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Structure and Control Co-Optimization for a CO_2 Heat Pump with Thermal Storages

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Abstract—Optimal design and control are coupled tasks for enhancement of energy system performances. Model-based dynamic optimization can enhance system performances significantly. However, it is difficult to obtain the optimal structure and control solution for a complicated nonlinear physical system model simultaneously, thus we proposed a coupled dynamic optimization method for structure and control co-optimization and implement it successfully for a transcritical CO_2 ejector expansion heat pump coupled with hot and cold thermal energy storages during energy charging process. A complicated nonlinear dynamic system model with genetic algorithm were used to obtain the structure and control co-optimization solution of the coupled system during energy charging. The structures of gas cooler, evaporator, hot and cold thermal storage tanks were optimized, and dynamic optimal control strategy was obtained for energy charging process. Compared to the constant control parameter strategy, the overall coefficient of performance can be increased by 21.1%. The performances can be enhanced more significantly if the water temperature at the hot tank outlet remains at a low level, i.e. the charging time reduced. This study would be helpful for a structure and control co-optimization of other dynamic energy systems.

Keywords—structure and control co-optimization, nonlinear dynamic system model, ejector expansion heat pump, thermal energy storages

I. Introduction

Heat pump coupled with thermal energy storages can minimize operational cost and CO2 emissions, enhance grid stability and can be the most cost-effective Smart Grid enabling option for supporting higher penetration levels of intermittent renewables in the energy system [1][2]. Combining heat pump with thermal energy storage allows the shifting of heat demand to off peak periods or periods with surplus renewable electricity [3][4]. Extra shifting flexibility of peak loads on the electric grid can be added in the form of a thermal energy storage tank [5]. Application of seasonal thermal energy storage with heat pumps for heating and cooling buildings has received much consideration in recent decades [6]. This study is to improve the overall charging performances of a transcritical CO2 ejector expansion heat pump coupled with hot and cold thermal energy storages by using a new coupled dynamic optimization method for structure and control co-optimization, which is an extension of our previous work on charging of hot and cold thermal storages using a transcritical CO2 heat pump [1][7][8][9].

The performances of heat pump system coupled with thermal storage are influenced significantly by the types of refrigeration cycles [10], operation strategies [11][12] and control strategies [7]-[9]. Liu et al. [8] introduced an ejector to replace the conventional expansion valve in the transcritical CO2 heat pump system with thermal storages and significantly enhanced the overall COP of system during energy charging process. There are some optimal control methods for maximizing the COP of a CO2 heat pump coupled with thermal storage [8][9][13]. Minetto [13] developed a control method for optimizing the upper pressure of a cycle to maximize the COP of a CO2 heat pump coupled with a hot water storage tank. Using the outlet water temperatures of thermal storage tanks as the control indicators, Liu et al.[9] proposed a novel experiment-based real-time near-optimal control strategy for charging of hot and cold thermal storages using a dual-mode CO2 heat pump with an expansion valve; furthermore, they developed a model-based single-objective dynamic optimization strategy for heat pump with thermal storages, and found that the later can enhance the overall COP during energy charging more significantly [7]. Liu et al. [8] used the controllable ejector throat area, compressor frequency, circulating hot and cold water flow rates as four control parameters, and proposed a multi-objective non-simultaneous dynamic optimal control method for maximizing the overall COP of an ejector expansion CO_2 heat pump with thermal storages during energy charging, which considers effects of thermal stratification in thermal storage tank on system performances. There are some studies on design optimization of a free-piston Vuilleumier heat pump [14][15]. However, there are few studies found on design and control co-optimization for an ejector expansion heat pump coupled with thermal storages in the literature.

