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An Optimal Controller Design for a Waste Water Source Heat Pump System

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Abstract

Using municipal or residential waste water (WW) as an energy source for heat pump systems offers a great opportunity thanks to huge energy potential in WW, which is otherwise wasted. Recent interest in waste water source heat pump (WWSHP) technologies considers new component designs, mainly heat exchangers. In this paper, however, we focus on developing methods for optimal dynamic operation of a WWSHP system by employing advanced control and optimization algorithms. We consider an experimental WWSHP developed in Yasar University, Izmir, Turkey. We focus on the heating mode of the HP system, and compute optimal set points to compressor and condenser fan motor speeds to manipulate temperature of the cooling fluid as well as air temperature at the condenser exit. Preliminary results suggest that the MPC controller enhances the efficiency of the HP system in the presence of varying heat loads.

Keywords - Waste Water; Heat Pump; Optimal Control; Energy Efficiency

1. Introduction

Using municipal or residential waste water (WW) as an energy source for heat pump systems offers a great opportunity thanks to huge energy potential in WW, which is otherwise wasted [1]-[4]. Recent interest in waste water source heat pump (WWSHP) technologies considers new component designs, mainly heat exchangers. In this paper, however, we focus on developing methods for optimal dynamic operation of a WWSHP system by employing advanced control and optimization algorithms.

Control strategies play a vital role engineering systems since they provide safety and protection, stable and robust operation, as well as high performance. The control application (temperature, humidity) cannot be easily separated from the control of the heat pump (HP) system itself. The HP application and HP system operation characteristics are often integrated with each other because any change desired in the application area characteristics (humidity, temperature, etc.) translates to a change in the HP system operation (pump speed, process temperatures, pressure, etc.) Most of the HPs reported in the literature are controlled on a unit control basis with simple ON–OFF logic and Proportional-Integral-Derivative (PID) controllers. More advanced integrated system control design is not a common practice, except in few applications.

In [5], the author investigated water loop HP systems and developed strategies for (i) water loop pump control, (ii) water loop temperature control, (iii) fan control. The setpoints were changed according to a predetermined logic, and no dynamic model based control strategy was developed. In [6], an on–off logic was developed to control WW level between two setpoints. In [7], two water level controllers were used to control the water level in the WW storage tank, which were actuating WW the feed line and the discharge line. The hot water temperature (T2) at the hot water storage tank was the key performance variable that was controlled in the system via an on/off logic. In [8], a data acquisition and control subsystem monitored and directed the WWSHP system. A simple control logic was implemented to check start-up conditions of the WWSHP system.When the WW temperature was detected to be higher than the wastewater set point temperature, the system could be started. In [9], an experimental fruit drying setup was developed by utilizing an HP system. A constant drying air temperature is essential in fruit drying, since large fluctuations in temperature may result in low yield. The experimental setup in [9] consisted ofan HP system, an axial fan, thermocouples, process control equipment, an invertor and a drying chamber. The desired humidity andtemperature was achieved by a PID controller by setting the axial fan speed to blow right amount of outside air through the condenser. The PID controller was able to keep the drying air temperature within the desired band of 40–40.2 C. In [10], the authors presented an experimental setup of a WWSHP. The waste heat source temperature in the water tank was kept almost constant by using three electrical heaters with 2 kW power capacities. The operation of the heaters was controlled by means of a proportional integral–derivative (PID) temperature controller.

