



Predictive System Curve Control for  
Secondary Chilled Water Pumps

次級冷凍水泵：  
預測系統曲線控制



## Introduction

A central air conditioning system usually consists of the refrigeration plant (chillers), chilled water distribution system, air side equipment and air distribution ductwork. The chilled water distribution system is a pipework system connecting the air side equipment to the refrigeration equipment and distributes the chilled water between the chillers and air side equipment.

A typical chilled water distribution system consists of pumps, chilled water pipework and a number of control valves. This pamphlet aims to introduce a new algorithm for controlling the secondary chilled water pumps and to discuss its energy saving potential.

## Primary-Secondary Chilled Water Distribution System

In a large central air conditioning system, the chilled water distribution is usually designed with Primary-Secondary configuration (see Fig. 1). The constant speed primary chilled water pumps keep sufficient chilled water flow through chillers while the secondary chilled water pumps distribute the chilled water to/from air side equipment. The air side equipment units are usually installed with flow controlling valves which control the amount of chilled water passing through their cooling coils according to the demand. The secondary chilled water pumps therefore have to be designed to handle variable flow. This requirement gives rise to the need of a control system for the secondary chilled water pumps operation.

## 簡介

一個中央空調系統通常包括製冷設備（製冷機），冷凍水分配系統、供風端設備和冷氣風槽。冷凍水分配系統連接供風端設備到製冷設備，并把製冷機的冷凍水分配到供風端設備。

典型的冷凍水分配系統包括水泵、冷凍水管道和一些控制閥。這個小冊子會介紹一種新的次級冷凍水泵的控制方法和討論它的節能潛力。

## 初級+次級冷凍水分配系統

在一個大型中央空調系統，冷凍水分配通常以初級+次級形式設計（參考圖 1）。初級冷凍水泵以定速運行，以維持充足的冷凍水流量通過製冷機，而次級冷凍水泵則分配冷凍水到供風端設備。供風端設備通常裝有控制閥根據需求去調節通過冷卻盤管的冷凍水流量。因此次級冷凍水泵的設計須兼顧可變流量而裝有相關的控制系統。

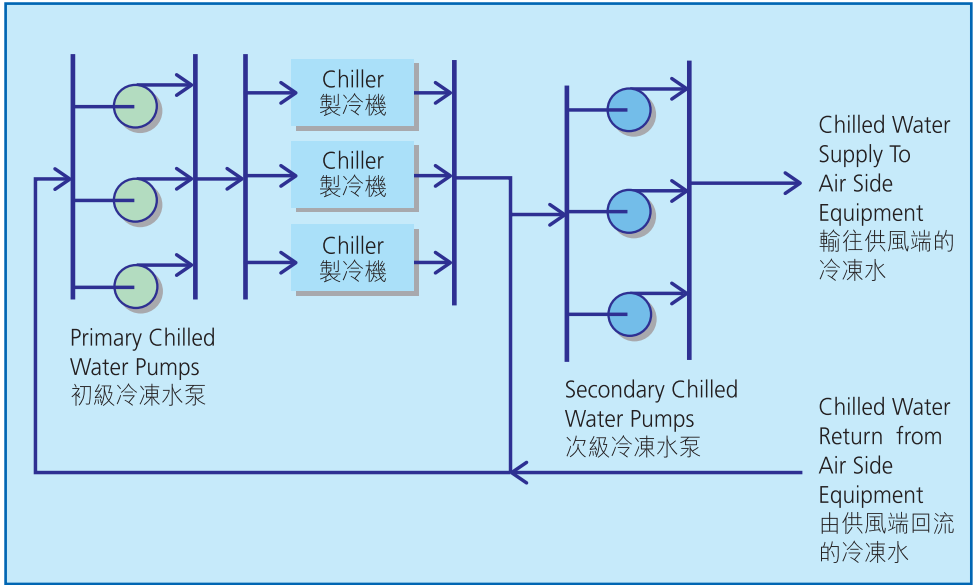


Fig 1 - Conventional Primary-Secondary Chilled Water Distribution System

圖1 - 初級+次級形式設計的冷凍水分配系統

## Conventional Control of Secondary Pumps

Control strategies are employed to adjust the flow of secondary chilled water pumps to match with the demand. The commonly adopted control strategies are constant differential pressure by-pass control, and constant differential pressure variable speed drive control.

### Constant Differential Pressure By-pass Control

In constant differential pressure by-pass control, the secondary chilled water circuit is fitted with a by-pass valve modulating to balance the pressure difference between the

## 傳統的次級水泵控制方法

控制方法是調整次級冷凍水泵流量以配合需求。通常採取的控制方法是恆定壓差旁路控制和恆定壓差可變速驅動控制。

### 恆定壓差旁路控制

在恆定壓差旁路控制中，次級冷凍水分配網路裝有旁通閥調整平衡冷凍水供水和回流水管之間的壓力（參考圖2）。次級水泵以定速運行。過多

chilled water supply and return pipes (see Fig.2). The secondary pumps are operating in constant speed. Excessive flow is returned via the by-pass valve to the pump suction side. This configuration is not widely used now because of its low energy efficiency.

