МОДЕЛИРОВАНИЕ И УПРАВЛЕНИЕ СТРАТЕГИЯМИ МИНИМИЗАЦИИ ЭНЕРГОПОТРЕБЛЕНИЯ ЦЕНТРА ОБРАБОТКИ ДАННЫХ

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Аннотация: *проанализированы методики минимизации объемов энергопотребления центров обработки данных путем получения оптимальных пропорций между электропотреблением системы охлаждения и вычислительной системы. Показано, что проблема ограничения энергоэффективности как основного ограничительного фактора для работы центров обработки данных может быть решена путем разработки моделирования динамики термо-профиля серверного зала. Проанализированы гибридные охладительные системы, которые сегодня широко используются в центрах обработки данных. Внедрение гибридных схем требует проведения анализа структуры виртуальных машин и использования более высокого уровня охлаждения благодаря высокой рабочей температуре активных серверов. Разработано решение для оптимизации гибридной архитектуры охлаждения, что позволяет достичь общей минимизации потерь мощности, удовлетворяя базовые требования, указанные в соглашении об уровне обслуживания центра обработки данных. Предложенное решение значительно расширяет удобство охлаждения для центров обработки данных, учитывая климатические условия, нагрузки серверов, температурный режим сервера и архитектуру системы охлаждения сервера. Было продемонстрировано, что для разработки модели оптимизации энергопотребления необходимо оценить оптимальный режим охлаждения и максимальное энергопотребление активных серверов. Для определения графика работы элементов системы охлаждения необходимо оценить энергопотребление центров обработки данных, базовые расходы, количество серверов, виртуальных машин и их размещения. Было проведено сравнение трех типов режима охлаждения для центров обработки данных: фиксированный температурный режим, P-адаптивный режим и PT-адаптивный режим. Фиксированный режим температуры, как обычный режим охлаждения, который использует свободное охлаждение только тогда, когда исходная температура ниже заданной температуры, оказался неэффективным, тогда как P-адаптивный режим и PT-адаптивный режим могут быть использованы в рамках разработанной методологии. Модель оценки эффективности режима охлаждения позволила рекомендовать PT-адаптивную схему, в наибольшей степени оптимизирует процесс потребления энергии и уменьшает затраты на переключение между режимами охлаждения.*

Ключевые слова: *центр обработки данных, потребление электроэнергии, виртуальная машина, режим свободного охлаждения, режим электро-охлаждения, режим фиксированной температуры, PT адаптивный режим.*

MODELING AND CONTROL OF DATA CENTER POWER CONSUMPTION MINIMIZATION STRATEGIES

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Abstract: *optimization of data center power utilization by getting a proper proportion of computing and cooling power consumption reducing was discussed. It was shown that energy-efficiency constraints problem as a main limiting factor for data centers performance can be solved by thermal modeling and control solutions development. Hybrid cooling solutions which nowadays widely used in a data centers were analyzed. Hybrid cooling schemes require to provide analysis of virtual machines structure organization and utilize higher cooling capability due to the high operating temperature of active servers. Computational and cooling power consumption optimization solution was developed for hybrid cooling architecture. It allows to achieve overall power loss minimization with satisfying of service-level agreement requirements. Proposed solution significantly extends the usability of free cooling for data centers, while it takes into account climate condition, servers' workload, server room's temperature profile and server cooling architecture. It was demonstrated that for development joint power consumption optimization model it is necessary to estimate optimal cooling mode regime and maximum power consumption of active servers. For determination of chillers work schedule it is necessary to estimate power consumption of datacenter, cooling mode transition overheads, number of servers, virtual machines and its placement. There were compared three cooling mode solutions for data centers: fixed temperature regime, P-adaptive regime and PT-adaptive regime. Fixed temperature regime as conventional cooling mode which uses free cooling only when output temperature is lower than pre-defined temperature was proved to be inefficient while P-adaptive regime and PT-adaptive regime was proved to be preferable ones. Developed model of cooling mode efficiency estimation allowed to recommend PT-adaptive regime as adaptive mode which jointly optimizes the power consumption and transition overhead.*
Keywords: *data center, power consumption, virtual machine, free cooling mode, electrical cooling mode, fixed temperature regime, PT-adaptive regime.*

1. Introduction

Data center power utilization level can be optimized by getting a proper proportion of computing and cooling power consumption reducing. Usually conventional computing power minimization solutions lead to actual CPU utilization increase and require higher cooling capability in order to work with increased heat density of active servers. Nowadays hybrid cooling solutions are widely used in a data centers [1-3], which requires to provide further analysis of virtual machines (VM) structure organization and reduces the chance of using free cooling; hybrid cooling schemes usually require high cooling capability due to the high operating temperature of active servers [4-8].