The ON/OFF and PID control strategies mentioned above are classified as ‘‘reactive’’. They generate new control actions when a deviation from the setpoint is detected, and do not consider the predictions of the future events, disturbances, or changes in the environment in a unified framework. In optimal control approach, however, dynamic relations between components of the system are described by mathematical models, and optimal control actions are computed through an optimization algorithm which takes a holistic look into the system behavior. From this perspective, optimal control is more complex to implement, yet, it provides better performance compared to on–off, pre-determined logic and PID controllers, which mostly control a single subsystem and lack system-wide coordination of the overall system components. In [11], increased energy efficiency with a 30% improvement in seasonal performance factor, compared to on–off control, is achieved by real-time optimization of the variable speed compressor, pump and fan operations. In [12], a hybrid heating system with a gas boiler and centrifugal HP utilizing sewage as a source of energy was presented. They developed an optimal operation strategy to minimize energy consumption based on thr mathematical model of the sewage source HP system. In [13], Kim et al. proposed an integrated WW and heatexchange network design using mixed integer nonlinear programming. In [14], Ikegami et al. developed an optimal control algorithm for a HP water heater (HPWH). They used a hybrid approach where a PV system was integrated with the HP system for overall efficiency increase. An extensive modeling effort including energy balance of PVs and loads, electric grid constraints, HP system constraints and dynamics, energy balance of the hot water demandand tank was pursued.

In this paper, we consider an experimental WWSHP developed in Yasar University, Izmir, Turkey. We focus on the heating mode of the HP system, and design a control algorithm to compute optimal set points to compressor and condenser fan motor speeds to manipulate temperature of the cooling fluid as well as the air temperature at the condenser exit.

2. Experimental WWSHP Setup

In this study a solar energy assisted wastewater source heat pump system has been investigated. The experimental setup is in Izmir, Turkey. A schematic illustration of the heat pump system is given in Fig. 1. There are three cycles in the experimental system; a wastewater cycle, a heat pump cycle and a heating/cooling utilization cycle. At the wastewater cycle, there is a heat exchanger between waste and refrigerant. The waste water temperatures are about 9-14°C and 26-29°C in winter and summer seasons, respectively. The velocity of the wastewater is about 1 m/s as similar with city

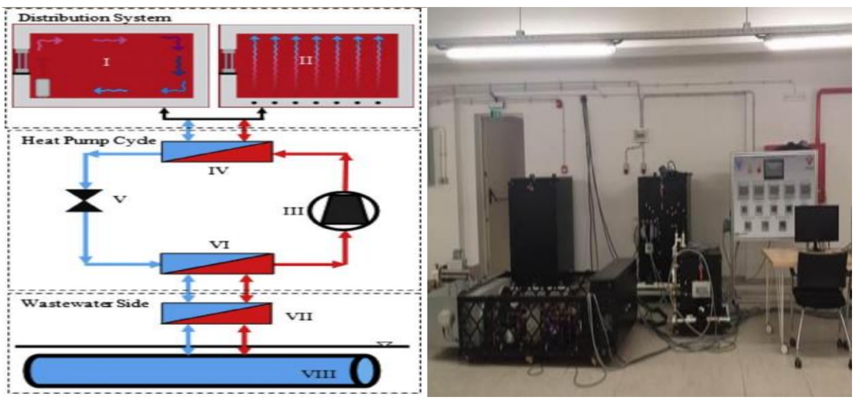

Figure 1. Schematic of experimental setup (I: Fan-coil system, II: Floor heating, III: Compressor, IV: Condenser/Evaporator, V: Expansion valve, VI: Evaporator/Condenser, VII: Wastewater HX, VIII: Wastewater line

wastewater lines. Wastewater cycle is a closed loop cycle and in the winter period, a photovoltaic thermal (PVT) system can be used as an auxiliary thermal source for the domestic hot water production. In the currents system, wastewater to air and wastewater to water heating/cooling can be realized. In this paper, only wastewater-air mode for heating is considered. The capacities of the heat pump cycle may be varied from 1.5 to 5kW using variable speed AC and DC compressors. R134a has been used as refrigerant in the HP cycle.

3. Model Development

In this section, we describe the development of the mathematical model of the heat pump system as it applies to our controllor design. For our control purposes, we identified the compressor and condenser fan speeds as the critical inputs affecting the cooling fluid temperatue and air temperature at the condenser exit. Thus, we focus our model development to identify the transient relation between the inputs and outputs as listed in Table 1.