的水流量通過旁通閥返回到水泵吸水口。由於它的能源效率低，這種設計現在並不普遍。

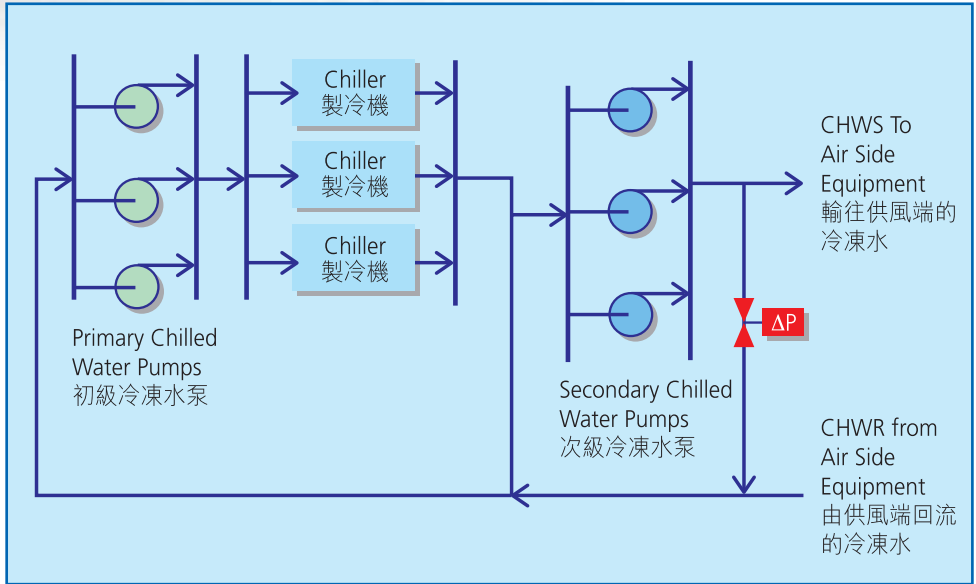


Fig 2- Conventional Primary-Secondary Chilled Water Distribution System with Constant Differential Pressure By-pass Valve

圖2- 恆定壓差旁路控制初級+次級形式設計的冷凍水分配系統

### Constant Differential Pressure Variable Speed Drive Control

With the advancement of power electronic technology and a reduction in price, variable speed drives (VSD) have now been commonly adopted in variable flow pump applications. In addition to the differential pressure by-pass valve, the pumps are driven by VSDs (see Fig.3) to achieve variable flow operation. The differential pressure by-pass valve is

### 恆定壓差可變速驅動控制

由於電力電子技術的進步和價格下降，變速驅動器（VSD）已廣泛地被應用在可變流量水泵裝置中。除壓差旁通閥之外，水泵在VSDs驅動下（參考圖3）達到可變流量操作。壓差旁通閥仍然是需要的，它的作用

still required: (1) to balance the system pressure during transient condition; (2) as a safeguard to prevent overpressure when control is malfunction and (3) to allow the chilled water distribution system for manual operation mode when the VSDs are disabled. For details of VSD applications, please also refer to "Application Guide To Variable Speed Drive" published by the Electrical and Mechanical Services Department (EMSD) which can be accessed on EMSD website.

是：（1）在過渡狀態時平衡系統壓力；（2）當控制故障時作為防止超壓力的保障，和（3）當VSDs無效時允許冷凍水分配系統以人手操作方式運行。關於VSD的應用細節，請透過網站參考機電工程署出版的變速驅動器之應用指引。

