Journal of Manufacturing Systems 37 (2015) 511–516

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Real-time monitoring and evaluation of energy efficiency and thermal management of data centers

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ARTICLE INFO

Article history:
Received 13 June 2014
Accepted 18 June 2014
Available online 12 July 2014

Keywords:
Data center
Energy efficiency
Thermal management
Real-time monitoring
Performance metrics

ABSTRACT

The rapid growth of IT industry and the miniaturization of semiconductors have resulted in substantial increase in energy consumption, power density of IT equipment and, subsequently, heat dissipated from data center racks. Metrics have been proposed to overcome these energy efficiency and thermal management challenges. Measuring the performance of the data centers using a combination of wisely chosen metrics can increase the opportunity for considerable energy reduction. A variety of metrics developed and applied for such evaluation are reviewed herein. The energy and cooling efficiency of a small data center is then evaluated by applying several metrics. To perform the analysis, real-time monitoring of 25 parameters over a period of six weeks was performed through design and implementation of a wireless monitoring network. The results are analyzed and current energy efficiency and thermal management issues are discussed with respect to the relative effectiveness of the various metrics.

1. Introduction

Real-time, automated energy monitoring and control of manufacturing processes offers the potential to reduce energy use and improve environmental performance [1]. The ever-increasing demand of IT support, however, along with the developments in semiconductor miniaturization have led to higher density processors and a sharp increase in the energy consumption and the heat dissipated per unit volume of racks in data centers [2]. A data center is a facility housing networked computers and servers as well as associated infrastructure, for the purposes of storage and management of large amount of data and information [3].

The United States Environmental Protection Agency (EPA) reported that the annual energy consumption of U.S. data centers is approximately 61 billion kWh, which is about 1.5% of the total U.S. electricity consumption [4]. It is also reported that data center electricity consumption in 2006 was nearly double that in 2000 [4]. Energy in data centers is consumed by two main categories of equipment: IT equipment and infrastructure that supports the IT facilities and provides reliable cooling and the thermal environment needed for IT equipment to operate.

Since the power consumed by IT equipment is converted into heat dissipated through the racks [5], reliable thermal management is imperative to provide an adequate environment for IT devices. Due to rapid growth of the IT equipment miniaturization and significant increase in rack level power densities, many thermal management challenges have been rising over the past few decades [6–8]. Poor thermal management lowers energy efficiency and can lead to higher risks of server failures and lower IT equipment longevity.

The data center cooling system often accounts for a significant portion of total energy consumption, and cooling cost drives the total operational cost of a typical data center [9]. It is estimated that about five times the server cost is spent on cooling and supporting infrastructure when a $1500 server is operated in an adequate thermal environment [10]. A successfully implemented thermal management system can significantly reduce operational cost by increasing the energy efficiency [6]. Thus, many efforts have been made to increase the efficiency and effectiveness of cooling system and thermal management of data centers.

The power usage effectiveness (PUE) of data centers, one of the most practiced metrics, was studied by Lawrence Berkeley National Laboratory [11]. Benchmarking 22 data centers revealed a PUE drop of 16% in 2005 when compared with that in 2003 (1.95–1.63). Despite all the efforts that have been taken, energy consumption of cooling systems is still a major concern, and there is plenty of room for efficiency improvements. In traditional data centers, there

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http://dx.doi.org/10.1016/j.jmsy.2014.06.008
0278-6125/

is additional pressure to cool the ever-increasing rack power densities using novel strategies due to inefficiencies of conventional thermal management. The first step in implementing new strategies is by evaluating data center performance. Thus, a challenge is to effectively monitor the energy consumption and environmental conditions.

Microelectromechanical system (MEMS) technology [12] has empowered wireless sensor networks (WSNs) by introducing more reliable, smaller, and inexpensive sensors that allow wider utilization of ad hoc wireless systems in industrial applications [13]. WSNs facilitate better insight into the industrial systems by real-time monitoring and provide the opportunity to improve the efficiency and productivity by evaluation and control of industrial operations. The monitoring applications of WSNs include environmental monitoring (indoor/outdoor), power monitoring, process automation, and structural monitoring, among other types of monitoring [14].

In this research, a data center in the city hall of Gresham, Oregon was evaluated. The data center consists of a row of seven racks, which was monitored by installing a wireless sensor network (WSN) to collect energy use, temperature, and humidity data for a period of six weeks. Energy efficiency and thermal management of the data center was evaluated using a combination of energy and thermal metrics. This study forms a pilot project for installation and performance monitoring of a new data center cooling technology to be installed for the data center [15]. The current split system AC units will be replaced with a rooftop mounted indirect evaporative cooling unit. Energy loads will be evaluated with the existing system (baseline) and new system over extended periods to account for seasonal variation. Ultimately, the goal is to evaluate and compare data center energy efficiency and thermal management performance in each case.

The following sections review a variety of metrics to be applied to data collected for the data center. The equipment configuration and setup is then described and results are presented. Finally, conclusions are drawn from the work and opportunities for future work are discussed.