Table 1. Inputs and outputs for the HP model

Control Inputs	**Units**
Compressor driver motor current (speed control)	**A**
Condenser fan motor current (speed control)	**A**
Outputs	
Cooling fluid temperature (Condenser exit)	**^{o}C**
Air temperature (Condenser exit)	**^{o}C**

The following linearized mathematical model of the HP system is considered for the control application:

$$\Delta x(k+1)=A\Delta x(k)+B\Delta u(k)+\mathrm{K}e(k)$$
$$\Delta y(k)=C\Delta x(k)+D\Delta u(k)+e(k)$$

where, k is the discrete time index, Δx represents the dynamical states of the HP system (as deviations from nominal steady state values), Δu are the control inputs, Δy denote the measured outputs (as deviations from nominal steady state values), and e(k) represents the measurement noise. The model matrices A, B,C, D and K are estimated using a subspace system identification technique [15]. Although a physics based first principles model could be developed for this system, we pursued system identification to better capture the dynamics of the experimental system. We first performed experiments to capture the dynamical response of the WWSHP system to changes in compressor and condenser fan motor speed as in Fig 2, and used these measurements to estimate the model parameters.

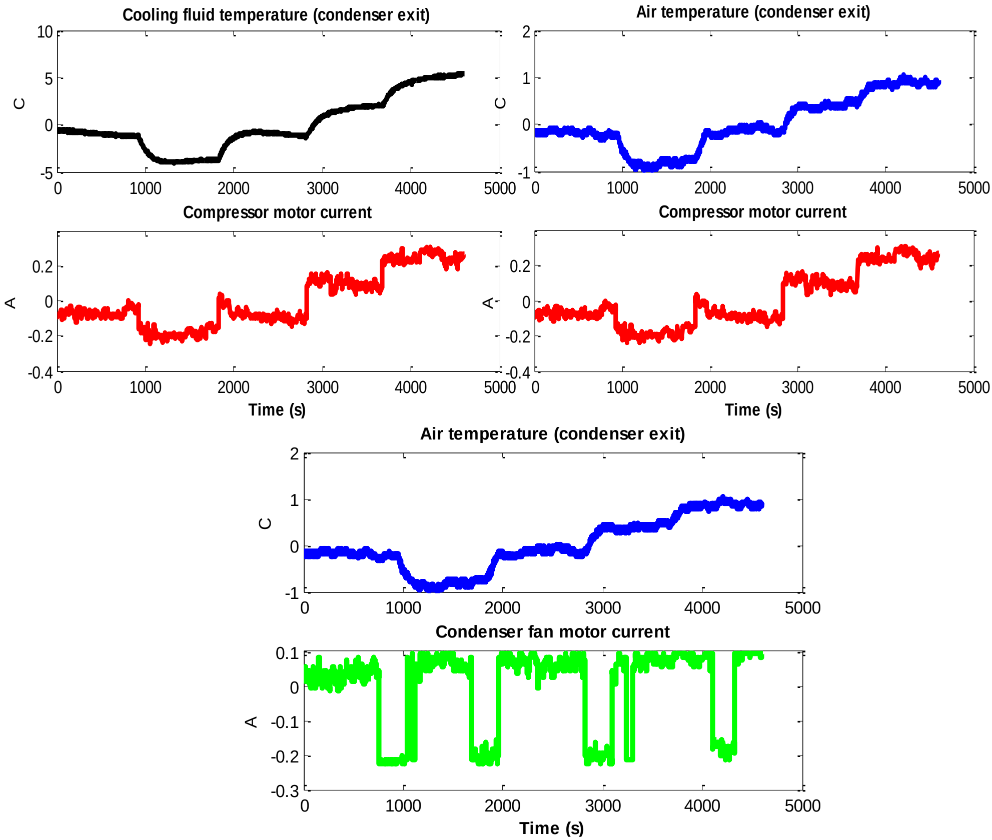

Figure 2. Dynamic response of the WWSHP system to changes in compressor and condenser fan motor speed (deviations from nominal values)

We used Matlab function `n4sid`, and estimated the model parameter matrices A, B, C, D and K as in Fig 3. For these model parameters, we observed that the system identification algorithm achieves a good fit between the mathematical model and the experiments on the physical HP system (see Fig 3). Thus, we concluded that our mathematical model is sufficiently accurate for designing the feedback control algorithm.