Therefore joint computational and cooling power consumption optimization solution for data centers was proposed (Figure 1). It was developed for hybrid cooling architecture and allows to achieve overall power loss minimization with satisfying of service-level agreement (SLA) requirements. Proposed solution significantly extends the usability of free cooling for data centers having a hybrid cooling architecture. It takes into account all input parameters of data center server room infrastructure, specifically climate condition, servers' workload, server room's temperature profile and server cooling architecture. Statistics of the climate condition and servers' workload [9-11, 19] forms artificial neural network (ANN) training dataset and further can be forecasted by predictive control scheme. In other hand server room's temperature profile and the dependency between the server temperature and cooling solutions can be simulated and modeled by standard algorithms [12-18].

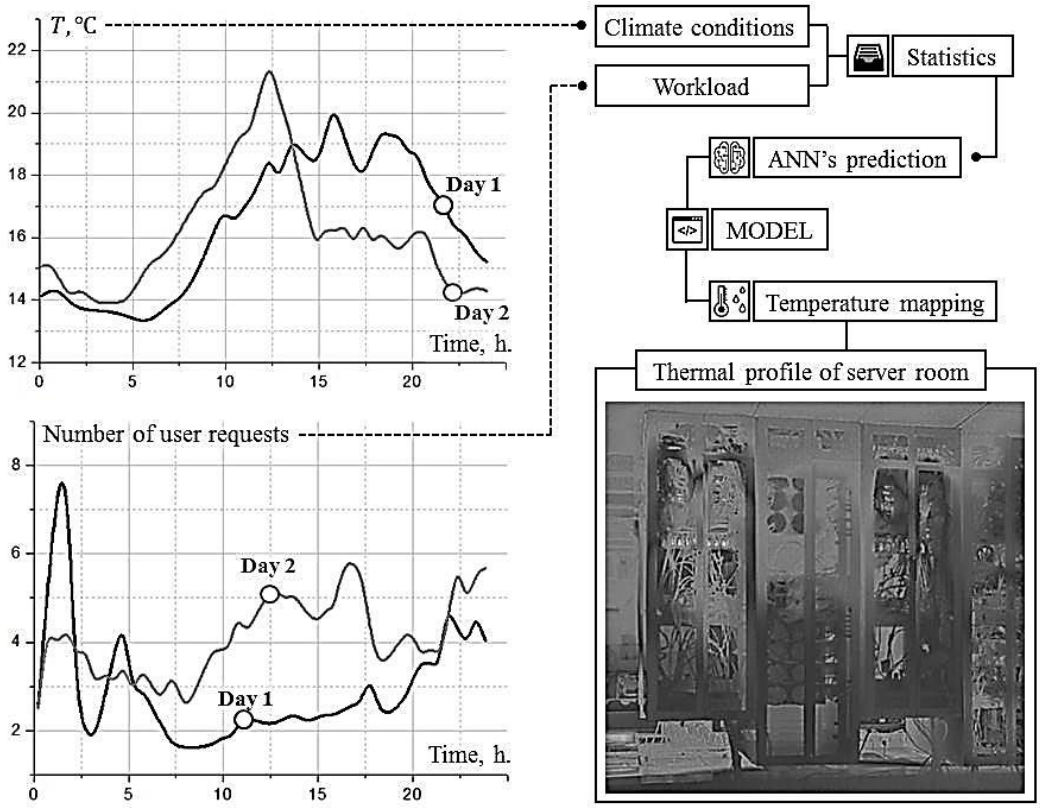

Fig. 1. Joint power consumption optimization scheme for hybrid cooling architecture

To identify the main aspects of the joint power consumption optimization model development, systematic analysis of recent studies and publications was done. There were analyzed modern cooling solutions for cloud services [1-3], VM placement schemes and free cooling system check [4-8]. Statistics of the climate condition and servers' workload [9-11] allowed forming requirement or predictive control scheme development. Computational algorithms that can be used for server room's temperature profile simulation [12-18] were also discussed.

