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A Stepwise Approach Based Optimal Energy Utilization Scheme for HVAC Secondary Chilled Water Pumps in Commercial Buildings

Sandali Walgama*, [1], Sisil Kumarawadu*, and D.P. Chandima*

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ABSTRACT

In many countries, buildings are responsible for as much as 40% of total energy consumption and in many commercial buildings, about half of total electricity is consumed by Heating, Ventilating and Air Conditioning (HVAC) systems. As a result, many research efforts have been made over the years aiming to maximize building energy efficiency and savings. This paper proposes a novel strategy to enhance the energy savings in the HVAC secondary chilled water pumps based on the required water flow variations due to the changes in the cooling load of the building. The resulting power usage minimization problem was solved using a stepwise approach that reduces the complexity, in order to determine the optimal number of pumps to be operated and their optimal operating speed also ensuring that the flow requirement and other operational constraints are duly satisfied. The pump characteristics were mathematically modelled, and the proposed method was validated comprehensively via simulation and case studies. As per results of the first case study, the suggested method offers a 15.26% reduction in consumed pump energy compared to that of the cascading method used in a large commercial building. The second case study provides a performance comparison of the proposed method with the Particle Swarm Optimization (PSO) method and the proposed strategy shows a 1.78% energy saving over to the PSO method with a comparatively small execution time. Therefore, a highly efficient, safe, and reliable pump operation can be assured with the proposed method. This approach is simple to implement, reliable, robust, efficient, and suitable for energy-based optimal control of HVAC secondary chilled water pumps in commercial buildings.

1. INTRODUCTION

Buildings are one of the most prominent energy consumers worldwide. In industrial and commercial buildings, Heating, Ventilating and Air Conditioning (HVAC) systems are often responsible for as much as 30-40% of the building energy consumption. Hence, much research work has been focused on exploring practically meaningful methods of improving energy saving and efficiency of HVAC systems considering both financial and environmental benefits. In the central air-conditioning systems, a considerable amount of energy is allocated for pumping systems, and they can account for more than 20% of the total power consumption of a complex building HVAC system [1]. Therefore, HVAC pumping systems particularly have the potential as a target for energy savings.

In order to satisfy higher flexibility and system efficiency, a group of pumps can be employed in central cooling systems [1], [2]. Shiels *et al.* [3] compared the pros and cons of running a single pump and dual pumps in terms of hydraulic characteristics, reliability, operating costs, capital investment, and safety. For compensating flow rate requirements and avoiding loss in production when pump maintenance is required, parallel small capacity pumps are advantageous over a single large unit pump [4].

Even though it is desirable to use a constant pump speed, at which the pumps perform more efficiently, for many common applications, much energy is wasted when the load varies over time. To tackle this problem, the subsequent pumps are staged or de-staged based on the demanded flow rate in a traditional pump control method.

In this strategy, once a pump turns on, it reaches the rated value neglecting the pump efficiency [5]. In order to accomplish the energy saving in pumping systems, encouraged by the affinity laws, the variable frequency drives (VFD)-based variable speed pumps can be deployed. However, when the pump operates far from its best efficiency point (BEP), this flexibility can cause poor system efficiency [6]. Also, the maximum reliability of a pump can be reached at the BEP and deviating the flow rate from that point causes to decrease in the reliability [7]. Operating the pumps within the maximum efficiency region extends the pump lifetime by avoiding harmful operations of the pumps [4]. Burke [8] highlighted that it is rare to have operation problems when the pumps are operated in the range of

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*Department of Electrical Engineering, University of Moratuwa, Sri Lanka.

[1] Corresponding author:
Email: 198081T@uom.lk; sisil@uom.lk; chandimadp@uom.lk

±20% of their BEPs. To circumvent radial thrust, operating each pump with a flow rate between 50% and 110% of the flow at BEP is beneficial [9]. Also, Hansen *et al.* [10] studied the parallel operation of the variable speed pumps in chilled water systems and discovered that the dissimilar operating speeds of the pumps configured in parallel are less beneficial.

In line with these extracted facts, obtaining an optimal deployment plan and control strategy for the HVAC water pumps while optimizing the system efficiency, minimizing the power consumption and maintenance costs, as well as satisfying performance and safety requirements is challenging.

By using an adaptive and derivative method to find the pressure set point, Wang *et al.* [11] proposed an online control strategy for the speed optimization of the condenser cooling water pumps. To decide the speeds at optimal conditions, Szychta [12] has considered the correlation between the changes in the pump speed and efficiency. Research carried out by Umashankar *et al.* [4] presented a control algorithm that maintains the cascade pumping system efficiency maximum at all operating conditions, with the optimum speed reference predictions. For cooling towers and chilled water pumps, the optimal control frequency was determined using a load-based speed control method in the literature [13]. Ma *et al.* [14] utilized differential temperature set point and deviations in conjunction with the Proportion Integration Differentiation (PID) strategy to control the frequency of chilled water pumps. Furthermore, intelligent algorithms such as evolutionary algorithm [15], genetic algorithm [16], and reinforcement learning algorithm [17] also have been applied to obtain optimal pump performance. Nonetheless, optimally deploying the pumps is also important to make the best use of energy and that has been ignored in the above studies.

For the determination of an optimal number of operating pumps, the intersection of power and flow lines at different pump frequencies has been taken into account [18]. Considering power consumption and maintenance cost of the pumps, Ma *et al.* [1] suggested a control strategy for pump sequence optimization using pressure drop models for different water networks. However, the opportunity for further energy optimization has been overlooked by not considering the energy-based pump speed control option. As an intelligent method, GA has been used in the literature [19], [20] to optimally schedule the pump station in a water supply system. Due to the requirement of operations such as chromosome encoding, selection, crossover, and mutation, the implementation of this complicated algorithm is more difficult.

