Simulation-Based Procedure for the Optimization of the Control Strategy of a SHC System

Chiara Dipasquale, Anton Soppelsa, Matteo D'Antoni, Roberto Fedrizzi
Eurac Research- Institute for Renewable Energy, viale Druso 1, 39100 Bolzano, Italy
Phone: +39 0471 055616, Fax: +39 0471 055 699
chiara.dipasquale@eurac.edu www.eurac.edu

Introduction

Solar technologies can cover all building energy needs (space heating and cooling, domestic hot water, lighting and electricity). Nevertheless, small scale solar heating and cooling (SHC) systems present several difficulties related to the existing SHC systems (mainly prototypes) [1], to the lack of expertise in the field and to the boundary conditions (weather and building loads). The complexity of the control system can present another problem in the feasibility of SHC systems. Facts that make challenging the control of such systems are the variability of the energy source (the solar radiation) and the strong dependence on the climatic conditions of the system behaviour. Moreover, the control of SHC systems concerns simultaneously the control of single hydraulic devices and the orchestration of all of them at the high level. According to this, the system performance and the comfort level perceived by the inhabitants may be improved adopting control configurations that maximize specific performance indexes.

Methodology

In this work, a simulation-based procedure for optimizing the control strategy of a SHC system is described. This methodology is suitable with any SHC systems; their complexity and amount of control parameters is tackled with the individuation of the most influencing parameters on specific indexes. Example of the feasibility of this procedure is shown in the study case presented. The analysed SHC system has been installed on an already existing heating system fed by a pellet boiler: limitations imposed by the plant layout have been dealt with an optimal control configuration individuated through this procedure. The methodology here presented consists of three main steps: 1) a model validation and calibration phase with a quantitative comparison between monitored and simulated data; 2) a sensitivity analysis oriented to individuate the most influencing parameters on defined performance figures; 3) a parametric analysis applied to the selected values for choosing the best configuration for the specific case.

Case study

The study has been applied to a passive house located in Bronzolo (BZ), in the north of Italy, where a SHC system has been installed. Eight apartments are distributed on three storeys for a total of 577 m^2 of conditioned living area. A 40 m^2 of evacuated solar collector field provides the hot water which can feed a 3000 litres stratified solar storage or be used for direct space heating (in winter) or sorption chiller charging in summertime. The storage is used for Domestic Hot Water (DHW) preparation; a 15 kW pellet boiler works as hot back-up of the system. An Air Handling Unit (AHU) recovers heat from the exhaust air. In winter the fresh air is pre-heated by an array of geothermal probes; during the summer season, it is cooled down through two coils located upstream and downstream the AHU and fed by a BrLi sorption chiller; the dehumidification of the air is not foreseen. The system heat rejection is covered by exploiting the exhaust air, the geothermal probes or a dry cooler, depending on their availability, the local environmental conditions and the state of the system [2].

Components and whole system models validation

The first step of the procedure concerns the validation of the behaviour of system components through measured data.

A comparison between simulated and monitored data has revealed as capacitance effects that can be neglected at the single component level, cannot be longer neglected when simulating the whole system behaviour. Despite the large availability of methods for the validation of dynamic models [4], an approach based on an iterative process of quantitative comparisons has been selected. In the first phase, named Parameter Identification, the numerical model of the component is defined according to datasheet characteristics. After that, a comparison between simulated and monitored data is done for identifying the appropriate components parameters [3]. In this phase, measured data are used as boundary conditions of the model, while simulated and monitored outlet quantities are compared. The range of the parameters variation has been fixed within realistic values in order to minimize the computational effort. The convergence towards the minimum of the objective function however may not be regarded as an indication of the accuracy of the model. In order to reach a good agreement between real and simulated values, a quantitative comparison of the numerical results with the monitored data has to be performed. This phase named “Performance Comparison” can be therefore applied to all those components in which a performance curve related to operative boundary conditions can be individuated (solar collectors, heat exchangers, dry cooler). If not possible (i.e. storage, geothermal probes and sorption chiller) the component validation procedure ends with the Parameter Identification. The quantitative comparison is based on the Root Mean Square Error (RMSE) of the performance curves. If this value is within the acceptance criterion defined by the user, then the validation is accomplished, otherwise the numerical model has to be revised or upgraded until an adequate level of agreement is found.