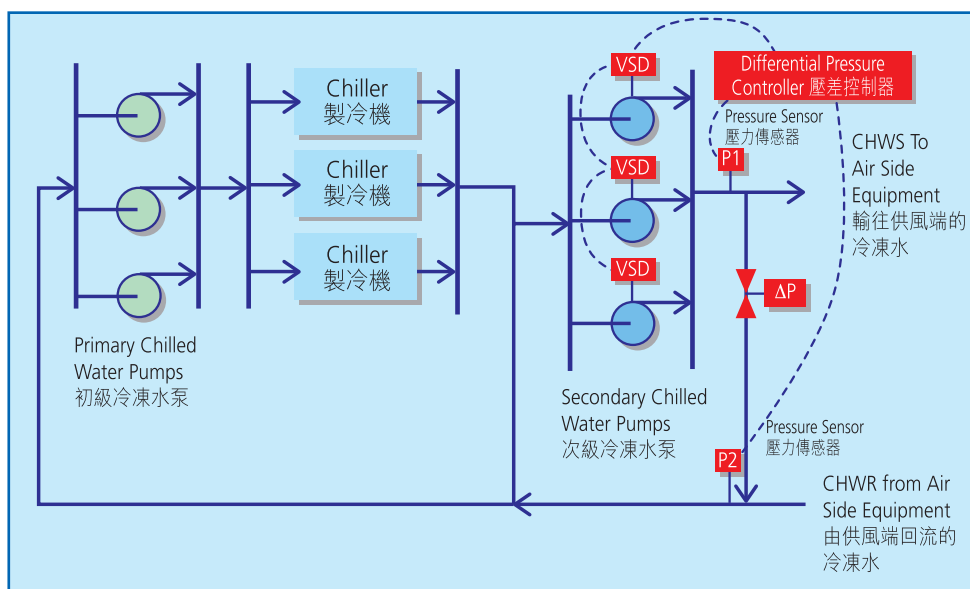


Fig 3 - Primary-Secondary Chilled Water Distribution System with Constant Differential Pressure Variable Speed Drive Control

圖3 - 恆定壓差變速驅動控制初級+次級形式設計的冷凍水分配系統

Compared with constant differential pressure by-pass control, studies show that incorporating VSDs for secondary pump application can save about 30% of secondary pumping energy.

據研究顯示，在次級冷凍水分配系統中使用VSDs可較恆定的壓差旁路控制方法節省大約30%的次級泵能源。

## Predictive System Curve Control

Predictive System Curve Control is a new advanced control algorithm that can produce further saving even in comparison with constant differential pressure variable speed drive control. Unlike constant differential pressure control, predictive system curve control operates the variable speed drive by signals from a pressure sensor at the pump discharge pipe and a flow sensor at the chilled water circuit return pipe (see Fig. 4).

## 預測系統曲線控制

預測系統曲線控制是一種新的先進控制方法，與恆定的壓差變速驅動器動控制比較，可進一步節省能源。不同於恆定的壓差控制，預測系統曲線控制主要是根據在水泵出口水管的壓力傳感器信號和在冷凍水回路管子的流量傳感器去操作變速驅動器（參考圖4）。

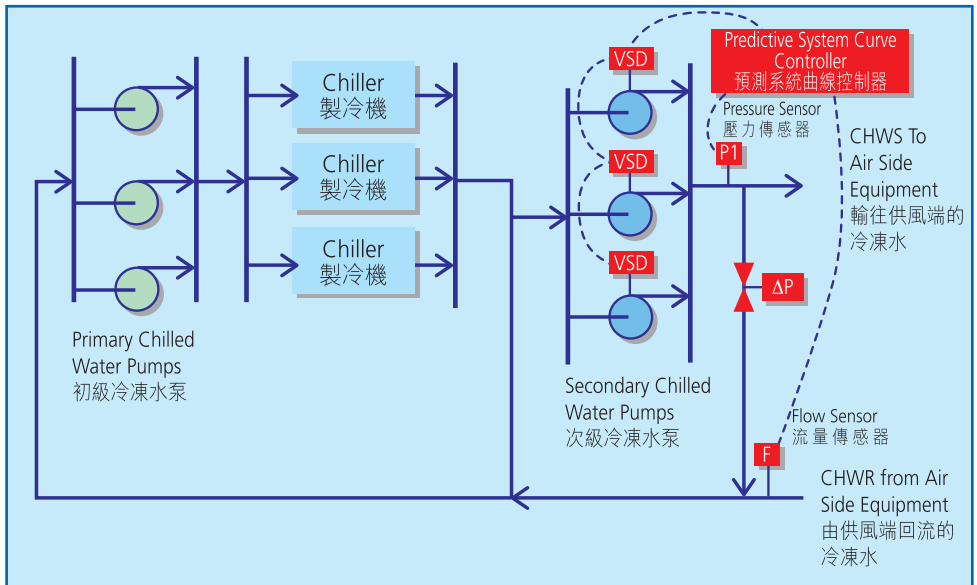


Fig 4 - Primary-Secondary Chilled Water Distribution System with Predictive System Curve Control

圖4 - 預測系統曲線控制初級+次級形式設計的冷凍水分配系統



## Principle of Operation

The Predictive System Curve Control, as its name suggests, controls the operation of Variable Speed Drives (VSDs) according to a predictive system curve which describes the relationship between the pump discharge pressure and the chilled water flow rate demand of the secondary chilled water circuit. The predictive system curve must be obtained by a precise commissioning process during the control system implementation.

## The Energy Saving Mechanism

The control algorithm saves energy mainly by:

- 1) The reduction of system resistance due to control valve throttling, especially during part load conditions; and
- 2) Avoiding delivering excessive chilled water flow through the by-pass valve.