According to work carried out by Tillack *et al.* [21], the wire-to-water efficiency of the pumping system can be used to sequence the pumps properly while utilizing the pressure differential transmitters at critical loops for speed control purposes. However, the use of transmitters may increase the system cost and maintenance. A hybrid control strategy that combines a single pump variable frequency and pump quantity control based on an analytical model, including characteristics of bypass-loop adjustment, was proposed in the literature [22]. As per results, that is suitable for chilled water systems with high differential pressure or a low flow ratio. For a pump system comprising different types of pumps connected in parallel, the number of pumps and their speed have been optimized using dynamic programming [23]. However, dealing with many pumps makes this method complicated. Tianyi *et al.* [24] obtained an optimized number of operating units and speed ratios of parallel variable frequency hydraulic pumps by using the extreme value analysis method. Although that has addressed the key salient requirements, the complexity of the approach may discourage real-time applications. With an aim to minimize the power usage of parallel pump systems while improving the reliability of pumps, Lai *et al.* [7] have adopted a Particle Swarm Optimization (PSO) algorithm to determine the optimal number of pumps and speed ratios. This method has shown superior performance through the results compared to the conventional PID speed regulation method and other intelligent algorithms. However, for a particular system, the parameters of the PSO algorithm should be carefully selected and the penalty coefficients are chosen by several trial and error.

In summary, much of the literature has focused on either speed control of pumps [11], [12] or pump sequence control [1], [18] of complex air conditioning systems. Though optimal deployment plan and pump speed optimization both together is of utmost importance to guarantee maximum energy saving, existing literature and related work on considering both together are still inadequate and the necessity of reduced complexity of the algorithms can be also noted. Furthermore, when defining the constraints in the optimization problem, actual problems and possible risks in serial-parallel systems such as cavitation and overheating are not considered in some studies [25], [26].

Therefore, the key contribution of this paper is to propose a novel algorithm with low complexity to operate and control HVAC parallel chilled water pumps by selecting the number of pumps to be operated and their operating speed which consumes minimal power to meet the variable flow requirement along with a safe and energy-efficient operation.

This paper is organized as follows. In Section 2, mathematical modelling of the system is presented. The methodology which consists of constraint definitions, the problem statement, and the proposed algorithm is described in Section 3. Section 4 discusses the obtained simulation results and Section 5 explains how to integrate the proposed method into buildings. Finally, Section 6 concludes the paper.

2. SYSTEM MATHEMATICAL MODELING

A primary constant, secondary variable chilled water plant with 2-way control valves and VFD on secondary pumps is considered for simulation studies as illustrated in Figure 1. For chilled water systems, having variable flow configurations is becoming popular since the constant chilled water flows through the cooling coil in the air handling unit (AHU) or fan coil unit (FCU) would waste a considerable amount of energy when the cooling load of the building varies due to many reasons such as outdoor air temperature variations, changes in occupancy and other thermal loads, etc.

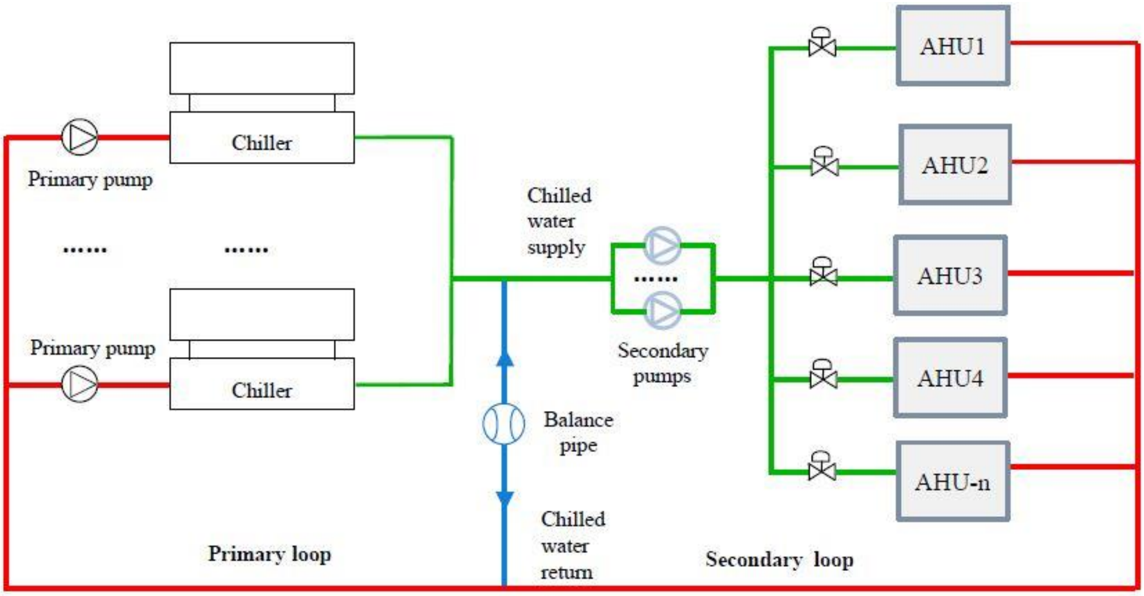

Fig. 1. Schematic diagram of the considered chilled water system [27].

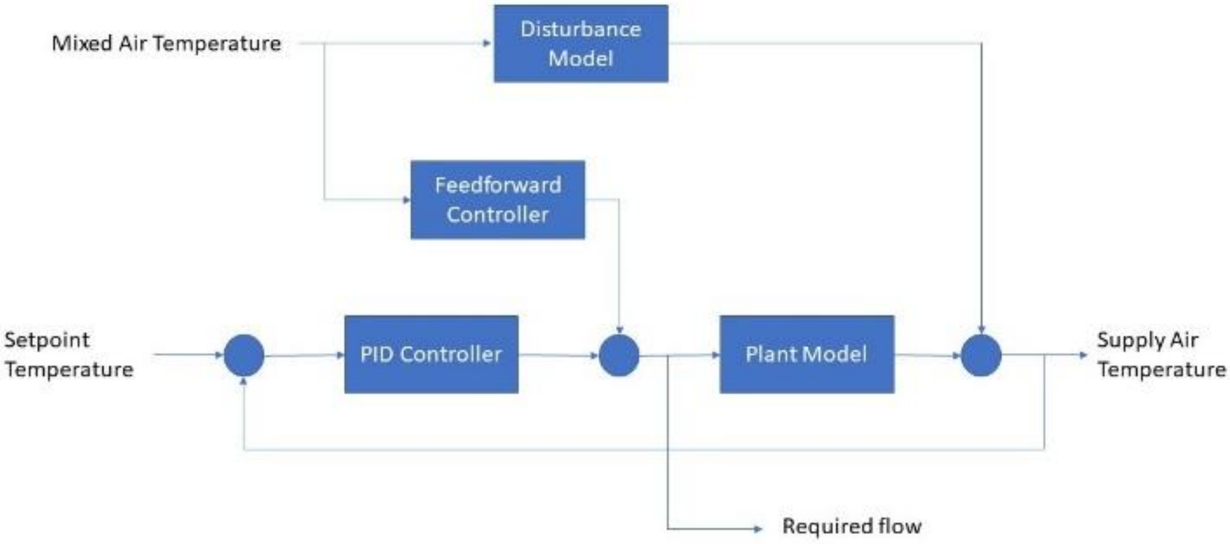

Fig. 2. Proposed control system for controlling room temperature.