For the validations carried out in the case study, the final difference of RMSE between model and real system components performance curves has been assessed around 3÷5%.

Sensitivity analysis on the control system parameters

The key element of the proposed optimization method is a sensitivity analysis oriented to individuate the control parameters most influencing the system performance. To this aim, a quantitative method that individuates the weight of each parameter on a certain target function has been employed, the Morris method [5]. The target functions used in this work are representative of the system energy consumption, the Primary Energy Ratio (PER) [6], and of the thermal comfort, the Predictive Percentage of Dissatisfied (PPD) [7]. This screening method allows to determining whether parameters have a negligible, linear and additive, non-linear effect on a target function or are involved in interactions with other parameters. The Morris method allows to estimate the influence of each parameter on the target function through a relation between the average (μ^*) and the standard deviation (σ) of the Elementary Effects (EE) [8]. The EE is calculated for each parameter involved in the sensitivity analysis and represents the incremental variation of the target function with respect to the parameter variation. The farthest points from the origin are those that most influence the target function. In this specifically case, the method has been applied to 39 parameters, among which a number of three emerged clearly as the most influencing the PER and PPD.

From this screening phase, 10 values have been selected. The control parameters to be selected are the farthest from the origin. The graph referred to the analysis made on the PER only is here reported in Fig.1. This graph shows that two parameters, number 1 and 2, have a higher influence on the PER than the other seven in the dashed lines. The remaining control parameters have a negligible influence. Parameter 1 is the width of the hysteresis used to determine when switching between charging the storage and performing direct heating in winter or charging the sorption machine in summer. Parameter 2 is the set-point of the DHW temperature. The other seven parameters are all involved in the DHW and heat rejection circuits.

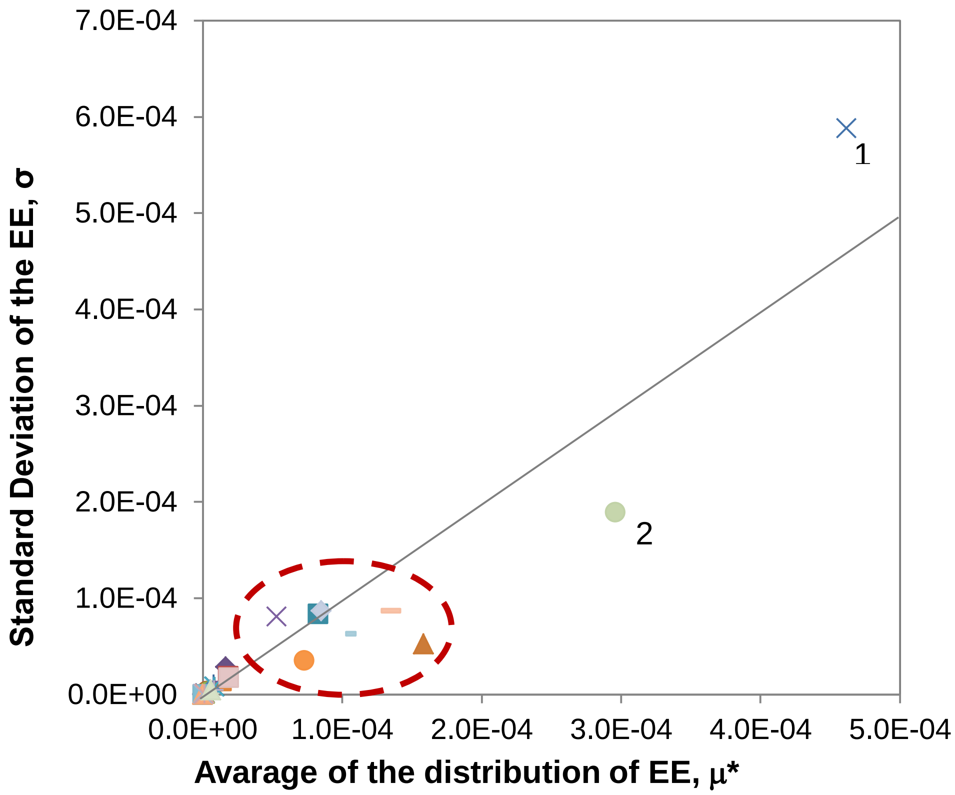

Fig. 1 Average (μ^*) and standard deviation (σ) for each parameter on PER

The tenth parameter selected for the analysis is the most influencing parameter on the PPD value, that is the set-point of the winter internal temperature. As expected, this value is more related to the internal comfort. The summer set-point temperature has a much minor effect on the PPD because of the cooling power of the system which is too low for reaching relevant results. The other control parameter have a negligible influence on the state of the internal comfort.