Design of physical systems and their associated control systems are often coupled tasks [16]. Deshmukh and Allison [16] presented a novel approach for optimizing wind turbine design using a simultaneous control and physical system co-design method to achieve system optimal solutions. Evins et al. [17] presented a new approach to the optimisation of Double-Skin Facades using a genetic algorithm to discover the best configuration and control strategies for a given scenario from scratch, rather than using a particular configuration type. Chen and Lin et al. [18] developed a general systematic and computationally-efficient method which enables automated and simultaneous optimization of passive selective catalytic reduction (SCR) system architectures and the associated non-uniform cylinder-to-cylinder combustion (NUCCC) controls based on a newly proposed highly reconfigurable passive SCR model structure and integer partition theory. Hosseinirad et al. [19] proposed a gradient-descent method to optimize simultaneously the configuration and the controller in a solar domestic hot water system, in which circulating water pumps rate and the heat pump compressor rate are control parameters, and the height of thermal storage tank is a configuration parameter; and found that simultaneous optimization of the system configuration and the feedfoward controller provides 53% improvements of the cost function compared to individual optimization only. However, the outlet temperature of the heat pump and the solar thermal collector were represented by a static model in their study. Renaldi et al. [3] presented an integrated framework for the design and operational optimization of an air-source heat pump system with hot water thermal energy storage tank, based on the mixed integer linear programming (MILP) technique, with discrete equipment sizing. During the optimisation the system sizes (HP rating and TES size), and the operational state of the units, e.g. HP output, are modified to find the lowest total cost for the given conditions, e.g. tariff and resistive heater rating [3]. The MILP-based optimisation framework which employs low complexity models can be solved relatively fast compared to dedicated software tools, such as TRNSYS. However, energy systems are complicated nonlinear dynamic systems. Model-based dynamic optimal control strategy can enhance charging performances of heat pump with thermal storages significantly [7][8]. But there is a lack of study on structure and control co-optimization of an ejector expansion heat pump coupled with hot and cold thermal storages during charging process based on a nonlinear dynamic system model, which considering the structures of gas cooler, evaporator, hot and cold thermal storage tanks.

Therefore in this study we proposed a model-based coupled dynamic optimization method for structure and control co-optimization of a transcritical CO2 ejector expansion heat pump coupled with hot and cold thermal storages, in which the transient performance parameters of such coupled system are used as the optimization objective functions, instead of the cost as often used in the literature. The structure parameters of gas cooler, evaporator, hot and cold thermal storage tanks were optimized, together with the control parameters of ejector throat area, compressor frequency, circulating hot and cold water flow rates. This study would be helpful for enhancing the dynamic performances of a heat pump with thermal storages during energy charging.

II. DYNAMIC MODEL AND VALIDATION

Figure 1 presents a transcritical CO2 ejector expansion heat pump coupled with hot and cold thermal energy storages. Nonlinear dynamic system model for energy charging has been developed and validated based on the experimental results in our previous study [8]. The readers are referred to [8] for the details of the dynamic system model and validation.

The water-side transient total COP and overall COP of HPTES through energy charging were calculated using Eqs. (1) and (2), respectively [8].

Transient total COP:

$$COP_{tot} = \frac{Q_{clg} + Q_{htg}}{W_{comp} + W_{pump,c} + W_{pump,h}} \quad (1)$$

Overall COP:

$$COP_{ov} = \frac{\sum_{i=0}^{n} Q_{htg,i} \cdot t_{i\rightarrow i+1} + \sum_{i=0}^{n} Q_{clg,i} \cdot t_{i\rightarrow i+1}}{\sum_{i=0}^{n} W_{tot,i} \cdot t_{i\rightarrow i+1}} \quad (2)$$

where i is the recorded number during energy charging, $t_{i\rightarrow i+1}$ is the interval time between two records, and $\dot{W}_{tot} = \dot{W}_{comp} + \dot{W}_{pump,c} + \dot{W}_{pump,h}$.