Reducing system resistance can reduce the pump head required to deliver the chilled water to fulfill the cooling demand. In the air side equipment, the control valve controls the amount of chilled water passing through the cooling coil of the equipment. During part load condition, the valve is closed to restrict chilled water flow through the coil. A high differential pressure is created across the valves and the pumps have to maintain sufficient discharge head to ensure sufficient chilled water flowing through the coil (see Fig.5):

## 操作原理

預測系統曲線控制，如名所示，是根據描述水泵出口壓力和次級冷凍水流量需求之間關係的預測系統曲線來控制變速驅動器（VSDs）。預測系統曲線必須在控制系統安裝期間透過精確的調試而獲得。

## 節能機制

控制方法主要透過以下機制節省能源：

- 1) 減少在部分負載狀態期間由於控制閥節流所產生的系統阻力;
- 2) 避免提供過多的冷凍水流通過旁通閥。

減少系統阻力可減低水泵運送冷凍水以滿足冷凍需求時需要的壓力。在供風端設備，控制閥控制著通過設備冷卻盤管的冷凍水量。在部分負載狀態期間，控制閥門會被關上以減少冷凍水流量。由於閥門兩端形成高壓差，水泵必須維持足夠的壓力以確保冷卻盤管有充足的冷凍水流量（參考圖5）：

Pressure balance:  $\Delta P_3 + \Delta P_2 = \Delta P_1$   
壓力平衡：

For constant differential pressure control system,  $\Delta P_1$  is nearly constant.  
在恒定壓差控制系統中  $\Delta P_1$  是不變的

At full load condition, the control valve is fully opened:  
在滿載負荷下，控制閥是全開的：  
 $\Delta P_3 > \Delta P_2$ , with  $\Delta P_2$  approximately equals to 25%-50% of  $\Delta P_1$   
 $\Delta P_3 > \Delta P_2$ , 而  $\Delta P_2$  大約是  $\Delta P_1$  的 25%-50%

When cooling demand is low, control valve is closed to restrict the flow:  
當冷量需求下降時，控制閥便會關上以減低流量：  
 $\Delta P_2 \gg \Delta P_3$

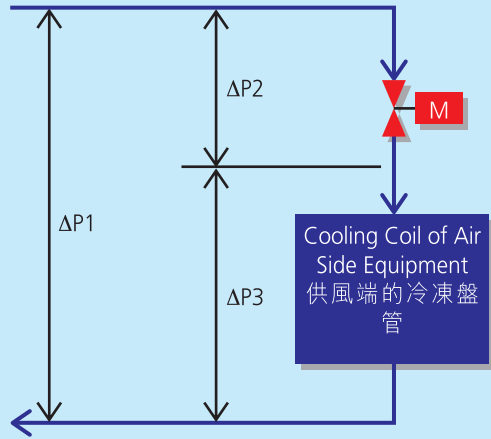


Fig 5 - Typical Air Side Control of Chilled Water Flow Rate

圖 5 - 典型的供風端冷凍水流量控制

If the pump flow and discharge pressure can be appropriately reduced during part load conditions, the control valves can be opened more widely. This can keep the cooling demand satisfied and at the same time reduce pumping energy.

Additionally, the adjustment of the pump flow and discharge pressure can prevent excessive flow returning to the pump suction through the by-pass valve under extreme part load condition. Fig. 6 shows the pump operating curve of the secondary chilled water pumps under different load conditions. At extreme part load conditions (Chart 3 in Fig.6), although the flow demand may be less than  $Q_1$ , the pump VSD frequency cannot be further lowered because the pumps have to maintain the set point differential pressure. Excessive flow will still be returned to the pump suction through the by-pass valve.

這時如果水泵流量和壓力可以適度地減少，便可把控制閥盡量打開。這既可滿足冷卻需求同時亦可減少水泵能耗。

另外，調整水泵流量和壓力可防止在極低負載狀態下過多冷凍水流經旁通閥返回到水泵吸水口。圖6展示次級冷凍水泵在不同負載狀態下的運行曲線。在極低負載狀態下（圖6中的圖表3），雖然流量需求也許比  $Q_1$  還少，但因為水泵必須維持固定壓差，水泵的VSD頻率不可能進一步下降。過多的流量將通過旁通閥返回到水泵吸水口。



On the contrary, a well implemented Predictive System Curve Control should have no water flow through the by-pass valve under normal operation.