2. Proposed method

To build joint power consumption optimization model it is necessary to estimate optimal cooling mode regime and maximum power consumption of active servers. It allows to determine chillers work schedule in order to have no overheads in terms of power and time. Main parameters to be analyzed are:

- power consumption of datacenter P_{DC};
- cooling mode transition overheads P_{TR};
- number of servers N_S;
- number of VMs N_{VM};
- binary matrix representing VM placement $B(i,j)$;
- binary parameter CM which determines cooling mode ($CM = 0$ for electrical cooling and $CM = 1$ for free cooling).

Power consumption of datacenter can be calculated as

$$P_{DC} = P_{Cool} + P_{Comp}, \qquad (1)$$

where P_{Cool} refers to power consumption of cooling system and P_{Comp} represents computational power consumption.

Mathematically the problem solving aspects can be formulated as determining of $B(i,j)$ and CM parameter by obtaining minimums of objective function of entire power consumption P_{Σ} (Figure 2):

$$\begin{cases} B(i,j) = \begin{bmatrix} b(1,1) & \cdots & b(1,1) \\ \cdots & \cdots & \cdots \\ \cdots & b(i,j) & \cdots \\ \cdots & \cdots & \cdots \\ b(N_S,1) & \ldots & b(N_S,N_{VM}) \end{bmatrix}. \\ CM \in [0;1] \\ P_\Sigma = P_{DC} + P_{TR} \end{cases} \quad (2)$$

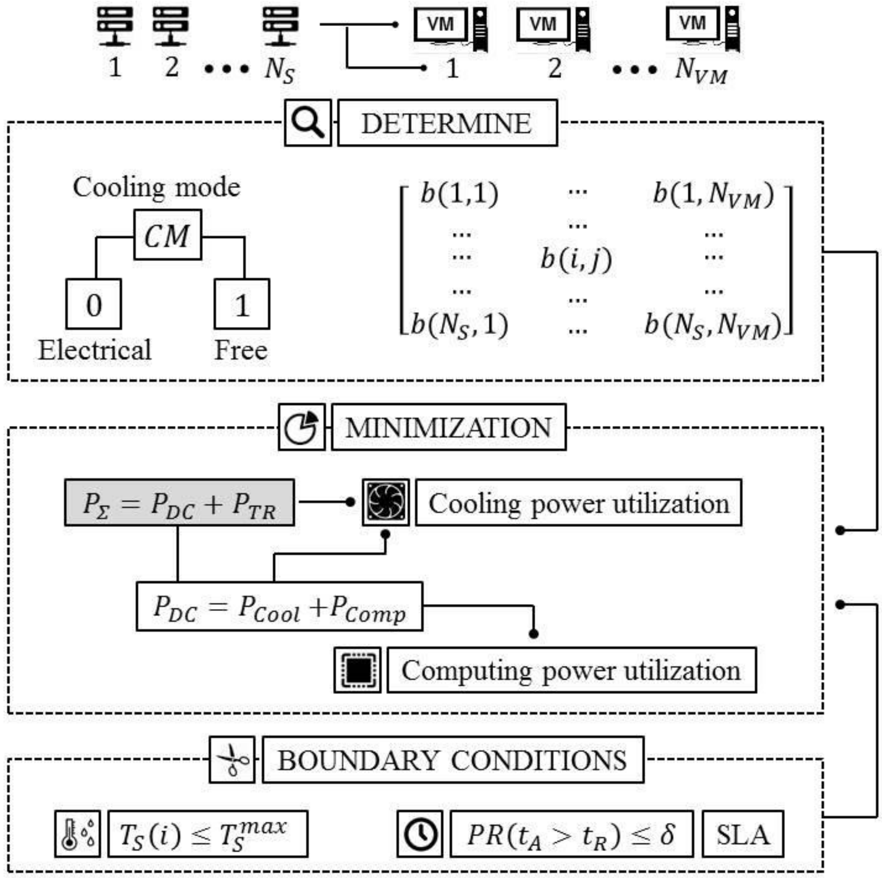

Fig. 2. Mathematical algorithm of joint power consumption scheme for hybrid cooling architecture

It has to be noticed that obtaining minimums of objective function minimum should also include analysis of boundary conditions for server temperature and server performance.