4. Model Predictive Controller

Model predictive control [16]-[17] (MPC) technique lies at the core of our waste water heat pump control system. MPC can optimize arbitrary performance metrics based on the dynamic model of the HP system. In the most general form of MPC, a finite horizon optimal control problem based on a nonlinear differential algebraic model of the process to be controlled is repeatedly solved online. Local solutions to the resulting discretized optimal control problem are computed using available algorithms for large scale

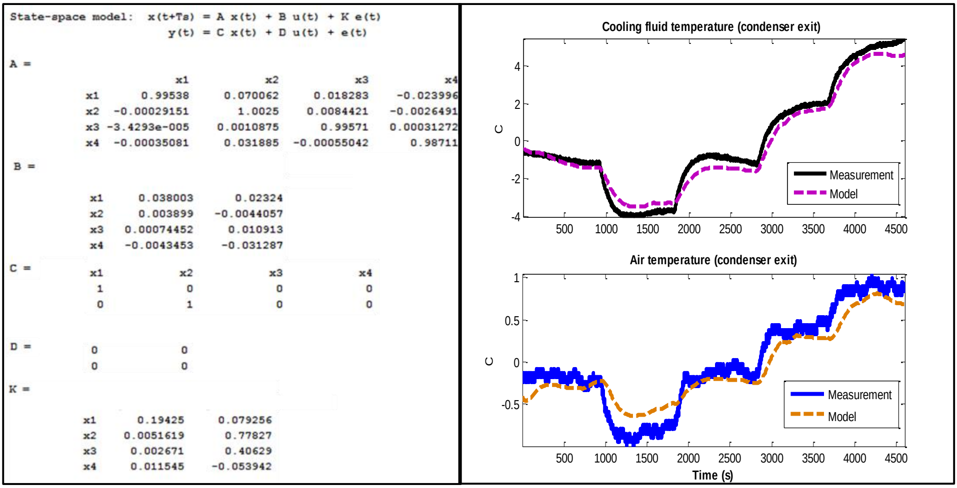

Figure 3. Model parameters (left) and comparison of the dynamic response of the mathematical model against the experimental results from the HP system (right)

sparse nonlinear programming problems, such as IpOpt [18]. MPC has seen widespread use in the industry thanks to its ability to calculate coordinated control actions to maximize defined performance criteria, while explicitly addressing both current and future constraints. Today, MPC technology development is a very active discipline, offering a large variety of techniques for industrial applications.

The operation of the MPC controller is described as follows. At every control step, data from measurements (or from state estimation algorithms) is acquired to obtain the most current representation of system dynamics. A system model is then called repeatedly to predict the dynamics and constraints within a time window of several minutes, while a constrained optimization problem is solved to obtain the optimal actuator set-points that minimize the defined objective, and is compliant with the operating constraints within the prediction window. Then, the first set of the optimal set-point values is sent as a reference to the actuators. Finally, a new set of measurements is acquired and the whole process is repeated for the subsequent control steps.

