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Optimal Predictive Control Strategies for Polygeneration Systems

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The optimal energy control and management for smart grids as per virtual power plant concepts is of great importance for the coming future of the electricity grid and the energy market. The optimal energy management for housing applications necessitates the combined use of heat and electricity by the way of technologies like cogeneration engines, heat pumps and thermal storage which can be used to dephase the electricity and heat demand of the building of the district concerned. A major factor that will play a role in the effective usage of these technologies is the proper and optimal sizing of each of the conversion and storage units as per the demands of the occupants. Another factor, that may affect the optimal energy management of domestic applications is the pricing of electricity done through the energy exchanges around Europe. Energy management is especially important for Switzerland as it is seen as a major transit and exchange country in the European energy market owing to its position and the trade of energy between France, Germany, Italy and itself.
Here, a study has been conducted that tries to link two of the above mentioned factors in the design of a polygeneration system design. This study aims to show the effect of implementation of cogeneration system (cogeneration engine with or without a back-up boiler) coupled with a heat pump to satisfy the needs of a building considering the use of an optimal predictive control strategy that is used to optimize the use of the storage tanks. The study aims to identify the differences in the demand with and without heat pump. Also, the study aims to show the potential for thermal/electric storage in a single family house for better management of demand from the grid. The effect of the implementation of thermal storage with cogeneration engine coupled with heat pump on the grid electricity is explored. The effect of change in the electricity prices and as well as of constraints imposed on the electricity variations through the day on the buildiing requirements with cogeneration engine coupled with heat pump and thermal storage over a day is studied and the different strategies are identified.
The study is then extended to include different buildings with different energy demand profiles. The objective is to study any possible changes in the strategy of one building due to the presence of another building in the grid which can also buy and sell using the control strategies mentioned above. As a result, this also reveals the effect of the use of optimal control of multiple buildings connected to a micro grid on the sale or purchase of electricity from or to grid as well.

1. Introduction

Energy and increasing use of different forms of energy for our purposes has defined the development of the world over centuries, but there has been a burgeoning increase in the use of energy, especially in the last century. The ever increasing demand for energy has been supplied until the last few

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decades without much forethought into the efficient use of energy and the wastage of energy that could be used for other purposes.

But, over the last few decades, due to varying factors like the fluctuating prices of fossil fuels, the peaking of the supply of fossil fuels and possible exhaustion of the resources of the fossil fuels, there has been increased focus and attention to possible ways of making efficient use of the existing fossil fuels and possible use of the renewable resources and the active participation of these resources in the electricity grid structure.

One way forward in the view of these goals is that of implementation of smart grids or virtual power plants using combined heat and power(CHP) systems among others and a competitive control of the various components of the different elements so that there is an element of active sale and purchase of electricity and an efficient use of the available heat through the use of various storage devices.

One of the major requirements of a micro-grid or a decentralised system is the need for control of the multiple sources of energy and power. The proper sizing ensures that each unit has right capacities to satisfy the loads required by the end-users, but for a micro-grid to work efficiently as pointed out by Lasseter (2007), a good, functioning control system is required. Lasseter (2007), also points out the potential shortfalls of a complex all encompassing control system that controls the entire DG system. The best way, that is thus, suggested and preferred is a local control that can autonomously take care of the islands in tandem with existing controls that the conventional grids use power-versus-frequency droop and voltage control used today could be applied along with the new technologies to make the system stronger.

2. Methodology and implementation

The work that is done here is continuation of the work done by Collazos (2009), the predictive control strategy introduced in Collazos (2009) has been modified to include models of heat pumps and thus, this strategy is used to provide all the results provided in this paper.

For the modeling of the heat pump, efficiency and COP data was taken from Girardin (2010). This was used in the implementation of the models and the models were then connected to form a coherent system of a building consisting of a heat pump, cogeneration unit, house, storage tanks and electricity supply units and multi-objective optimisation was performed on the system using the strategy devised at LENI (Laboratoire Energetique Industrielle) used in papers like Weber (2006) where a master-slave optimization is performed with the following objective:

$$\min\left[OpCost, InvestCost, CO_2 emis.\right] s.t.\left(Sys.Models, slaveopti, EnvironEval\right) \quad (1)$$

The master optimization minimizes the operating costs using the models and the slave optimization is performed for the total costs and the CO_2 emission calculations. The optimization is performed in a tool which performs the multi-objective optimization using an evolutionary algorithm. This gives us the sizes of the units in the system. Multiple papers have been published regarding the sizing of the units by LENI.