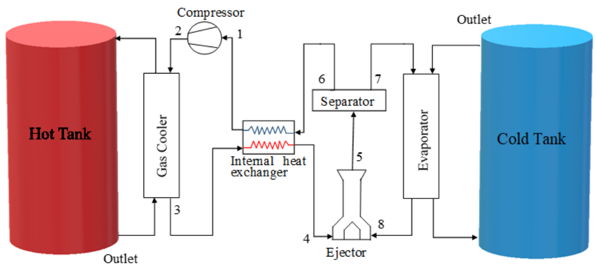


Fig. 1. Ejector expansion CO_2 heat pump coupled with thermal storages

III. STRUCTURE AND CONTROL CO-OPTIMIZATION

In order to solve the structure and control co-optimization problem of a heat pump with thermal storages, a coupled dynamic optimization method was developed based on the nonlinear dynamic system model. Figure 2 presented the flow chart of structure and control co-optimization method for an ejector expansion heat pump with thermal storages. The optimization procedure can be presented as the following steps.

Step 1: Input the initial values of $T_{h,o}$ and $T_{c,o}$, and experimental system structure parameters into the dynamic system model for control optimization.

Step 2: Determine the optimal control parameters using GA under initial operating condition.

Step 3: Input the initial optimal control parameters into the dynamic system model for system optimization.

Step 4: Determine the optimal structure parameters using GA under initial operating condition and initial optimal control parameters.

Step 5: Repeat Step 2 to Step 4 until the termination criterion is satisfied, for example, the differences of all structure parameters between two consecutive iterations is less than 5%.

Step 6: Input the final optimal structure parameters into dynamic system model for dynamic optimal control strategy of energy charging.

Step 7: Determine the transient optimal setting points using GA during energy charging.

Step 8: Input the optimal setting points into dynamic system model and update the values of $T_{h,o}$ and $T_{c,o}$.

Step 9: Repeat Step 6 to Step 8 until the average water temperatures in thermal storage tanks reach the set values.

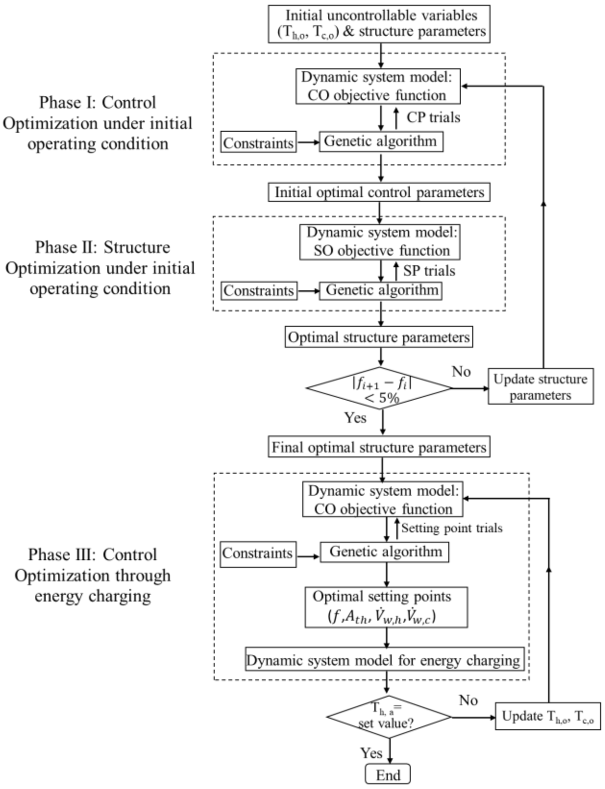


Fig. 2. Flow chart of structure and control co-optimization method

IV. Results and Discussions

TABLE 1. STRUCTURE AND CONTROL CO-OPTIMIZATION CONSTRAINTS

	Parameters	start	min	max
Structure	N_{gc} (-)	10	3	20
	$L_{gc,pl}$ (m)	0.329	0.2	0.5
	$W_{gc,pl}$ (m)	0.072	0.05	0.1
	$\varphi_{gc,pl}$ (°)	35	15	80
	L_{ev} (m)	5.47	2	10
	$D_{ev,i}$ (mm)	12.7	0	30
	$D_{ev,o}$ (mm)	22.2	0	30
	D_h (m)	0.4	0.25	0.8
	H_h (m)	1.4	0.8	2.2
	D_c (m)	0.4	0.25	0.8
	H_c (m)	1.3	0.8	2.2
Control	f	40	30	50
	$\dot{V}_{w,c}$	0.18	0.10	0.50
	$\dot{V}_{w,h}$	0.18	0.10	0.50
	A_{th}	0.5	0.2	0.70

