue points are the results of NSGA-II algorithm and obviously they coincide with those results that minimize the consumption regarding uniformity in the interval finite element method.

Each one of the points of scatter plots is a vector consisting of three variables; height of the luminaire mounting, distance between poles and average illuminance (H, d, E_{av}). Subsequently have been selected those solutions that minimize the consumption regarding uniformity. The plots of the results (Pareto optimization or dominant solutions) are shown in Figure 3 for the most typical lighting arrangements; one-sided, two-sided coupled and two-sided staggered installations.

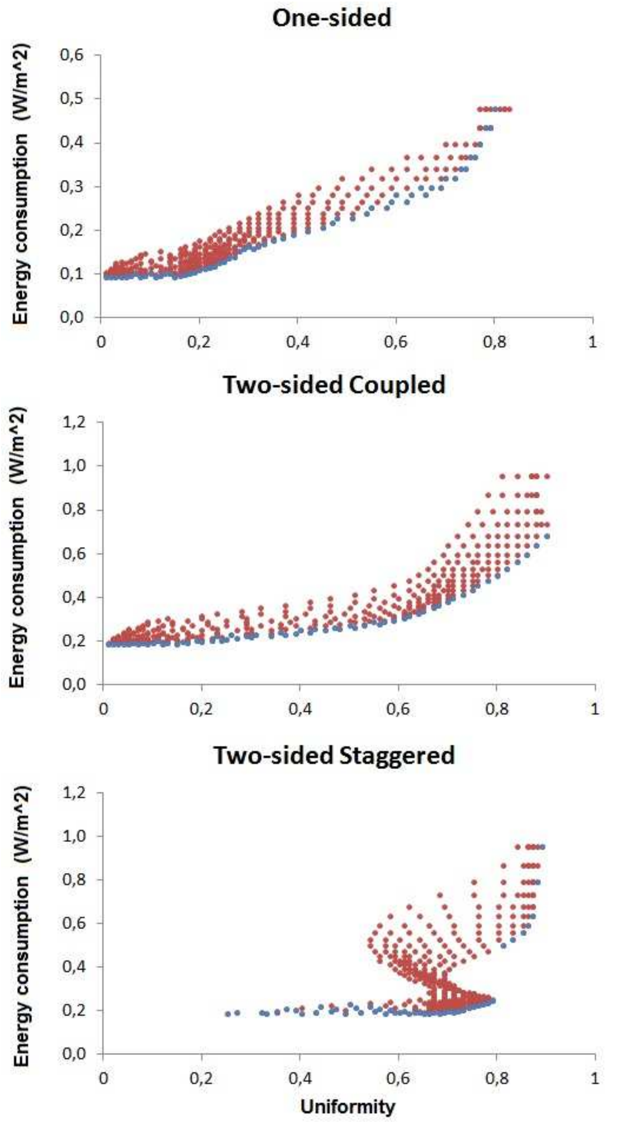

Fig. 3. Power vs. Uniformity of all possible configurations (red points), and the result of the Multi-objective optimization or Pareto optimization (blue points) when electricity consumption is minimized and maximized uniformity.

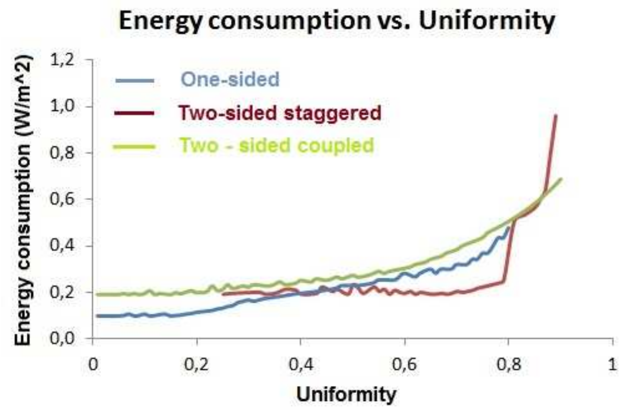

Fig. 4. Pareto optimization for the most typical lighting arrangements.

If the energy consumption of the typical lighting arrangements are compared (Figure 4), and only those solutions with average illuminance higher than 15 lux (see Table III) are selected, we can deduce that the optimal configuration is one-sided arrangement.

