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Research Paper

Multi-objective optimization of the operational modes for redundant refrigeration circuits

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HIGHLIGHTS

- Optimal control for redundant refrigeration circuits and multiple compressors.
- A method is presented to optimize the provision of the required cooling capacity.
- Different goals, such as reducing the wear or energy demand can be achieved.
- Implementation with little computing power by using off-line optimization.

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ABSTRACT

This paper presents a method to optimize the provision of the required cooling capacity in redundant refrigeration circuits with respect to several conflicting goals. The proposed method is presented for a refrigeration system with redundant refrigeration circuits and multiple compressors. The cooling capacity required by an arbitrary controller can be delivered by such a system using several different operation modes. Each mode is characterized by the respective active components and the values of the individual continuous control variables. The resulting degrees of freedom can be utilized to optimize additional goals such as energy consumption and wear. The optimal process operation can thus be formulated as a optimization problem for a hybrid system. An important highlight of the proposed method is the computational efficiency, which allows the implementation in an inexpensive micro-controller. This is achieved by solving the computationally most expensive part of the problem off-line and storing the result in look-up tables. Simulation examples demonstrate the effectiveness and performance of the proposed method.

1. Introduction

Refrigeration systems (RSs) consume a substantial amount of energy and are a large source of peak electrical demand. There is also a rising trend towards higher consumption of several food products with consequent increase in environmental impacts. Such a significant impact are greenhouse gas emissions, [1]. In UK the commercial food sector, including agriculture, food manufacture, transport and retail is responsible for 22% of the total greenhouse gas emissions. Technologies and approaches in food transport refrigeration and their environmental affects are reviewed in [2]. The impacts are expressed in terms of greenhouse gas emissions arising from the fuel consumption of the vehicle and refrigeration system engines and refrigerant leakage to the environment. Norway is yet another example. In Norway, seafood is one of the largest exports, mostly in fresh, frozen or dried form, [3]. One study reported by [4] shows that there are at least one million refrigerated road vehicles in use in the world. Therefore, one of the objectives of technical development of RSs is to increase their energy efficiency. In the case of using an internal combustion engine as primary energy source also the reduction of emissions is crucial.

Typically, an RS is designed for one specific operating point, but it operates most of the life time in conditions significantly different from design cases. Therefore, it is worth to analyze how to make these systems operate more efficiently by optimizing all operational modes.

One method of achieving higher efficiency is through cooling capacity control. Cooling capacity control methods commonly employed are optimal on-off control, hot gas bypass, suction pressure control, multiple compressor control and variable speed

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Nomenclature

$\boldsymbol{c}$	all counts of compressor switching for $\boldsymbol{\sigma}_{\mathrm{act}}$
c_l	count of compressor switching for $\boldsymbol{\sigma}_{\mathrm{act}_l}$
E_{el}	energy consumption in J
f_i	function of the static RC i model
f_h	function of the compressor status
g_{eq}	equality constraint
$\boldsymbol{g}_{\mathrm{ineq}}$	inequality constraints
$\boldsymbol{h}$	hours of all compressors of the RS in h
$h_{i,j}$	operating hours of compressor j of RC i in h
$\boldsymbol{H}$	sum of the operating hours of all combinations σ_{act} in h
H_l	sum of the operation hours of the lth combination of σ_{act} in h
i	index for the RC
j	index for the compressors
J_{C}	cost function of the continuous decision values
J_{D}	cost function of the discrete decision values
J_{D1}	cost function of compressor switching
J_{D2}	cost function of operating hours
J_{E}	cost function of power consumption
J_{o}	cost function of other criteria (such as control settling time)
J_{W}	cost function of wear
k	index of the permutations
K	indices of the permutations which can provide $\dot{Q}_{req}$
l	index of the subset of the compressor combinations σ_{act}
$\mathcal{L}$	Lagrange function
mc_{p}	thermal mass capacity of the ICB in $\frac{\mathrm{kg\ m^2}}{\mathrm{s^2\ K}}$
n_c	sum of all compressors in the RS
n_i	sum of all compressors in the RC i
n_k	number of permutations
n_l	number of all compressor combinations in the subset $\boldsymbol{\sigma}_{\mathrm{act}}$
$n_{n_{RC}}$	sum of all compressors in the RC n_{RC}
n_{RC}	number of RCs
$p(\overline{\dot{Q}})$	probability density function
p_{D_i}	discharge pressure of RC i in bar
P_{el}	total electrical power of the active RCs in kW
$P_{\mathrm{el},i}$	electrical power of the RC i in kW
P_{el}^k	total electrical power of the permutation with index k in kW
p_{S_i}	suction pressure of RC i in bar
$\dot{Q}$	total cooling capacities of the active RCs in kW
$\overline{\dot{\boldsymbol{Q}}}_{\Sigma}$	possible cooling capacity range of all permutations in kW
$\dot{Q}_{\mathrm{H}}$	total heating capacity of the active RCs in kW
$\dot{Q}_{\mathrm{H},i}$	heating capacity of the RC i in kW
$\dot{Q}_i$	cooling capacity of the RC i in kW
$\overline{\dot{\boldsymbol{Q}}}_k$	range of possible cooling capacity from permutation k
$\overline{\dot{Q}}_{\mathrm{min},k}$	smallest possible cooling capacity from permutation k
$\overline{\dot{Q}}_{\mathrm{max},k}$	maximum possible cooling capacity from permutation k
$\dot{Q}_{\mathrm{M}}$	average cooling capacity of the active RCs in kW
$\dot{Q}_{\mathrm{req}}$	desired cooling capacity in kW
$\boldsymbol{S}$	switching event
$\boldsymbol{s}$	compressor states of all compressors of the RS
$\boldsymbol{s}_i$	compressor states of all compressors of RC i