Using the above coupled dynamic optimization method, structure and control co-optimization has been conducted for an ejector expansion heat pump with hot and cold thermal storages. The initial transient outlet water temperatures of hot and cold thermal storage tanks are set as 27°C. The structures of gas cooler, evaporator, hot and cold water tanks in the experimental setup were used as the initial values for the co-optimization as listed in Tables 1. The charging process ended when the average water temperature in hot storage tank increased up to 60°C. Table 2 lists the determined optimal structure parameters of gas cooler, evaporator, hot and cold water tanks. Table 3 lists the dynamic optimal control strategy during energy charging, which can be divided into three phases according to the dynamic operating conditions.

TABLE 2. OPTIMAL STRUCTURE OF A HEAT PUMP WITH THERMAL STORAGES

	Gas cooler		Evaporator		Thermal storage tanks	
	Parameters	Value	Parameters	Value	Parameters	Value
Structure	N_{gc} (-)	15	L_{ev} (m)	6.64	D_h (m)	0.47
	$L_{gc,pl}$ (m)	0.39	$D_{ev,i}$ (mm)	12	H_h (m)	1.55
	$W_{gc,pl}$ (m)	0.089	$D_{ev,o}$ (mm)	24	D_c (m)	0.36
	$\varphi_{gc,pl}$ (°)	40			H_c (m)	1.56

TABLE 3. DYNAMIC OPTIMAL CONTROL STRATEGY DURING ENERGY CHARGING

Stage no.	Charging time(s)	f (Hz)	A_{th} (mm^2)	$V_{w,c}$ (m^3/h)	$V_{w,h}$ (m^3/h)
1	0 - 1785	30	0.303	0.2	0.120
2	1785 - 4210	34	0.298	0.3	0.108
3	4210 - 5730	35	0.390	0.3	0.250

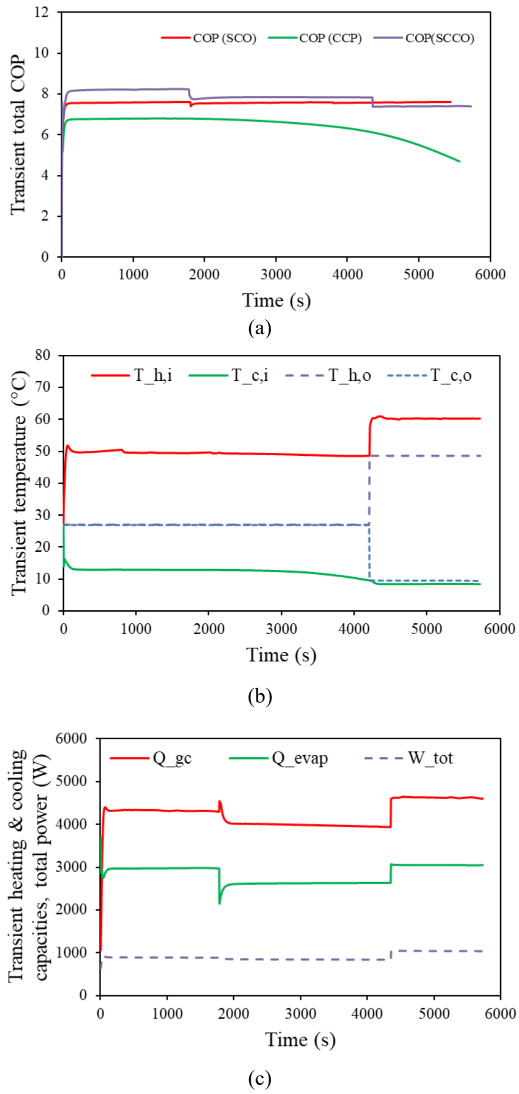
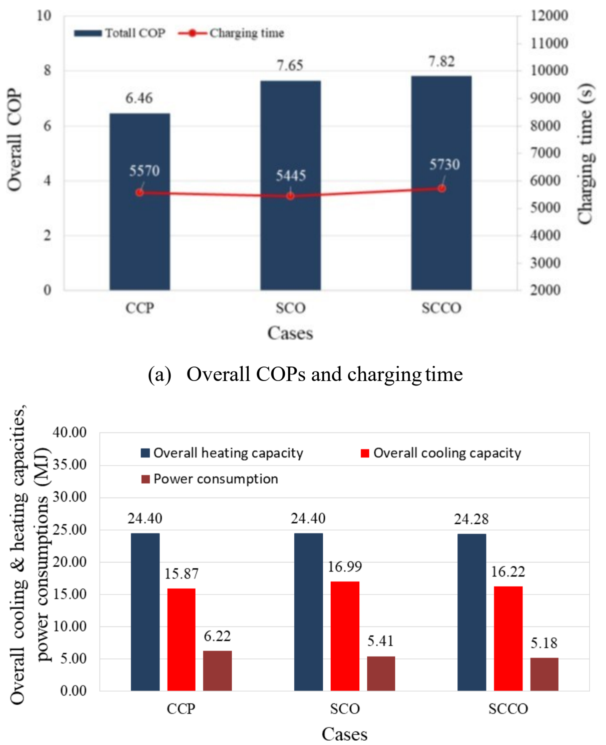