For boundary conditions estimation on should found $T_S(i)$ which refers to temperature of i-th server and probability $PR()$ of actual execution time t_A exceeding required execution time t_R:

$$\begin{cases} T_S(i) \le T_S^{max} \\ PR(t_A > t_R) \le \delta \end{cases}, \quad (3)$$

where T_S^{max} is maximum temperature constraint for data center servers and is δ SLA requirement parameter. Thereby optimization problem can be translated into a bin-packing problem by exploiting the analogy between a bin and a server.

3. Experimental results and analysis

To simplify developed methodology two-phase algorithm can be proposed. It includes determination of optimal pair of parameters of cooling regime and active servers' utilization threshold level $\{CM; U_S^{TH}\}$ which allows to satisfy temperature and performance requirements (3). At the second stage VMs have to be assigned to servers in order to minimize number of servers. Optimization procedure should be iterated at every predefined time interval. Thereby equations (2) and (3) could be estimated as:

$$\begin{cases} B(i,j) \in [0, U_S^{TH}];\ CM \in [0;1] \\ P_\Sigma(k) = \sum_{l=k}^{k+N_T-1} \alpha^{l-k} \cdot \left(P_{Cool}^{PR} + P_{Comp}^{PR} + P_{TR}^{PR}\right) \end{cases} \quad (4)$$

and boundary conditions could be defined as:

$$\begin{cases} U_S^{TH}(l) \geq \widehat{U}_R/N_S \\ l \in [k, k+N_S-1] \end{cases}, \quad (5)$$

$$\begin{cases} U_S^{TH} \leq \min\left(U_S^{max}, U_S^T(l)\right) \\ \forall l,\ 1 \leq \alpha \leq 0 \end{cases}, \quad (6)$$

where

- N_T is number of time periods;
- P_{Cool}^{PR}, P_{Comp}^{PR} and P_{TR}^{PR} are predicted values of P_{Cool}, P_{Comp} and P_{TR} values at the l-th time period;
- $\widehat{U}_R$ is the prediction of average user requests normalized with maximum number of user requests for single server;
- α is a weighting factor;
- U_S^{max} is maximum acceptable performance loss regime power;
- $U_S^T(l)$ is highest utilization satisfying maximum temperature constraint.

Figure 3 shows dependence of the power consumption on the U_S^{TH} value. Figure demonstrates that total power consumption at free cooling mode is usually changes in proportion to computing power as U_S^{TH} increase is more significant than the cooling power consumption growth. However, the cooling capability of the free cooling is limited, and maximal value of U_S^{TH} for this cooling mode is also limited.