Table III. – Solutions optimized whose illuminance is $E_{av} \geq 15$ lux and $U_0 \geq 0.2$.

ARRANGEMENT	U_0	W/m^2	D (m)	H (m)	Poles/m^2
One-sided	0.81	0.48	10	8	0.013
Two-sided Coupled	0.86	0.60	16	10	0.017
	0.88	0.64	15	10	0.018
	0.89	0.69	14	10	0.019
Two-sided Staggered	0.86	0.60	16	10	0.017
	0.87	0.64	15	10	0.018
	0.88	0.80	12	10	0.022
	0.89	0.96	10	10	0.027

On the other hand, as we can see in Table II, the minimum number of luminaires per m^2 coincides with the optimized solution.

4. Photovoltaic System Calculation

When a PV system is designed to provide energy, two alternatives are possible; isolated installation (stand alone) or connected to the network. In this case an isolated installation has been the choice.

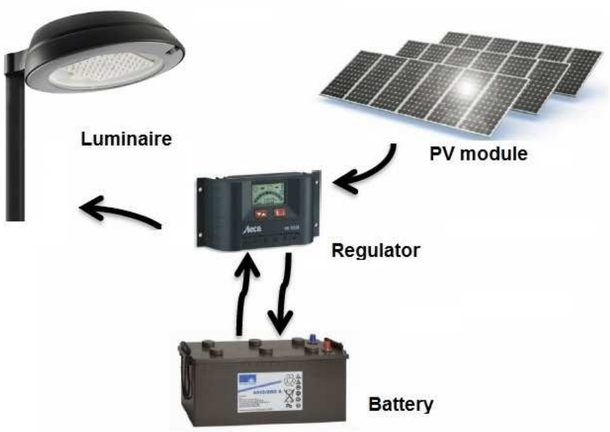

Fig. 5. Stand alone PV lighting system

In Figure 5 are shown the elements that constitute the photovoltaic lighting systems. According to the optimized solution and the place where the system would be installed, the photovoltaic system is dimensioned in the following sections.

A. Maximum installed power

As mentioned, the installation will be held in any city in the south of Spain. This means that according to the National Geographic Institute [10], on the longest night of the year the installation must be running 14 hours, therefore the maximum power installed per luminaire will be 0.50 kWh/day (if we apply 10% margin of safety the power installed would be 0.55 kWh/day).

B. Battery sized

As the luminaire is powered by battery, it will be necessary to know the battery's capacity. The battery's capacity is the amount of electrical charge it can deliver at the rated voltage (according to the voltage provided by the PV module), in our case 24V, as consequence applying the equation (3), the capacity of the battery is maximum current is 100 Ah/day:

$$C_m = \frac{P_{\max} \cdot F}{U_n \cdot P_d} \qquad (3)$$

where P_{max} is the power consumption (0.55 kWh/day), F is a factor that represents the autonomus days (3 days), U_n nominal voltage (24 V) and P_d is the depth of discharge (70%).

C. PV sizing module

To calculate the current supply by the PV module we apply the following equation:

$$W_{PV} = \frac{P_{\max}}{PHS \cdot f_c \cdot V} \qquad (4)$$

where W_{PV} is the power provided by a PV array, *PSH* is the peak sun-hour, *V* is the lost due to the wiring, battery, regulator, etc and f_c is a correction factor due to the orientation and slope of the panel. The values in our case are: PHS = 2 hours (in the worse case in January), f_c = 1.72 and V = 0.75 so the power supply by the module is 237 W_p.

In this case, we will need a single module with a margin of 10% for energy losses.

5. Conclusion

The target of this research has been to present a method that guarantees to minimize power consumption in street lighting installations in order to use stand-alone solar power system.

The only free variable was the choice of the luminaire, so the only way to minimize the infrastructure is to select a more efficient luminaire and the Multi-objective algorithm proposed or the results that minimize the consumption regarding uniformity in the interval finite element method does the rest.

A future line of research will be to solve the inverse problem, get the characteristics of the luminaire from a specific PV + battery system.

Acknowledgements

This research work was partially carried out under the support provided by the Research Project RNM-6349, granted by the Junta de Andalucía (Spain).

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