Required chilled water flow through a cooling coil can be determined with the help of a temperature control system. Figure 2 shows the proposing control system which can be used to generate variable flow signals to maintain the temperature setpoint at a constant along with the system input variations. Therefore, expected chilled water flow across the secondary pump system is the addition of the required flow through each cooling coil in the building. Other than that, the loop differential pressure variation also can be utilized to determine the required chilled water flow since the differential pressure represents the changes in coil loads. Then, the secondary chilled water pumping system is responsible to compensate the chilled water flow requirement with minimum power consumption to facilitate energy savings from the HVAC system while the constant flow primary pumps are maintaining the primary side pressure. This paper discusses an optimal control strategy for secondary chilled water pumps to fulfill this responsibility.

Head, power consumption, and efficiency for a typical pump, are varied with the flow rate through the pump. Therefore, these parameters can be modelled using mathematical equations. At the constant speed, the head can be expressed as a quadratic function of the flow rate similar to Equation (1), and this gives the pump curve [9].

$$H = aQ^2 + bQ + c \tag{1}$$

Here, H is the pump head (m) at the rated frequency, Q is the chilled water flow rate through the pump (m^3/s) at the rated frequency, and coefficients a, b and c can be determined based on the data provided by the manufacture.

Similarly, power consumption also can be presented as a quadratic function of the flow rate which gives the power curve of the pump as given in Equation (2) [9].

$$P = a'Q^2 + b'Q + c' \tag{2}$$

In Equation 2, P is the power consumption (kW) of the pump running at rated frequency. a', b' and c' are constants of the performance and can be determined similar to the a, b and c.

The use of multiple pumps in parallel allows the production of a wider range of flow rates than would be possible with a single pump and the pump curve for the group of pumps is obtained by combining individual pump curves as shown in Figure 3. Therefore, when the identical pumps are connected parallel in the system, for a given head, flow can be increased by the times the number of pumps. When the parallel pump system comprises dissimilar pumps, a significant contribution cannot be expected from the small pump and its dead head may be exceeded by the system requirements. If the lowest head of the larger pump exceeds the smaller pump's dead head, the small pump is unable to contribute to increasing the flow while the large pump is operating. Therefore, similar pumps are mostly preferred in HAVC parallel pump systems.

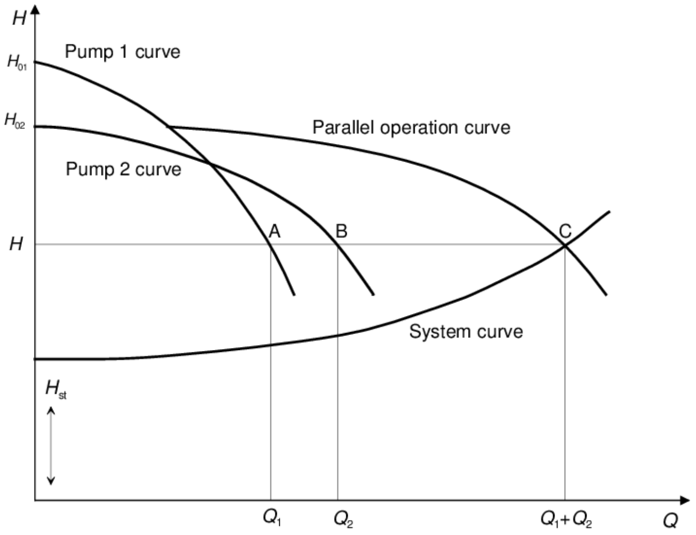

Fig. 3. Pump curve for parallel operation.

The operating flexibility of the system can be further increased by varying the operating frequency of the pumps by using VFD. To obtain performance models for a pump at variable frequencies, the above-developed models for pump head and power consumption can be modified using the Affinity laws. Flow rate, head, and power at variable frequencies can be derived from the Affinity laws as presented in Equations (3), (4), and (5).

$$Q_f = \left(\frac{f}{f_{rated}}\right) Q \tag{3}$$

$$H_f = \left(\frac{f}{f_{rated}}\right)^2 H \tag{4}$$

$$P_f = \left(\frac{f}{f_{rated}}\right)^3 P \tag{5}$$

Where f is the variable frequency and f_{rated} is the rated frequency (Hz), Q_f is the flow rate through the pump (m^3/s) at the frequency f, H_f is the pump head (m) at the frequency f and P_f is the power consumption (kW) for the pump running at the frequency f. It is observed from Equation (5) that the power usage can be significantly reduced by lowering the operating frequency.

Substituting for Q and H in Equation (1) from Equations (3) and (4),

$$H_f = a{Q_f}^2 + b\left(\frac{f}{f_{rated}}\right) Q_f + c\left(\frac{f}{f_{rated}}\right)^2 \tag{6}$$

Using Equation (6), the required frequency for the variable flow rate and head can be calculated.

Similarly, Equation (2) also can be modified by substituting parameters from Equations (3) and (5). Then, power consumption at the variable frequency can be found using Equation (7).

$$P_f = a'\left(\frac{f}{f_{rated}}\right) {Q_f}^2 + b'\left(\frac{f}{f_{rated}}\right)^2 Q_f + c'\left(\frac{f}{f_{rated}}\right)^3 \tag{7}$$

The efficiency of the pump system, η_s is expressed by Equation (8). Q_s is the flow rate, H_s is the pump head, P_s is the power consumption, ρ is the density of the water, and g is the acceleration due to gravity.

$$\eta_s = \frac{Q_s H_s g \rho}{P_s} \tag{8}$$

When the power consumption is minimized, efficiency will be increased. Hence, reducing the power consumption of the pumping system is the aim of proposing this algorithm.

The flow signal which is received from the temperature control system is only the required total flow rate to be flown through the cooling coils. However, the chiller system should deliver chilled water to create more head than to the value giving the required flow to compensate the losses (h_f) as well. If the system head is H_{sys}, the total required head from the pumps; H_{total} equals to,

$$H_{total} = H_{sys} + h_f \tag{9}$$

After the required total flow and head are determined accurately, the optimal operating point of the pump(s) can be decided according to minimal power consumption criteria.