$s_{i,j}$	compressor state of the compressor j of RC i
T	simulation time in sec
t	index of the simulation time
T_{amb}	ambient temperature in °C
T_{box}	ICB temperature in °C
$T_{\mathrm{box,set}}$	ICB set temperature in °C
t_{cst}	control settling time in sec
T_{D_i}	discharge temperature of RC i in K
T_{evap_i}	evaporator temperature of RC i in K
ΔT_{SH_i}	superheat of RC i in K
v_i	valve position of RC i in %
$\boldsymbol{W}(S\|K)$	switching probability of all permutation indices in K
$W_k(S\|K)$	switching probability of the permutation with index k
$\boldsymbol{z}_{\mathrm{env}}$	measurable environmental conditions

Greek

α	weighting factor
$\varkappa A$	heat transfer coefficient of the ICB in $\frac{\mathrm{W}}{\mathrm{K}}$
λ	Lagrange multiplier for equality constraints
$\boldsymbol{\mu}$	Lagrange multiplier for inequality constraints
$\boldsymbol{\sigma}$	vector of all discrete decision variables of the RS
$\boldsymbol{\sigma}_{\mathrm{act}}$	subset of σ with the actual compressor combinations
$\boldsymbol{\sigma}_{\mathrm{act},l}$	the lth compressor combination of $\boldsymbol{\sigma}_{\mathrm{act}}$
χ_{ar}	set of constraints
$\boldsymbol{\Psi}$	vector of all continuous decision variables of the RS
$\boldsymbol{\Psi}_i$	vector of all continuous decision variables of the RC i
$\overline{\boldsymbol{\Psi}}_{\mathrm{max},i}$	vector of time-varying maximal system constraints of the RC i
$\overline{\boldsymbol{\Psi}}_{\mathrm{min},i}$	vector of time-varying minimal system constraints of the RC i
$\boldsymbol{\omega}$	speed of all compressors of the RS in rad s^{-1}
$\boldsymbol{\omega}_i$	speed of all compressors of RC i in rad s^{-1}
$\omega_{i,j}$	speed of the compressor j of RC i in rad s^{-1}
$\boldsymbol{\omega}_{\mathrm{FC},i}$	speed for the condenser fan of the RC i in rad s^{-1}
$\boldsymbol{\omega}_{FE,i}$	speed for the evaporator fan of the RC i in rad s^{-1}
ω_m	speed of the ICE in rad s^{-1}

Sub-/superscript

$\bullet_{,\mathrm{B}}$	subscript for method B
$\bullet_{,\mathrm{b}}$	subscript for method b
$\bullet_{\mathrm{max}}$	subscript for the maximal value of $\bullet$
$\bullet_{\mathrm{min}}$	subscript for the minimal value of $\bullet$
$\bullet^{\star}$	optimal value of $\bullet$
$\overline{\bullet}$	value of $\bullet$ considering constraints

Abbreviations

COP	coefficient of performance
EXV	electronic expansion valve
ICB	insulated cool box
ICE	internal combustion engine
PID	proportional-integral-derivative controller
PI	proportional-integral controller
RC	refrigeration circuit
RMSE	root-mean-squared error
RS	refrigeration system

control. The most energy efficient method is the variable speed control and the multiple compressor strategy, [5].

Several studies have demonstrated the potential savings associated with the use of variable speed control. In [6] the potential electricity savings by using a variable speed compressor and a controller for air conditioning systems is shown. In [7] a feed-forward control for a variable speed refrigeration system is introduced. A PI controller manages the thermal capacity and superheat independently for saving energy and to improve the coefficient of performance (COP).