The control strategy used in this system is as mentioned earlier an extension of the Collazos model with a few additional constraints. Initially a day has to be chosen to retrieve the electrical and the heat demands for the day. The temperature of the day is also calculated using an ARX model which can be used in a variety of ways. The information that could be used could be the the temperatures of the previous day or the average of the previous 5 days, depending on what method we need to use. The dynamics and the space heating models inside the buildings are calculated using a simulink model developed and used by Gähler and Collazos and is also mentioned by Collazos(2009).

The control strategy used here can be varied depending on the needs of the hour. But for the case in question we have used a day in January and a day in April. The calculations are done over 24 h. The horizon is 25 h where the 25-th hour is used as the starting point for the next day's calculations. A MILP optimisation is performed with the objective function of the control strategy being:

$$\min\left[OpCost\right] s.t.\left(SystemModels, PredictedDemands\right) \quad (2)$$

There are different bounds and constraints placed on the control strategy which will be mentioned through the results section as we go through the different results. One of the main things to notice here is that all of the heat that is produced by the heat pump and cogeneration engine in all cases are sent to the storage tanks(both heat storage and domestic hot water). Further constraints on electricity power sale and purchase and other constraints will be mentioned as and when needed. In the system considered below, initially a optimally sized heat pump was used, but to show the flexibility of the controller, in the results section, we are also showing you results using non-optimal sizes of heat pumps.

3. Results

Simulations performed are for different conditions. The first day that has been considered is for January 20, where the electricity and thermal energy demand for a single family house by SIA standards have been considered and the data is given below. Another day considered for later simulations have also been mentioned in the table given below. This data gives us an idea as to how the daily electricity and thermal demand changes for different days.

Table 1: Information regarding the day in consideration

Day	Electrical energy demand	Thermal energy demand	External temperature	Internal temperature
January	10.989 kWh	96.6 kWh	0-2 °C	16-20 °C
April	9.654 kWh	37.3 kWh	12-15°C	16-20 °C
Electricity prices:	Purchase: 0.07 €/kWh b/w 10 PM and 6 AM	Purchase: 0.18 €/kWh other times	Sale: 0.0584 €/kWh	

The first case that was considered here was for the day of January 20th where only a cogeneration engine with a back-up boiler has been considered as being part of the system.

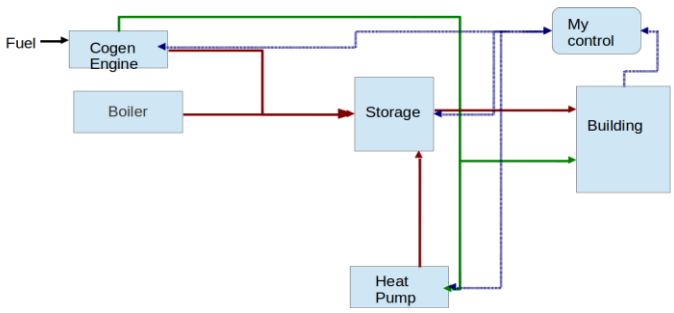

Figure 1: Schematic representation of the system

As mentioned above, the strategy for the 24 h is calculated by solving a mixed integer linear programming(MILP) problem where the operating cost is to be minimized. The cogeneration engine in question is a Stirling engine, the characteristics of the Stirling engine is as per the engine used in Collazos (2009) and the models used for the boiler, the house and the storage tank are also similar to the ones used in that paper. The CHP units, I.e, the Stirling engine and the heat pump, where they are used are switched on and off through the use of integer variables. This is the reason why MILP is performed for the optimal predictive control strategy.