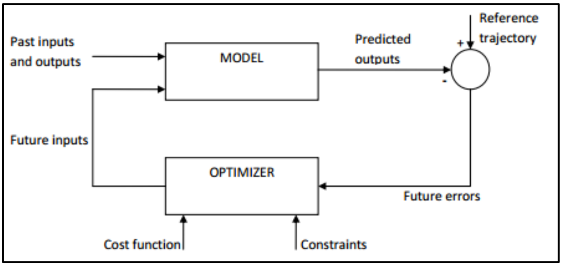

Figure 4. Structure of a Model Predictive Controller

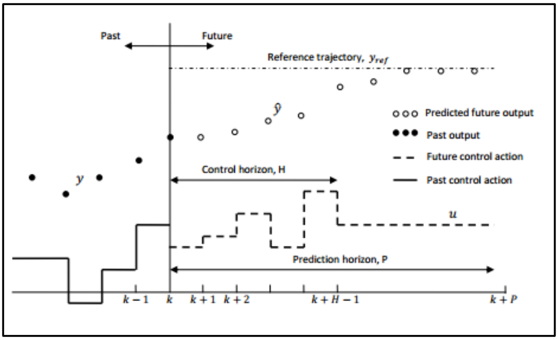

Figure 5. Basic Model Predictive Control Strategy

Our MPC controller is designed for the heating mode of the HP system, and at each time step it solves the following quadratic optimization problem to compute the optimal control inputs:

$$\text{Minimize} \quad \sum_{k=1}^{N} \left\{ \Delta x^T(k) P \Delta x(k) + \Delta u^T(k) Q \Delta u(k) + (\Delta y(k) - \Delta y_{\mathrm{ref}}(k))^T R (\Delta y(k) - \Delta y_{\mathrm{ref}}(k)) \right\}$$

$$\text{subject to} \quad \begin{aligned} &\Delta x(k+1) = A\Delta x(k) + B\Delta u(k) \\ &\Delta y(k) = C\Delta x(k) + D\Delta u(k) \\ &\Delta u_{\mathrm{min}} < \Delta u(k) < \Delta u_{\mathrm{max}} \\ &\Delta x_{\mathrm{min}} < \Delta x(k) < \Delta x_{\mathrm{max}} \\ &\Delta y_{\mathrm{min}} < \Delta y(k) < \Delta y_{\mathrm{max}} \end{aligned}$$

where k is the discrete time index, Δx represents the dynamical states of the HP system (as deviations from nominal steady state values), Δu are the control inputs, Δy denote the measured outputs (as deviations from nominal steady state values), N is the prediction horizon, P, Q, R are positive definite weighting matrices (MPC design parameters) in the objective function. In our problem, we used the following values in Table 2.

Table 2. MPC design parameters for the HP system

Parameter	**Value**
N (prediction horizon)	30
T (sampling period)	1.0 s
P	[0 0 0 0;0 0 0 0;0 0 0 0;0 0 0 0]
Q	[1.0 0.0; 0.0 0.5]
R	[0.5 0; 0 0.5]
Δx_max	[20.0 5.0 5.0 20.0]
Δx_min	[-20.0 -5.0 -5.0 -20.0]
Δu_max	[1.0 1.0]
Δu_min	[-1.0 -1.0]
Δy_max	[10.0 10.0]
Δy_min	[-10.0 -15.0]

The performance assessment of the optimal control algorithms is pursued by simulation on Matlab/Simulink platform. The MPC algorithm computes optimal *incremental* compressor and condenser fan motor current (variation from nominal value) at every time step.

5. Simulation Results

The design and preliminary tests of the control system is done in Matlab/Simulink environment. The linear discrete-time dynamic model of the heat pump system is embedded into the controller. The control system has a hierarchical structure (Fig 6). In the top layer, sensor measurements, reference values for the outputs of interest and MPC design parameters are collected.