Parametric analysis and best configuration

The last step of the optimization procedure presented in this work concerns a parametric analysis aimed at individuating the best parameter set to be implemented in the SHC control system. For the most influencing variables individuated with the Morris method, a range of reasonable values has been selected according to operating conditions and the interaction with other parameters.

The values here individuated are strictly connected to the layout and operating modes of the system. For each simulation in addition of PER and PPD, the following performance figures have been calculated: Solar Fraction referred to the DHW preparation (SF_{DHW}), to the space cooling (SF_{cool}) and to the space heating (SF_{heat}); Gross Solar Yield (GSY) and the saving of Primary Energy (ΔPE) [6].

Table 1 Values of the performance figures associated to the best configurations for PER (CMB_PER) and PPD (CMB_PPD)

Combination	**SF_{heat}**	**SF_{DHW}**	**SF_{cool}**	**PER**	**GSY**	**ΔPE_{tot}**	**PPD**
	[%]	[%]	[%]	[-]	[kWh/m^2]	[kWh]	[%]
CMB_PER	44.9%	51.0%	0.5%	0.35	748	31165	11.3
CMB_PPD	45.5%	5.5%	0.1%	0.69	760	13642	11.1

The results shown in Table 1 underline as control configurations that improve energy savings (CMB_PER) usually disadvantage the thermal comfort and vice-versa. Nevertheless, while both combinations have close values of PPD, the PER is double in case CMB_PPD. Case CMB_PER has been therefore taken as the best configuration for the system here studied. In particular, the contribution of solar energy to cover the cooling loads is not satisfactory. This can be ascribed to 1) the poor overall performance of the chiller, and 2) the habits of the tenants. The high values of SF_{heat} and SF_{DHW} imply a reduced use of primary energy for the space heating and DHW production (higher ΔPE_{tot}); the GSY is not far from the one in the CMB_PPD.

Conclusions

The control of a SHC system is a challenging task due to the need of orchestrating multiple devices as a whole to achieve energy saving or optimal internal thermal conditions. The definition of the operating modes priority, set-point temperatures and pump speed modulations can strongly influence the system performance and the internal comfort. Moreover, configurations that improve energy savings usually penalize the tenants environmental thermal conditions. For this reason, an optimization of the control strategy of a SHC system is usually needed.

In this work, a procedure for individuating the best configuration for both an energy savings and thermal comfort point of view has been described. The procedure is based on three steps. The first one consists in the construction of a reliable model of the system. In this case study this model has been developed and calibrated with monitored data. In the second step the parameters that mainly influence the system behavior are selected through a sensitivity analysis. In this study, the Morris method has been applied to 39 parameters of the control system with respect to the Primary Energy Ratio (PER) and the Predictive Percentage of Dissatisfied (PPD). The third step consists of a parametric analysis to be performed on the (reduced) set of the most influential parameters. This has been made in our case by evaluating the performance figures on a multi-dimensional grid of points within feasible ranges of the individuated parameters. As a result of the application of the method, the best configuration for the given performance figures is obtained. In our demonstrative application, depending on the case, reduction of primary energy or internal comfort has been chosen as the quantities to be optimized; in this case the configuration with the best PER allowed suitable values of SF for heating and DHW as well as an overall value of PPD close to the best case, however there is no guarantee that this will be the case for other SHC systems.

The procedure here presented fits with any SHC system, where a large amount of control parameters is commonly required. Moreover, the successful application to the Bronzolo (BZ) house shows that this methodology may allow to optimizing a SHC system performance installed in an existing system in order to improve energy savings and thermal comfort.

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