相反，一個完備的預測系統曲線控制在正常運作之下是不應該有冷凍水流通過旁通閥的。

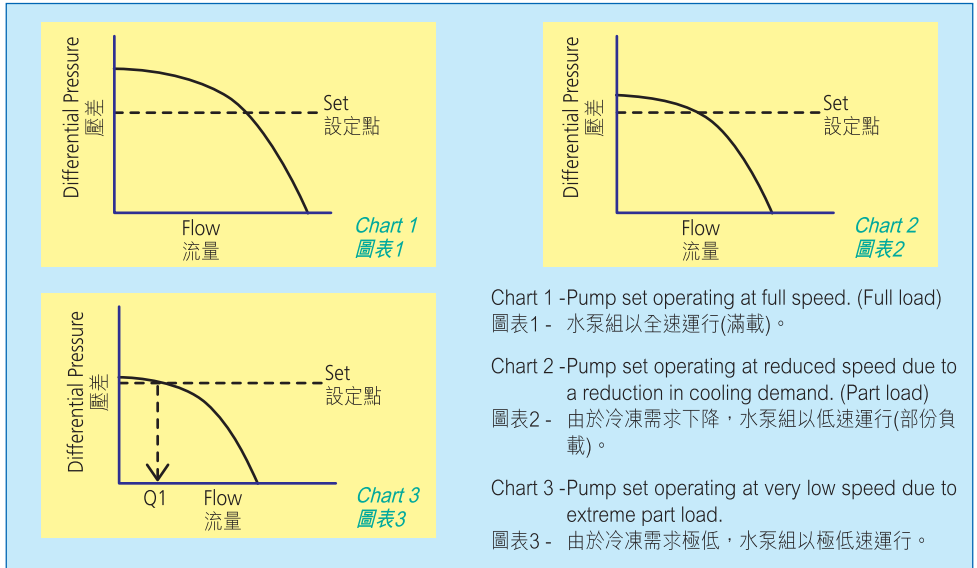


Fig 6 - Typical Pump Curve Under Constant Differential Pressure VSD Control  
圖 6 - 恆定壓差可變速驅動控制下的典型水泵運行曲線

## Implementing The Control Strategy

The system can be implemented relatively easy if the secondary chilled water pumps are already operating with VSDs. The followings are some general prerequisites for effective system implementation:

- The cooling capacity of the chiller plant, the chilled water distribution system and the air side system should be sufficient (or have some spare capacity) for the premises. Undersized plant or marginal plant will have fewer (or no) chances to

## 實施控制方法

如果次級冷凍水泵已經以 VSDs 操作，要實施有關的控制方法便相對地容易。以下是一些有效實施這個系統的一些先決條件：

- 樓宇的製冷機組、冷凍水分配系統和供風端系統應該有充足的冷凍容量（或具備一些剩餘容量）。在部分負載下運行是水泵達致節能的其中一個條件，容量不足或僅僅足夠的機組很少有（或沒有）機會在部分負載下運行。

operate under part load condition which is one of the operating criteria to achieve pump energy saving.

- There should be a sufficient section of straight pipe run for installation of the flow meter sensor. Usually a straight section with length equal to about 10 - 15 diameters of the main chilled water pipe in the secondary circulation loop is required for accurate flow measurement.
- The temperature control of the air side equipment should be functioning properly.
- Control valves of air side equipment should be two-port valve. Three-port valves are not suitable for this control system unless they are replaced.
- The scale of the chiller plant should be large enough to generate meaningful energy saving.
- For retrofit, if the original system is not equipped with VSDs, consideration should be taken for technical requirement of installing VSDs for the pumps.

The predictive system curve control algorithm is embedded in a standalone Direct Digital Control (DDC) controller. For existing secondary chilled water pumping system, the algorithm can be implemented to co-exist with the existing secondary pump control system with a selector switch selecting the signal being fed to the analogue input of the VSDs (see Fig. 7). This ensures that the existing control system can be used in case the new control system is malfunction. A selector switch can be installed with "signal isolator" to enhance smooth switchover and to reduce risk of control system damage due to incorrect analogue signals.

- 流量傳感器需要安裝於一段足夠長度的直線管道上。通常，流量計傳感器要準確測量流量，需要安裝在一段長度相等關於10 -15倍主冷凍水管直徑的直管道上。
- 供風端設備的溫度控制需能正常地運作。
- 供風端設備控制閥需是二通閥。三通閥門並不適用於這個控制系統。
- 樓宇的製冷機組規模需足夠大型以提供較可觀的節能效果。
- 在翻新工程中，如果原系統沒有裝備VSDs，應該同時考慮為水泵安裝VSDs的技術要求。

預測系統曲線控制的計算程序可內嵌於一個獨立直接數字控制（DDC）控制器中。在現有的次級冷凍水泵系統中，這個計算程序可以與現有的次級水泵控制系統共存，並用選擇器揀選輸出至VSDs模擬輸入的信號（參考圖7）。這可以保證如新的控制系統出現故障時可使用原有的控制系統。選擇器可以配備「信號分隔器」使信號轉換時更順暢和減少由於不正確模擬信號引致損害控制系統的風險。