Fig. 3. Transient charging performances of an ejector expansion heat pump with thermal storages during energy charging

Figure 3 presents the transient charging performances of an ejector expansion heat pump with hot and cold thermal storages during energy charging. Fig. 3(a) shows that the transient total COP remains at a higher level by SCCO than that by using single-objective dynamic optimal control strategy (SCO), which was developed in our previous study [8], from the beginning of energy charging process until the charging time around 4350 seconds, then the transient total COP dropped down lower than that using SCO strategy, which could be due to the rapid increase of the outlet water temperature in hot storage tank (Fig.3b). Fig. 3(c) shows that the transient heating capacity, cooling capacity and total power consumption vary with the energy charging time, and increase rapidly as the outlet water temperature of hot storage tank increases suddenly.

Figure 4 presents comparisons of the overall energy charging performances of an ejector expansion systems using SCCO with constant control strategy and single-objective dynamic optimal control strategy, which were developed in our previous study [7][8], for a whole charging process. As shown in Fig. 4(a), the total charging time is 5730 by using the co-optimization method, while the total charging time is 5445 seconds by using SCO strategy. Using SCCO, the overall COP reached up to 7.82, increased by 2.2% compared to the overall COP using SCO and increased by 21.1% compared to the overall COP using constant control parameter as shown in Fig. 4 (a). The total power consumption using SCCO is less than those using SCO and CCP as shown in Fig. 4(b). If the energy charging ended earlier, more significant enhancement on overall COP can be achieved by using this proposed SCCO method.



(a) Overall COPs and charging time

(b) Overall heating and cooling capacities and total power consumption

Figure 4. Comparisons of overall charging performances of an ejector expansion systems using SCCO with CCP and SCO control strategies

Above all, structure optimization cannot be dynamic, while energy charging is an unstable process, thus it should be very careful for selection of structure and control co-optimization strategy for a dynamic system, such as a heat pump coupled with thermal storages.

V. Summary

In this study, we proposed a coupled dynamic optimization method for the structure and control co-optimization of an ejector expansion heat pump with thermal storages during energy charging, and implemented it successfully. Comparisons of charging performances of HPTES using a structure and control co-optimization method and using only dynamic optimal control strategy show that the overall COP of such coupled dynamic system during energy charging can be enhanced slightly, which could be owing to our good design before. The advantage of structure and control co-optimization could be more obvious for a lower outlet water temperature of hot water tank, i.e. a shorter charging time. This study would be helpful for selection of optimization method for a dynamic energy system. In the future, effects of thermal hysteresis induced by thermal storages would be considered into the dynamic optimal control strategy.

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