The first study performed reveals to us that for the January 20 situation, to satisfy the hourly electricity and thermal energy demand, the cogeneration engine is used to provide electricity and the heat demands as well. Figure 2 reveals to us that over the period of 24 h, the cogeneration engine is run for a large period of time, as the temperature needs to be maintained around 20 °C although, the external temperature is consistently around 0-1 °C which means that there needs to be large amount of heat supplied from the storage tanks and the cogeneration engine is used as a cheap source of thermal energy. The resulting thermal energy is transferred to the storage tank and the figure on the right side shows that the storage tank(shown in blue) provides the bulk of the heat. The electricity produced as the by-product of cogeneration is used to satisfy the electricity demand of the house. The excess electrical energy produced is sold back to the grid. This strategy is implemented under the assumption that the building in question has the ability to interact directly with the electricity market. The electricity prices considered here as mentioned above in Table 1 changes through the day, it is low for the night and high for the day, so the system prefers to use the cheaper electricity produced by cogeneration engine. An extra of 26 kWh is produced in this process.

When the heat pump is also attached to the system, you see a sharp variation in the system strategy that is implemented. Figure 3 shows that the heat pump is used during the night as the electricity.

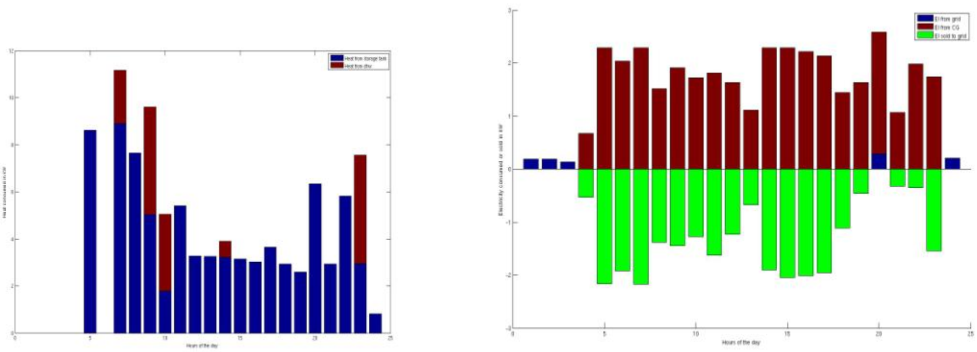

Figure 2: Consumption of electricity predicted when only cogeneration engine is attached to system(blue is electricity bought from grid, green sold, and red is cogeneration, heat : red is domestic hot water and blue is space heating)

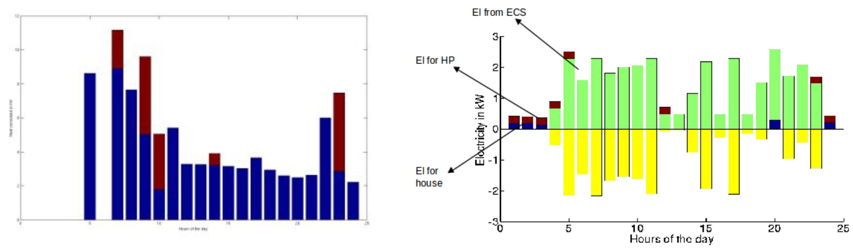

Figure 3: Consumption of electricity predicted when heat pump is also attached to system(yellow is electricity sold, blue is bought from grid, red is heat pump electricity use and rest Is cogeneration electricity)

prices during the night is cheaper and the heat captured from the heat pump is then stored in the storage tank and only used when needed as can be seen from the demand curve in Figure 3, which shows that the storage tank only gives out the heat when it is required. For the second case we have used an under-optimal heat pump compared to the optimally sized heat pump as when the heat pump is bigger, it naturally prefers to run the heat pump to satisfy the heat requirements and the cogeneration engine is rarely used for the case of January 20. Only 21 kWh_e is produced. On the other hand, an extra 20 kWh of heat is produced.

Now, for the second study, constraints were imposed on the electricity that is purchased or sold to and from the system. The system considered for this study had all the previous units except the heat pump. This is done by imposing a constraint:

$$param(MaxPvariation) = P_{el_{grid}}(t) - P_{el_{grid}}(t-1) \quad (3)$$

A similar constraint was placed for the electricity sold by the system to the grid. In both cases the electric power variation was assumed to be a value, in figure 3 different strategies are show for a variation parameter for 0.1 kWe, 0.2 kWe and 0.3 kWe.