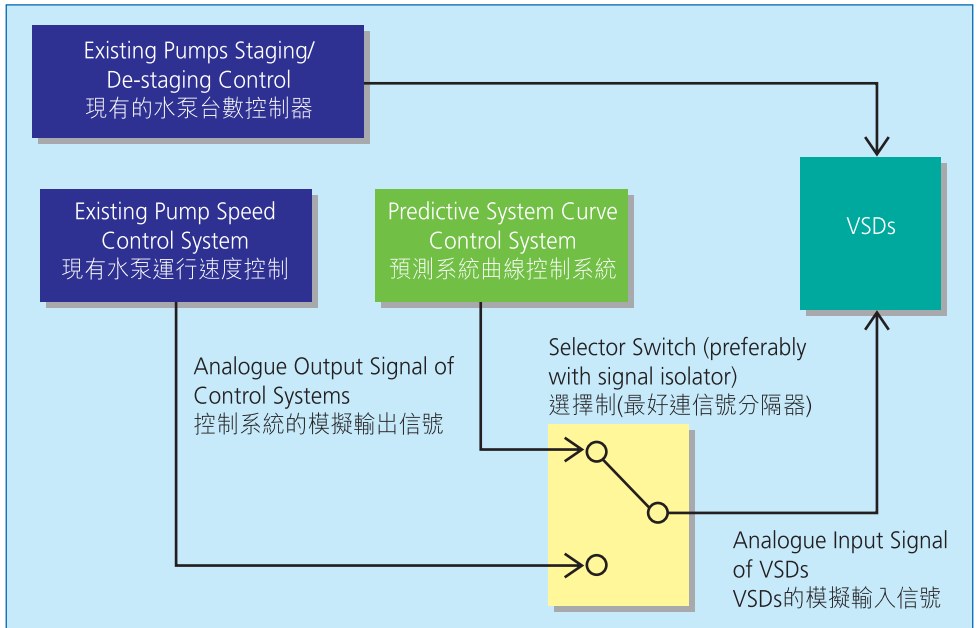


Fig 7 - Typical System Implementation Diagram for Existing Secondary Chilled Water Pumping System

圖 7 - 在現有次級冷凍水泵系統內的典型實施示意圖

## Compatibility With the System's Existing Staging Controller

The pumps staging and de-staging control has to be checked for compatibility. Pump staging and de-staging determine how many pumps are switched on for operation. Secondary pumps operated manually (that is, the number of pump being operated is selected by site operating staff) should have no problem in implementing the control. Site operators only need to operate the pumps base on their usual practices.

## 與現有系統的水泵台數控制器的兼容性

水泵台數控制器決定多少台水泵運作，必須檢查預測系統曲線控制與現有水泵台數控制器的兼容性。人手操控的次級水泵（水泵運行台數由操作人員選擇）在實施控制時應該沒有問題。操作員只需依照他們的習慣操作水泵。

Computerised pump staging and de-staging based on differential pressure set point (that is, a computer or a local electronic controller adjusts the number of pumps to operate in order to maintain a constant differential pressure set point) is not compatible with the new control because both controls are pressure based set point control. In this case, modification will be required.

If the computerised pump staging and de-staging is based on flow rate requirement (that is, a computer or a local electronic controller adjusts the number of pumps to operate in response to the water flow demand in the circuit), there is good chance for compatibility without any need for modification.

## **Deriving the Predictive System Curve**

The predictive system curve control adjusts the frequency of the VSDs according to a curve describing the relationship between the discharge pressure and the chilled water flow rate. The curve is site specific and has to be determined through a precise commissioning process. The energy saving potential is hinged on accuracy of the predictive curve model. A typical predictive system curve is shown in Fig. 8 below:

根據壓差設定點決定水泵台數的電腦化控制器（即以電腦或電子控制器調整水泵的數量以維持一個恆定的壓差設定點）不能與新的控制兼容，因為兩個控制方法都是基於壓力設定控制。在這種情況下，必須要修改原有系統。

如果電腦化的水泵台數控制器是根據流量要求（即以電腦或電子控制器調整水泵的數量以回應水流量需求），有很大機會不需要為原系統作出修改以達致兼容。

## **如何推演出預測系統曲線**

預測系統曲線控制是根據描述水泵出口壓力和冷凍水流量之間關係的曲線來調整VSDs的頻率。曲線是個別冷凍水系統所獨有的，並且必須通過一個精確的調試過程獲得。節能潛力取決於預測曲線模型的準確性。典型的預測系統曲線顯示在圖8如下：