3. METHODOLOGY

The objective of this work was to develop a low complexity algorithm, which will reduce the power consumption of HVAC parallel chilled water pumps by giving the optimal number of pumps to be operated and their optimal speed while satisfying the system flow requirement and other performance constraints. The optimization problem was formulated after the mathematical approach and then, the algorithm was developed in MATLAB®. Finally, the effectiveness can be discussed and compared through the simulation results.

3.1 Definition of the Constraints

Let the required flow as Q_{total}, head as H_{total}, the number of available pumps as N, the selected number of operating pumps as n, and their operating frequency as f. Therefore, n is limited by N and f should be in the allowable frequency range. The recommended minimum frequency is 20 Hz since frequencies below this threshold will not save much energy and could cause problems in motors, chiller minimum flows, *etc.* [25]. Also, the efficiency of VFD decreases rapidly when the speed ratio (f/f_{rated}) of the drives is less than 0.5 [7].

$$0 < n \leq N$$

$$f_{min} \leq f \leq f_{max}$$

The flow rate through each operating pump should be within the range of 50% and 110% of the flow at the BEP to avoid radial thrust [9]. It is rare to have operational problems when the pumps are operated in the range of ±20% of their BEPs [8]. By combining these two facts,

$$\frac{f}{f_{rated}}\, 0.\,8 Q_{@BEP} \leq \frac{Q_{total}}{n} \leq \frac{f}{f_{rated}}\, 1.1\, Q_{@BEP}$$

Also, selected pumps with optimal frequency should be able to provide the required total head.

$$H_{total} = a\left(\frac{Q_{total}}{n}\right)^2 + b\left(\frac{f}{f_{rated}}\right)\left(\frac{Q_{total}}{n}\right) + c\left(\frac{f}{f_{rated}}\right)^2$$

3.2 Problem Statement

Total power consumption of the secondary chilled water pumps; P_{total} equals the accumulated power consumption of each operating pump.

$$P_{total} = \sum_{i=1}^{n} P_i \tag{10}$$

If all pumps connected in parallel are identical and each pump consumes P_p power,

$$P_{total} = n\, P_p \tag{11}$$

Using Equations (7) and (11), the minimization problem can be defined as,

$$min\left(n\left[a'\left(\frac{f}{f_{rated}}\right)\left(\frac{Q_{total}}{n}\right)^2 + b'\left(\frac{f}{f_{rated}}\right)^2\left(\frac{Q_{total}}{n}\right) + c'\left(\frac{f}{f_{rated}}\right)^3\right]\right)$$

Subject to,

$$f_{min} \leq f \leq f_{max}$$

$$0 < n \leq N$$

$$\frac{f}{f_{rated}}\, 0.8\, Q_{@BEP} \leq \frac{Q_{total}}{n} \leq \frac{f}{f_{rated}}\, 1.1\, Q_{@BEP}$$

$$H_{total} = a\left(\frac{Q_{total}}{n}\right)^2 + b\left(\frac{f}{f_{rated}}\right)\left(\frac{Q_{total}}{n}\right) + c\left(\frac{f}{f_{rated}}\right)^2$$

3.3 Proposed Algorithm

The algorithm which is described in the flow chart in Figure 4, is developed and validated using MATLAB® simulation in order to find the combination of n and f, which gives the minimum power consumption for a given flow rate signal. First, the required total head is calculated, and the total flow is determined. Then, the algorithm checks whether Q_{total} and H_{total} are greater than or equal to the minimum system requirements for the assurance of better operating conditions. Next, water flow and head through each pump are found by varying the number of pumps. The optimal frequency and total power consumption will be calculated if the flow value and obtained optimal frequency were within the high-efficiency region and the acceptable range, respectively. Finally, the optimal speed and number of pumps with minimum power consumption are selected from the set and these values will be provided as the output. This step-wise approach is capable of reducing the complexity of solving the formulated minimization problem.