2. Energy efficiency and thermal management metrics for data centers

Higher energy efficiency leads to lower operational costs in data centers. In order to improve and optimize the energy consumption and thermal management in data centers, appropriate metrics are imperative to evaluate their efficiency and performance. Measuring the performance of a data center based upon a standard metric provides the opportunity to track improvements and changes, to estimate the impact of changes, and to draw comparisons to other technologies and data center configurations.

A variety of metrics have been proposed [8] to quantify data center efficiency and performance. In this study, metrics were selected which would enable better insight into energy efficiency and thermal management issues from among the most widely used metrics. The metrics reviewed below help in understanding the operational health and the load on different types of equipment. The objective is to measure baseline performance of the data center, so performance-related impacts of future changes, such as installation of a new cooling system, can be evaluated. Metrics have been previously introduced to evaluate the performance of servers inside the racks, which are not the focus of this paper.

3. Power usage effectiveness (PUE) and data center infrastructure energy (DCiE) metrics

Two primary metrics, power usage effectiveness (PUE) and data center infrastructure energy (DCiE), were introduced by the Green Grid industry consortium over the past decade [16] to measure data center energy efficiency. PUE is defined as the total energy delivered to the data center over the total energy drawn by the IT equipment. IT equipment energy is defined as "the energy consumed by equipment that is used to manage, process, store, or route data within the compute space" [16]. PUE is the most widely-used metric and can be calculated using Eq. (1).

$$\mathrm{PUE} = \frac{P_{\mathrm{inf.}} + P_{\mathrm{IT}}}{P_{\mathrm{IT}}} \tag{1}$$

In this equation, $P_{\mathrm{inf.}}$ is the power input into the supporting infrastructure, mainly the cooling system, and P_{IT} is the power consumed by the IT equipment in the racks.

Ideally, PUE would hold a value of 1.0, meaning all the power into the data center is consumed by the IT equipment. However, in reality, due to the heat dissipated, energy consuming cooling strategies are imperative to reject heat from the racks. Additional power used for rack cooling purposes increases the value of PUE as suggested by Eq. (1). Higher values of PUE imply inefficiency in cooling systems and thermal management of data center. An average data center PUE of 2.0 is reported by the U.S. Department of Energy, while several efficient data centers have reported a PUEs of about 1.1 [17].

DCiE represents a reciprocal of PUE and, thus, can be calculated using Eq. (2).

$$\mathrm{DCiE} = \mathrm{PUE}^{-1} = \frac{P_{\mathrm{IT}}}{P_{\mathrm{inf.}} + P_{\mathrm{IT}}} \tag{2}$$

As seen in the above equations, PUE and DCiE measure the portion of the total power into the data center that is consumed by the IT equipment and infrastructure.

3.1. Rack cooling index (RCI)

The rack cooling index (RCI) proposed by Herrlin [18] measures the degree to which the IT equipment inside the racks are maintained in the rack intake air temperature range recommended by American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) [19]. Thus, the RCI metric evaluates how effectively an adequate environment is provided for the racks and is expressed by the range defined by Eqs. (3) and (4).

$$\mathrm{RCI_{HI}} = \left[1 - \frac{\sum (T_{\mathrm{intake}} - T_{\mathrm{max-rec}})_{T_{\mathrm{intake}} > T_{\mathrm{max-rec}}}}{(T_{\mathrm{max-all}} - T_{\mathrm{max-rec}})n}\right] \times 100\% \tag{3}$$

$$\mathrm{RCI_{LO}} = \left[1 - \frac{\sum (T_{\mathrm{min-rec}} - T_{\mathrm{intake}})_{T_{\mathrm{intake}} < T_{\mathrm{min-rec}}}}{(T_{\mathrm{min-rec}} - T_{\mathrm{min-all}})n}\right] \times 100\% \tag{4}$$

$\mathrm{RCI_{HI}}$ is the rack cooling index value at the high end of the recommended temperature spectrum, $\mathrm{RCI_{LO}}$ is the value at the low end of the recommended temperature spectrum, T_{intake} is the rack intake air temperature, n is the total number of intakes, $T_{\mathrm{max\text{-}rec}}$ is the maximum recommended temperature, $T_{\mathrm{max\text{-}all}}$ is the maximum allowable temperature, $T_{\mathrm{min\text{-}rec}}$ is the minimum recommended temperature, and $T_{\mathrm{min\text{-}all}}$ is the minimum allowable temperature.

According to ASHRAE, the recommended and allowable ranges for rack intake temperature is 18–25 °C (64–77 °F) and 15–32 °C (59–90 °F), respectively [19]. An RCI of 100% reflects intake temperatures within the recommended range. Lower percentages of $\mathrm{RCI_{HI}}$ imply that heat rejection from the racks is not effective and there is a possibility of hot spots within the racks. Similarly, lower percentages of $\mathrm{RCI_{LO}}$ indicate that the racks are overcooled, which suggests low cooling power efficiency due to poor thermal management.