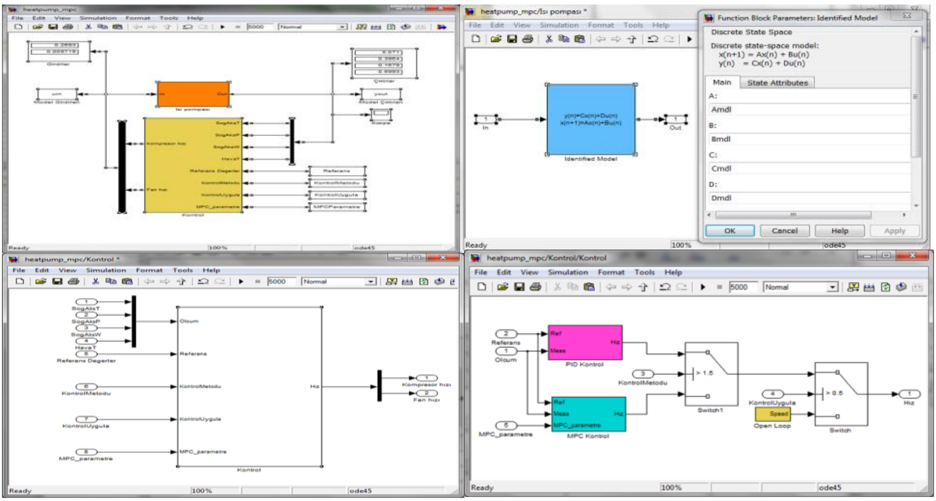

Figure 6. Matlab/Simulink implementation of the MPC controller

The MPC algorithm was run on a notebook computer with Windows7/64 bit, 4GB RAM, and an Intel Core i-5 2430 2.40Ghz CPU. Each MPC optimization run, on average, took 0.2 seconds to converge. Given that the system is sampled at 1Hz, this execution time is sufficient to run the MPC algorithm in real-time.

As seen in Figure 7, the MPC control algorithm has driven all of the output values to their reference values (equivalenty, zero daviation from nominal value). We observe that the MPC controller effectively regulates the compressor and fan motor currents to track cooling fluid and air temperatures at the condenser exit. It avoids costly on/off cycles and achieves close tracking by a relatively small incremental current commands. The response in the temperature is monotonically decreasing (ignoring chatter due to the sensor noise), showing that the MPC controller avoids large oscillations typically induced by on/off controllers.

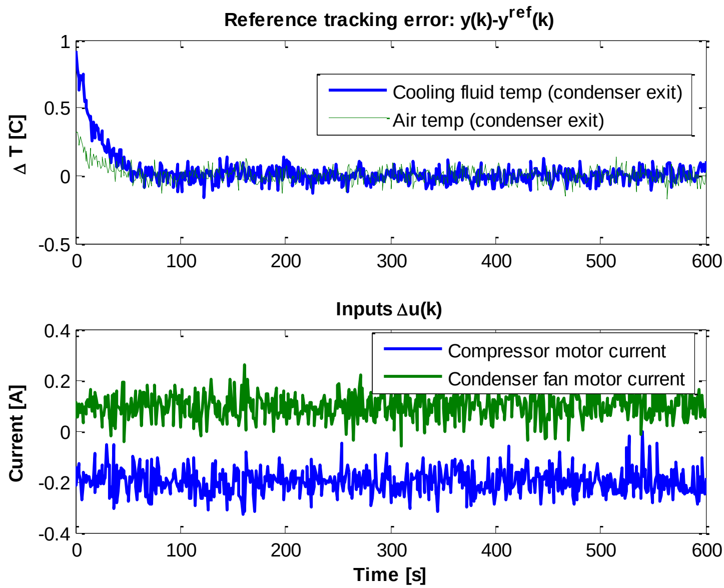

Figure 7. Response of the MPC controller to error in cooling fluid temperature and air temperature tracking (i.e. deviation from reference value). It commands nonzero incremental for compressor and condenser fan motors.

6. Conclusions

In this paper, we presented an optimal control framework for efficient operation of a waste water source heat pump system. The underlying mathematical model of the dynamic system is obtained by system identification methods. These models were then used in a model predictive controller that regulates motor speeds in the HP system. Simulation results suggest that the optimal control algorithm can provide a significant benefit by simply better operating the WWSHP system, and thus reduces the need for a significant investment in new hardware. Currently, we are implementing and testing the control algorithms in the experimental HP system.

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