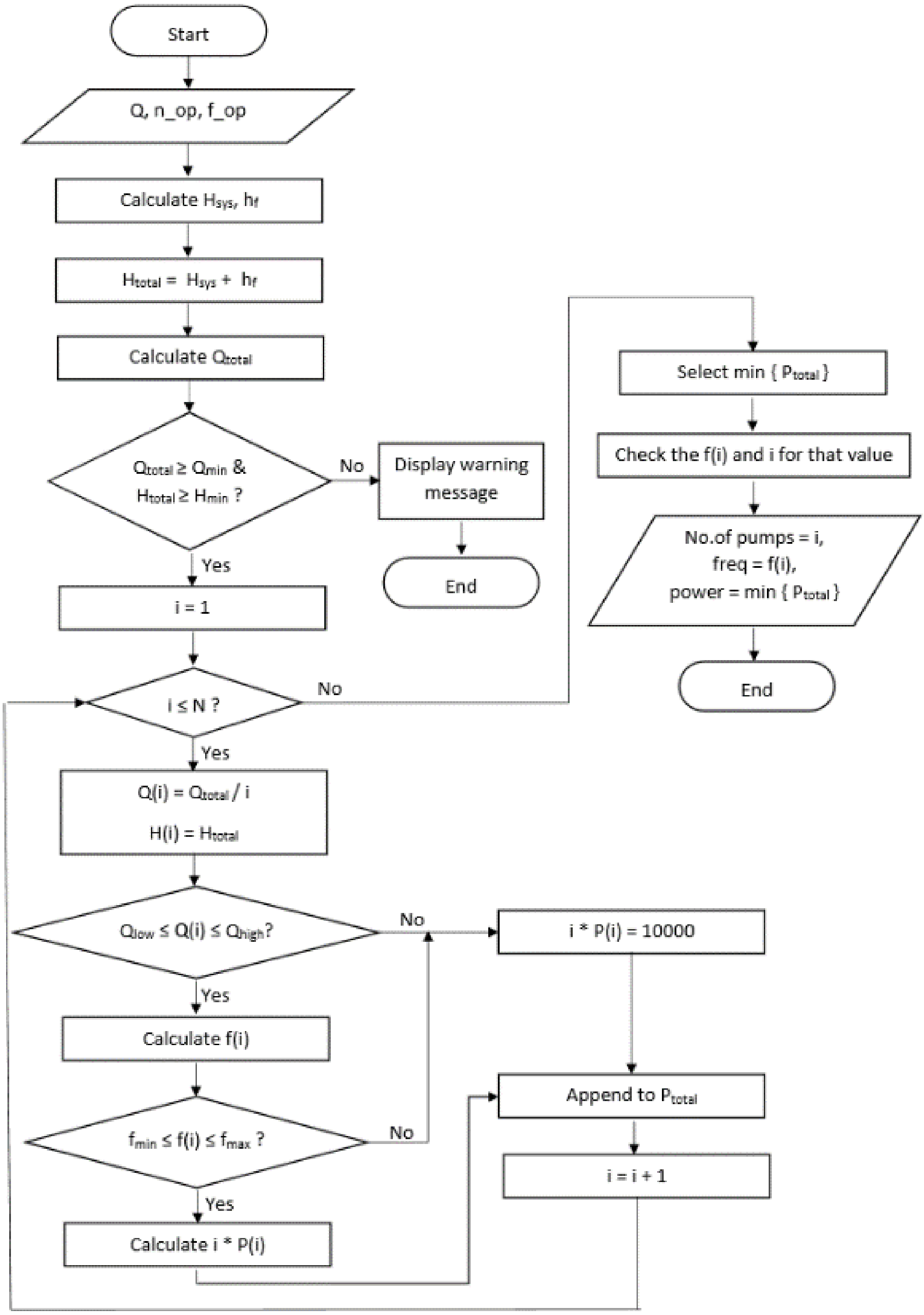

Fig. 4. Flow chart for the proposed algorithm.

4. SIMULATION RESULTS

4.1 Case Study I: Comparing the Proposed Method with Conventional Methods

The purpose of this study was to investigate the performance of the proposed method through the simulation results of an actual system with and without the developed algorithm. A commercial building in Colombo, Sri Lanka was considered for this study, and the model parameters were modified accordingly. This system consists of five Paco KPV 80153 secondary chilled water pumps in parallel and they are operated based on a conventional cascading method. When the flow requirement comes to certain defined levels, pumps are staged or de-staged and then the frequency will be determined. For the comparison, operational data at every 5 minutes of a weekday was utilized. Figure 5 depicts the assumed water flow variation during the considered period.

The number of operating pumps and their frequency determined by the proposed algorithm and the actual system are presented in Figure 6 and Figure 7, respectively. When the flow requirement is higher, the difference in the results given by the two methods can be observed. Although there are five pumps, due to low cooling demand in the considered season, the number of operating pumps has not exceeded three.

This system has been designed to maintain the frequency between 30-50 Hz. Figure 7 depicts that the proposed method has not violated this constraint at any time. Also, a lot of frequency dynamics can be observed in the actual system.

By using these results, the power consumption of the pumps when applying and not applying the proposed strategy can be calculated. Through Figure 8, the energy-saving capability of the proposed algorithm can be emphasized.

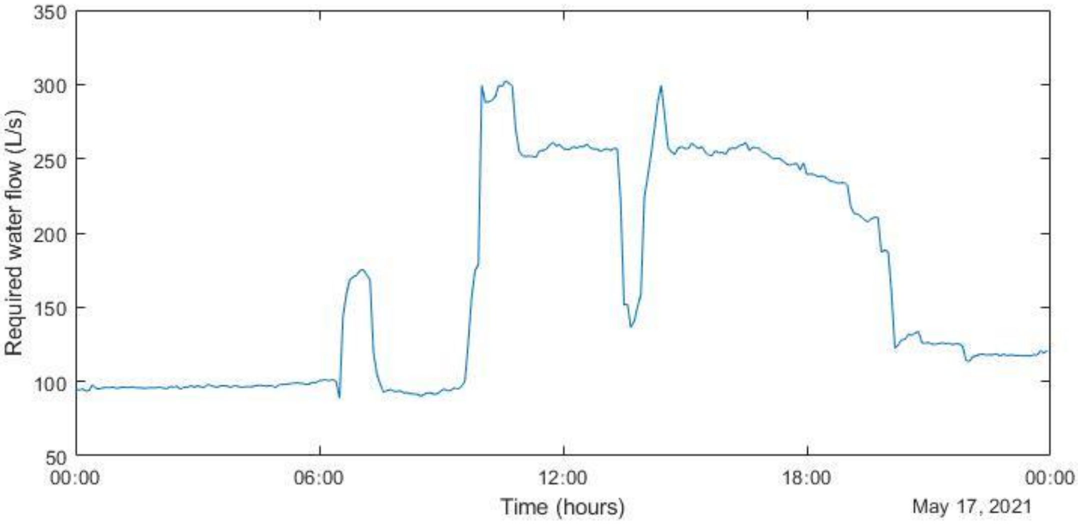

Fig. 5. Required water flow variation.

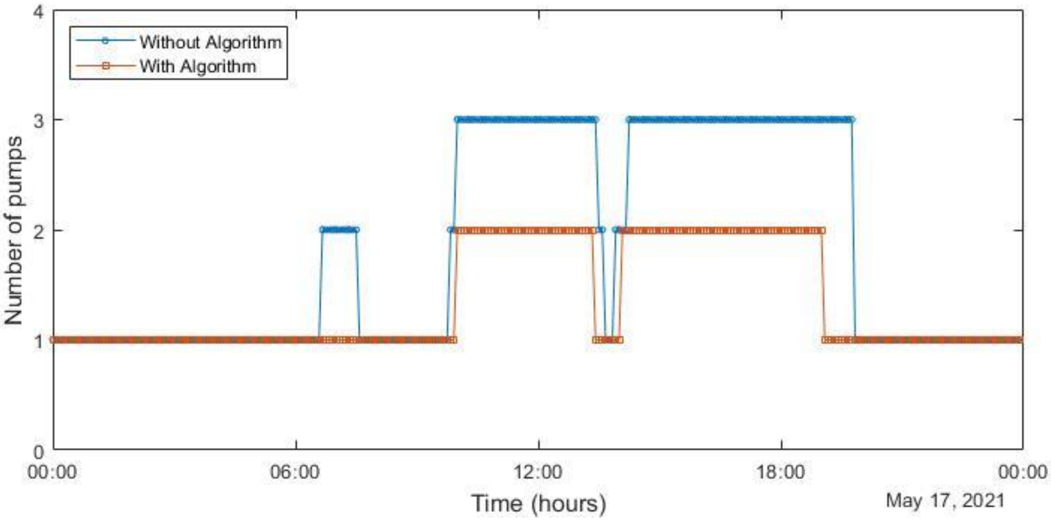

Fig. 6. Number of operating pumps with and without the proposed algorithm.