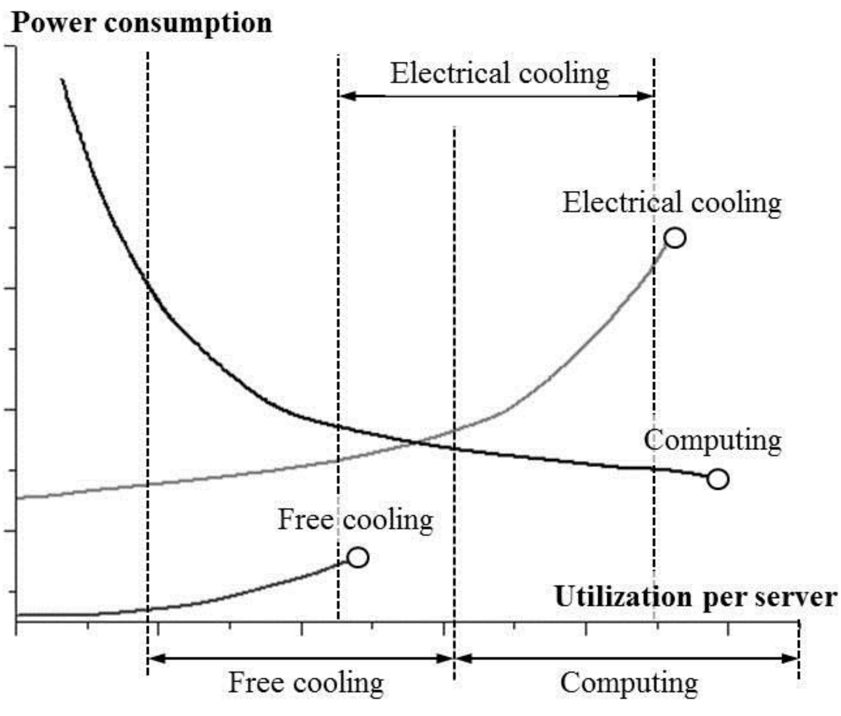

Fig. 3. Dependence of the power consumption on the active servers' utilization threshold level for free cooling and electrical cooling regimes

To evaluate the effectiveness of the joint optimization model statistical dataset of CloudSim simulation [19] was used (Figure 4). There were compared three cooling mode solutions for data centers:

- fixed temperature regime as conventional cooling mode which uses free cooling only when output temperature is lower than pre-defined temperature ($U_S^{TH} = U_S^{max}$);
- P-adaptive regime as adaptive mode which adjusts the cooling and the utilization threshold to minimize power consumption of data center;
- PT-adaptive regime as adaptive mode which jointly optimizes the power consumption and transition overhead.

The highest power consumption savings were observed at comparison of fixed temperature regime and P-adaptive regime while output temperature was usually higher pre-defined temperature so free cooling mode utilization was usually impossible. In other hand PT-adaptive regime allowed to use free cooling mode by lowering the maximum server power consumption.

Comparison of P-adaptive and PT-adaptive regimes has shown almost similar level of power consumption savings. However, PT-adaptive regime allowed to significantly decrease number of cooling modes transitions by accounting for the overhead caused by the cooling mode transitions. It is important to notice that the effectiveness of PT-adaptive gets enhanced as the power consumption proportion of servers gets to be improved.

Normalized power consumption as the power proportionality of servers should be defined as the ratio of the static power P_{ST} to the total power consumption P_{Σ}. For low value of P_{ST}/P_{Σ} can be used free cooling for longer periods of time due to lower server utilization threshold. Thereby minimal number of active servers can be used and developed methodology can be used to achieve higher energy-proportionality. Experiments' simulation statistics datasets demonstrates that PT-adaptive allows to provide higher level of power consumption savings for data center infrastructure.