It is clear to see the difference in strategies. This constraint was imposed on the system to limit the amount sold from the system and the purchased to attempt to see, if this would maximise the use of the cogeneration engine.

4. Discussion

The results show that the predictive control strategy is able to handle the different situations and create strategies for a lot of different cases, regardless of the constraints that has been thrown at it by us. This reveals the robustness of the approach used and provides a strong base to build from.

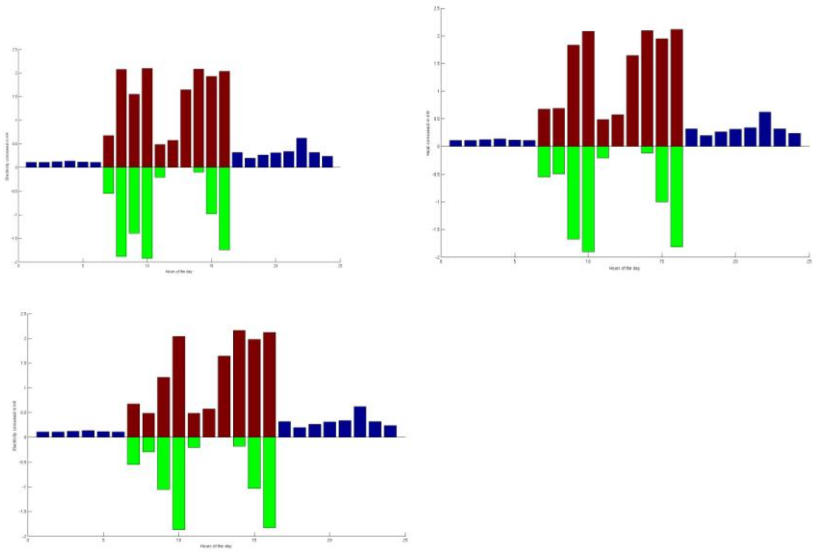

Figure 4: Consumption of electricity predicted when electricity purchase-sale constraints are included, the top left is constrained to 0.1, top right to 0.2 and bottom left to 0.3kWe each. Colours signify the same, red for cogeneration, green for electricity soid and blue, purchased.

At the same time, we would like to point out that some of the assumptions made for these studies are flawed. We realise this, but the aim of the study was to see if the optimal predictive controller could provide solutions to different situations and the different constraints thrown at it. The flaws or shortcomings of the current system are:

- The electrical flows are characterised in this study using just the active power components. In a real case, there is a need to maintain the quality of the power supplied from the grid and back to the grid and thus, the active and reactive power components need to be shown clearly
- The control at the level of a single building is robust but, in case of multiple buildings, the ability is still untested and this can only be tested through a better formulation of the power flow calculations and a better characterisation of the thermal components as well.

- The ability of the control to work as a virtual power plant or in a micro-grid which would imply the ability to work in an islanded case has still not been studied.

All of the above mentioned flaws have been studied and is being implemented in a revamped optimal predictive control system that uses multi-level calculations. This would be dealt with in a separate paper.

5. Conclusions

This paper shows the influence of the presence of or lack of heat pumps in tandem with cogeneration units in the scope of an optimal predictive control strategy. The difference in strategies that are shown here clearly elucidate the difference in energy stored due to the presence of a heat pump in a system along with a cogeneration and the lack of heat pump in a system. The constraints put on the electricity purchase and sale, clearly show the control strategy is able to adapt to new situations with different situations.

The optimal control strategy needs to be improved to more accurately incorporate the electrical components of the grid, so that a more accurate prediction of the electrical power can be done. Also, as the electrical power dynamics is much faster than the thermal system dynamics, that also needs to be considered.

There is also a need to improve the existing strategy to better represent the power flows using voltage control and sensitivity analysis and this is something that is being tested as of now. There is a need to validate the ability of the control robustly in a real-time situation. For this purpose, the controller will be put through a rigorous test on a micro-grid testbed being developed at EPFL.

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