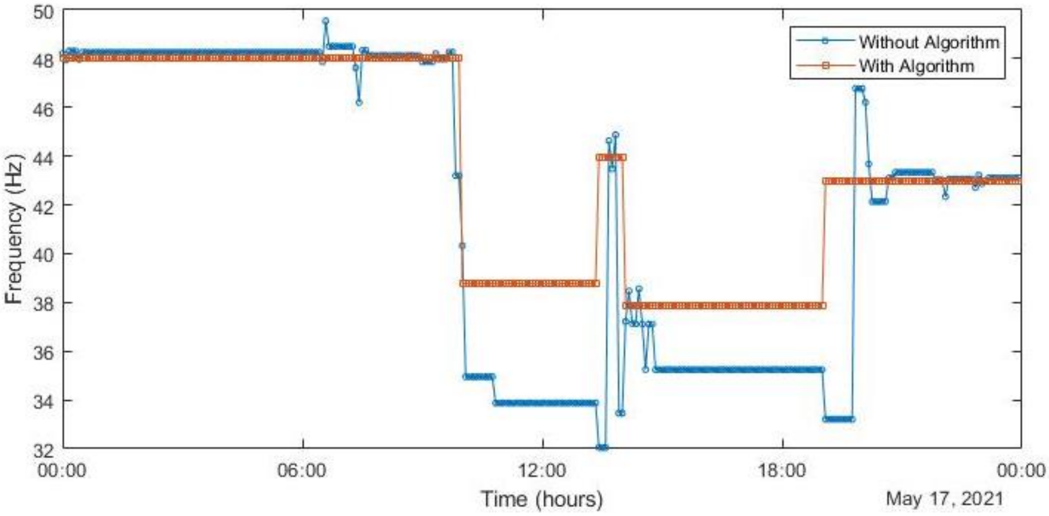

Fig. 7. Frequency variation of the pumps with and without the proposed algorithm.

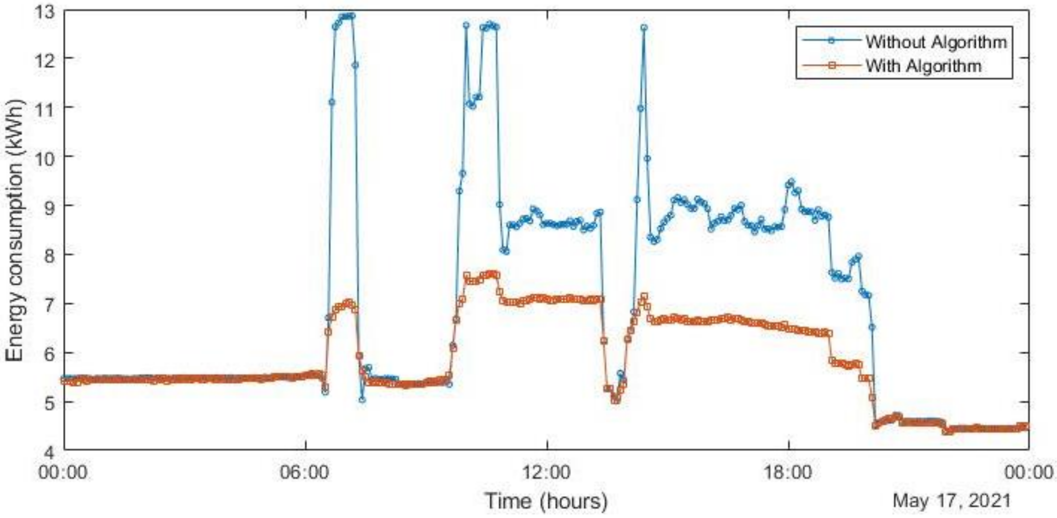

Fig. 8. Energy consumption of the pumps with and without the proposed algorithm.

As per Figure 9, total energy consumption at the end of the day has been reduced by the introduced approach in comparison with the existing system. The difference in total energy consumption between the two scenarios was 303.96 kWh and this was a 15.26% of energy saving which could be achieved by the proposed method.

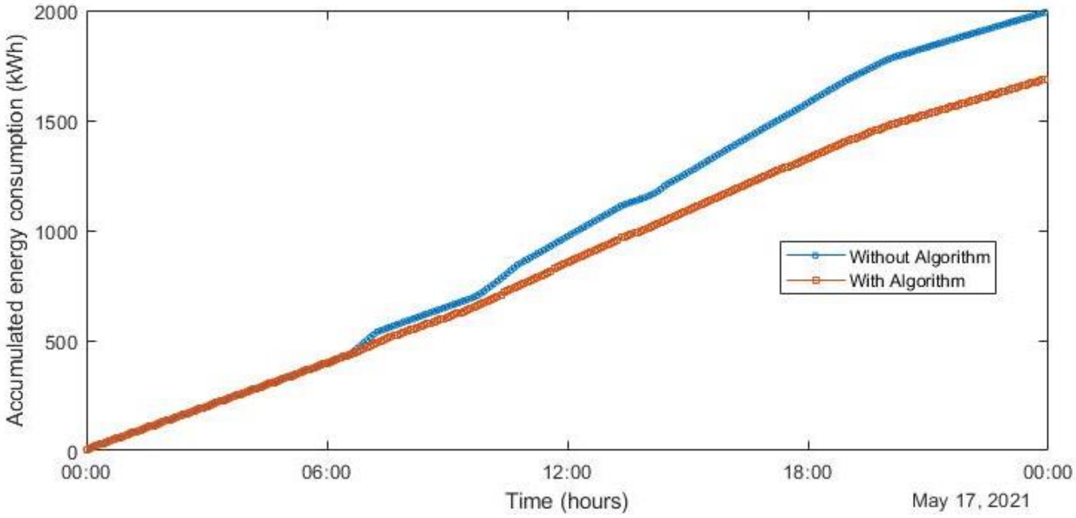

Fig. 9. Accumulated energy consumption of the pumps with and without the proposed algorithm.

4.2 Case Study II: Comparing the Proposed Method with Intelligent Methods

Here, the study carried out in [7] for the application of PSO in the operation optimization of a parallel pump system was considered due to its validated better performance compared to other intelligent methods. All the system model parameters were updated and instead of frequency limitations, the pump speed ratio (f/f_{rated}) has been constrained in the proposed algorithm as provided in the same literature. The respective system consists of two VFD driven centrifugal pumps and results were obtained for ten, hourly-time slots with different water flow requirements. The considered flow variation is shown in Figure 10.