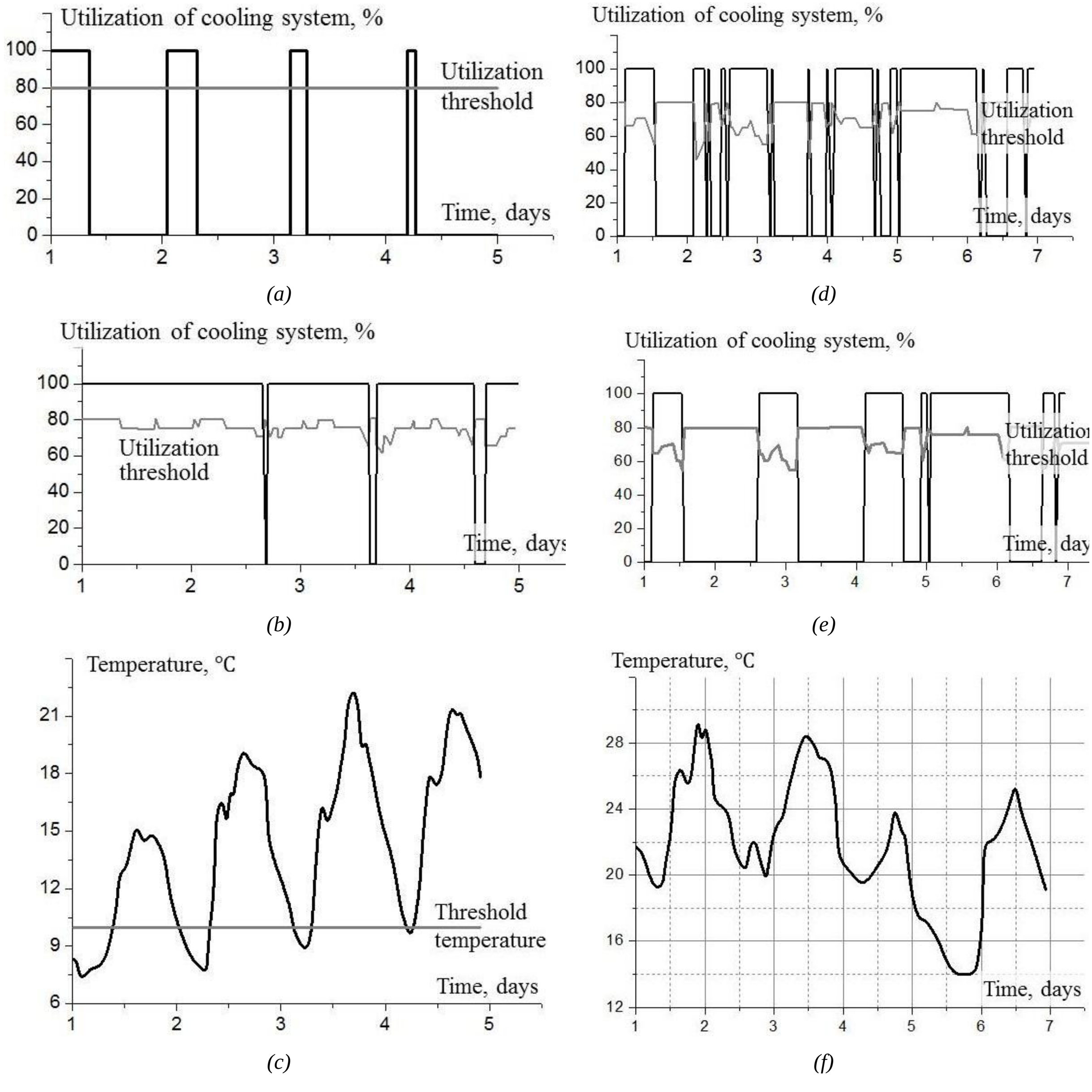

Fig. 4. Comparison of power utilization of fixed temperature (a) and PT-adaptive (b) cooling modes at temperature regime "1" (c) and power utilization of P-adaptive (d) and PT-adaptive (e) cooling modes at temperature regime "2" (f)

Thereby energy-efficiency constraints problem as a main limiting factor for data centers performance can be solved by thermal modeling and control solutions development which have to be considered as key aspect of power consumption reducing.

4. Conclusions

Key aspects of data center power utilization optimization by getting a proper proportion of computing and cooling power consumption reducing were analyzed. Energy-efficiency constraints problem have to be be solved by thermal modeling and control solutions development. While nowadays hybrid cooling solutions are widely used in a data centers it is important to provide analysis of virtual machines structure organization and utilize higher cooling capability due to the high operating temperature of active servers. It allows to achieve overall power loss minimization with satisfying all requirements.

Proposed methodology extends the usability of free cooling for data centers. It takes into account climate condition, servers' workload, server room's temperature profile and server cooling architecture. It was demonstrated that for development joint power consumption optimization model it is necessary to estimate optimal cooling mode regime and maximum power consumption of active servers. For determination of chillers work schedule were estimated power consumption of datacenter, cooling mode transition overheads, number of servers, virtual machines and its placement. There were compared three cooling mode solutions for data centers: fixed temperature regime, P-adaptive regime and PT-adaptive regime. Fixed temperature regime was shown as inefficient one while P-adaptive regime and PT-adaptive regime was proved to be preferable ones. Developed model of cooling mode efficiency estimation demonstrated preferences of PT-adaptive regime as adaptive mode which jointly optimizes the power consumption and transition overhead.

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