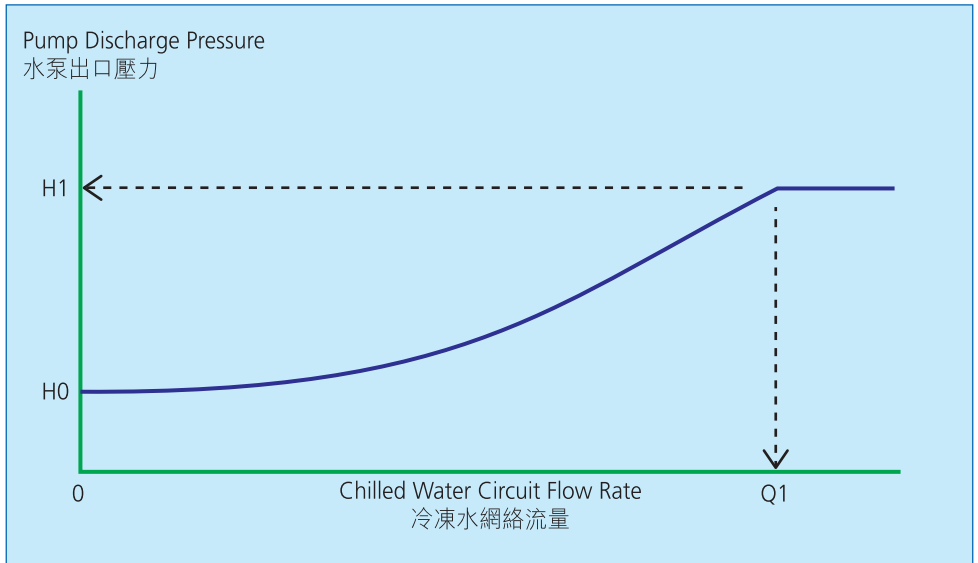


Fig 8 - Typical Predictive System Curve

圖 8 - 典型的預測系統曲線

In the above diagram,  $H_0$  is the minimum pressure required at the pump discharge to pump water to the air side equipment at the farthest end of the chilled water pipe work. This is the minimum pressure that the secondary pumping system will be maintained to ensure sufficient pump head to reach the farthest end air side equipment.

$H_1$  and  $Q_1$  are the pump discharge pressure and flow rate when all the control valves in the air side equipment are fully opened. The predictive system curve can then be determined by curve fitting the flow

在上述圖中， $H_0$ 是把冷凍水輸送到距離水泵最遠的一個供風端設備的最少壓力要求。這是次級泵裝置保持的最少壓力以保證系統有足夠壓力到達最遠的供風端設備。

$H_1$ 和 $Q_1$ 是當所有的供風端設備控制閥全部打開時水泵出口壓力和流量。利用曲線擬合各壓力和流量的條件便可獲得預測性曲線模型方程式中必需

conditions to a pre-determined predictive curve model equation to solve for the required coefficients of the model equation. These coefficients are site specific. Checking of the predictive system curve is then carried out by opening and closing of air side equipment control valves floor by floor to verify against the predictive system curve conditions.

The process of finding the predictive system curve is much easier if the air conditioning system can be controlled by building automation system (for switching on/off of air side equipment, varying set point to fully open the control valves, etc.). For building that is not equipped with building automation system, the curve can still be determined with the air side equipment being operated manually. However, it will take much longer time and will be more labour intensive.

### **Energy Saving From Better Control Strategy**

The Predictive System Curve Control strategy enables the secondary chilled water pumps to be operated more closely with the cooling demand of the building and reduces energy wastage. It should however be noted that the energy saving achievable is site specific which depends on the load pattern and the conditions of the plant equipment. For further information, please contact the Energy Efficiency Office of The Electrical and Mechanical Services Department.

的系數。這些系數是個別冷凍水系系獨有的。然後把各樓層的供風端設備控制閥打開和關閉以核實該預測系統曲線的可靠性。

如果空調系統可以由樓宇自動化系統控制（開關供風端設備，變化設定點以全面打開控制閥等等），測試出預測系統曲線的過程是比較容易的。沒有裝備樓宇自動化系統的大廈，用人手操作供風端設備仍可測試出預測系統曲線。然而，這將需要較長的時間，和較大量的人手。

### **利用更好的控制方法節能**

預測系統曲線控制方法使次級冷凍水泵更緊密地依從大廈的冷凍需求運作，減少能源消耗。然而應該留意節能效果於不同冷凍水系統是不同的，這取決於大廈的負載模式和製冷系統的狀況。如希望獲得更多資料，請與機電工程署能源效益事務處聯絡。



## Case Study

A Predictive System Curve Control system has been implemented in a Government premises as a pilot project.

## 個案研究

在一個政府樓宇內安裝了預測系統曲線控制作為試驗計劃。

### Basic Information of the Case:

#### 個案的基本資料

Number of chilled water pump:	3 Nos. (2 duties + 1 standby)
水泵數量：	3台（2台運行+1台後備）
Rating of pump motor:	37 kW
水泵功率：	37千瓦
Original control system:	Constant differential pressure
原有系統：	恆定壓差變速驅動器控制
Variable speed drive equipped:	Yes
已裝置變速驅動器：	是
Pump staging/destaging control:	Manual
水泵台數控制：	人手控制
Pump Operating Hour:	According to office hours (10 hours each day) of the building
水泵運行時間：	依照大廈辦公室時間（每天10小時）
Chilled Water Circuit:	The chilled water circuit is serving the high zone of the building.
冷凍水網絡：	冷凍水網絡分配冷凍水給大廈高層