As depicted in Figure 11, the optimal number of pumps determined by both algorithms is the same for most time slots. For only two flow values, decisions show a difference.

In the considered system, the speed ratio should be maintained between 0.5 and 1. Figure 12 illustrates that the proposed method has not violated this constraint at any time. Also, the suggested algorithm has offered nearly similar results as given by PSO, except for two-time slots.

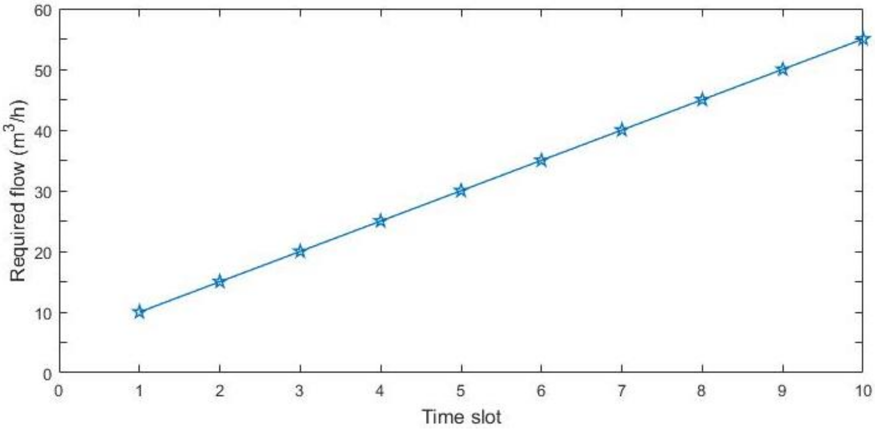

Fig. 10. Required flow variation for 10 time slots.

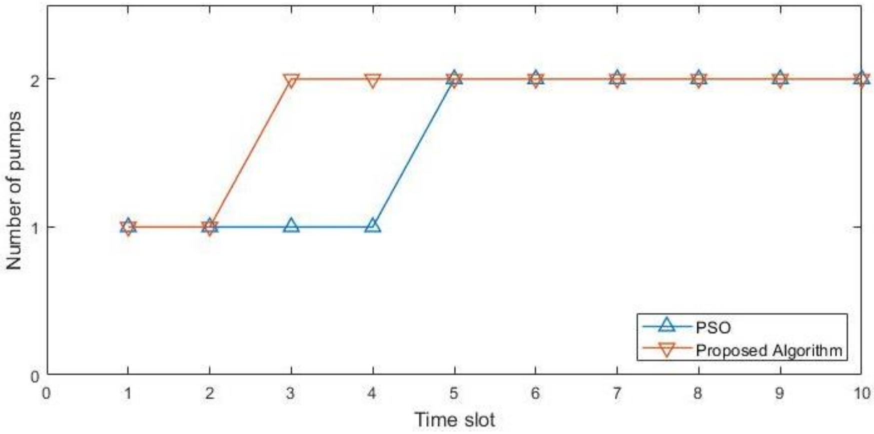

Fig. 11. Optimal number of operating pumps determined by the proposed and PSO methods.

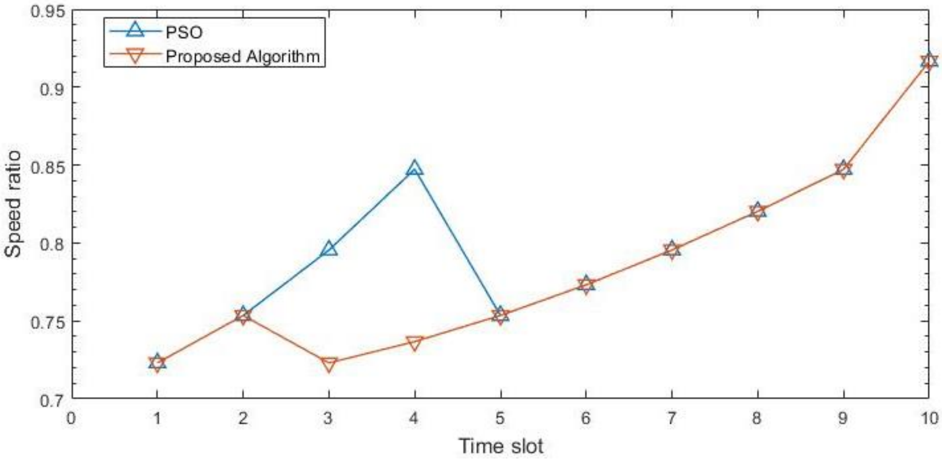

Fig. 12. Optimal speed ratio of operating pumps determined by the proposed and PSO methods.

Figure 13 presents the total power consumption of the secondary pumps at each time slot according to the optimal values of pump number and speed ratio decided by the two methods. As per Figure 14, total energy consumption at the end of the considered period has decreased by 1.78% in the introduced approach compared to the PSO method.

The execution time of the PSO method is about 3 s on a 2.3 GHz Intel CPU for each optimization case [7]. However, this time is about 0.006 s for the proposed method in a similar facility.

Therefore, these results prove the better performance of the proposed method in comparison with the PSO intelligent method.

5. INTEGRATION WITH BAS

Attaining ultimate benefits from the energy saving strategy for HAVC secondary chilled water pumps that is proposed in this research can be accomplished by the proper integration with Building Automation System (BAS) in the considered building. Generally, protocols such as Open Platform Communications (OPC) and Transmission Control Protocol (TCP) are utilized to link these control algorithms with BAS. Real-time data for the algorithm can be collected directly by accessing the supervisory controllers through relevant protocols. However, if the developed algorithm needs historical data for processes such as predictions, accessibility for databases will also be needed. Microsoft Structured Query Language (SQL) databases can be used in such cases. When embedding the novel algorithm developed in MATLAB® to a controller, sometimes installing addons or converting to intermediate language may be required. Finally, the output of the developed control algorithms can be delivered to appropriate actuator systems by the controllers via the previously mentioned protocols.

The developed algorithm can be stored either in a physical device or in a cloud platform. Cloud platforms are more reliable than physical devices and easily accessible from any location. It will be an advantage for a client who has several buildings to optimize. However, it is more secure on physical devices because of the risk of data theft.

Figure 15 explains how the integration of these systems appears in the BAS architecture.

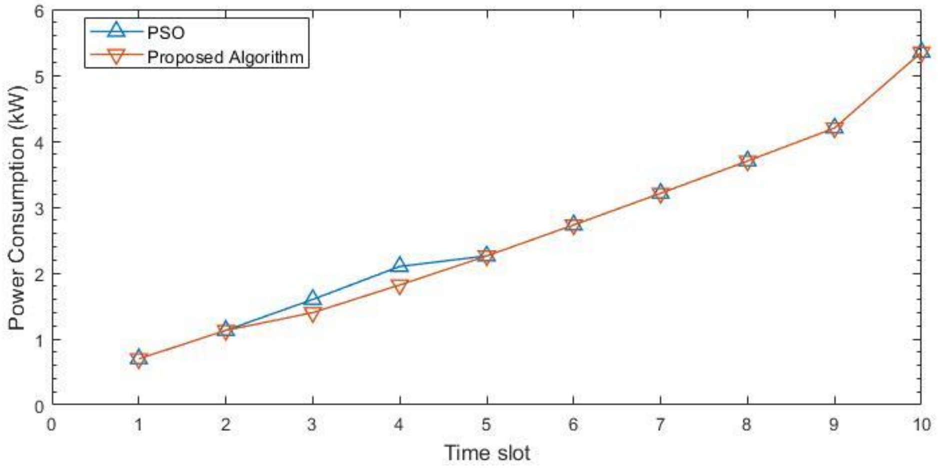

Fig. 13. Power consumption of the pumps at each time slot.

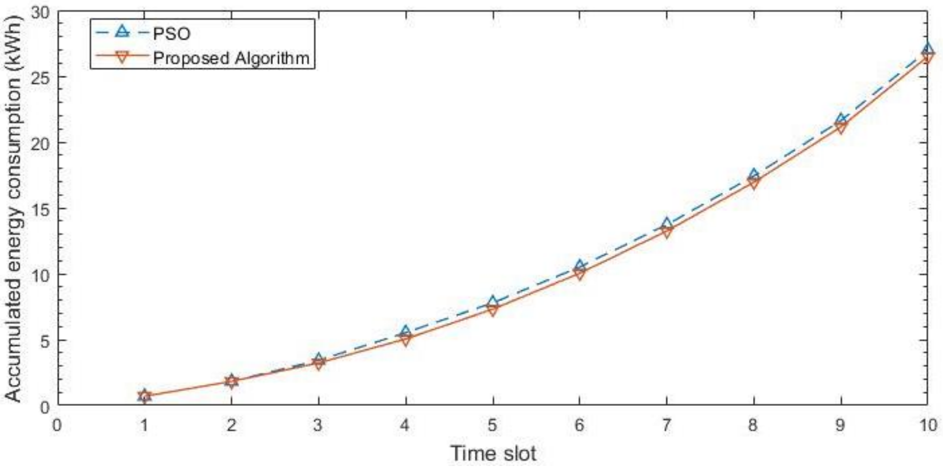

Fig. 14. Accumulated energy consumption of the pumps at each time slot.

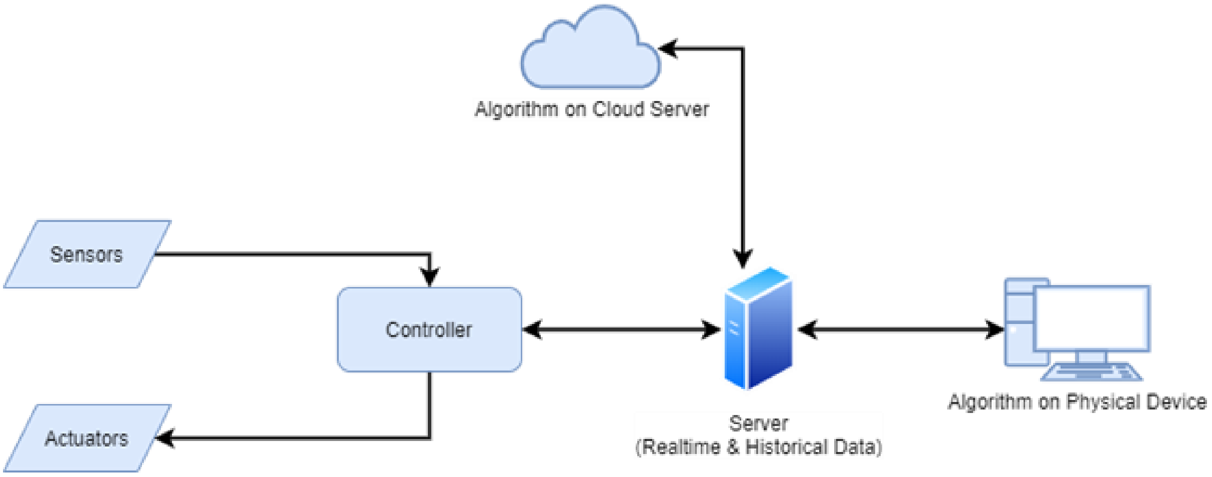

Fig. 15. Integration of the developed algorithm with BAS.

6. CONCLUSION AND FUTURE WORK

This paper has presented a novel algorithm to select the optimal number of parallel pumps to be operated and their optimal operating speeds with an aim to optimally reduce the power consumption of HVAC chilled water pumps while essentially satisfying the inevitable operational constraints and variable flow requirements imposed by the varying thermal load conditions of the building. After formulating the power usage minimization problem, a stepwise approach was used to solve it with low complexity using an algorithm that is developed using MATLAB®. The simulation results showed that the suggested approach outperforms the conventional cascading method and intelligent PSO method. The first case study resulted in a 15.26% decrement in energy consumption compared to the conventional method by applying the algorithm that was introduced in this paper. Case study II provided a performance comparison of the proposed method with the PSO method. In the simulation studies, the suggested strategy offered a 1.78% of energy saving over to the PSO method with a comparatively small execution time. Therefore, a highly efficient, safe, and reliable pump operation can be assured with the proposed method. Owing to its simplicity, reduced computational complexity, less computational time, ease of implementation, and reliability, the proposed algorithm is applicable in real-world applications to optimize the energy performance in industrial and commercial buildings. For the identification of further possible improvements and to enhance the performance, this algorithm will be combined with the temperature control system which creates a complete energy management and control system for future work.

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