### Result of the Pilot Project:

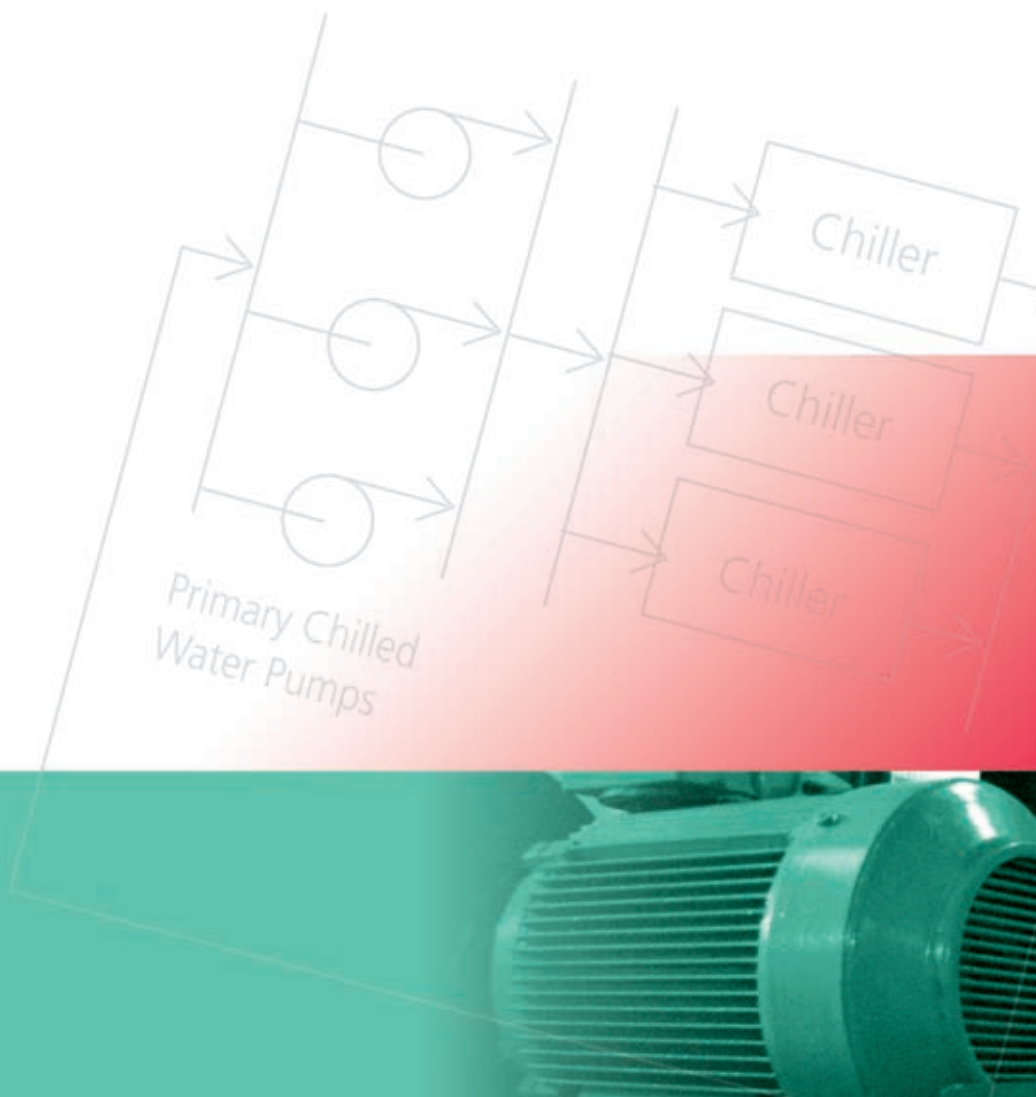
#### 試驗計劃的結果

The power consumption of the original control system was recorded during January 2007. This forms the base case data in establishing a mathematical model for predicting the power consumption for the pump operation under other conditions.

The energy consumption of the secondary chilled water pumps were recorded from February 2007 to July 2007 with the pumps controlled by the Predictive System Curve Control. The period covered a full range of operating conditions from cold winter to hot summer. In this pilot case the energy saving of the secondary pumps was found to be about 69% in winter, 48% in spring and 13% in hot summer. The overall saving throughout the period is about 38%. Operating staff of the premises did not receive any negative feedback about indoor environmental condition during the test period.

試驗中利用了2007年1月期間原有控制系統的水泵電力消耗記錄作基準數據，建立一個數學模型，用來預測水泵在其他運作情況下的電力消耗。

加入預測系統曲線控制後，記錄了次級冷凍水泵從2007年2月到2007年7月的能源消耗。期間包括寒冷的冬天及炎熱的夏天，是一個頗全面的操作環境。在這個試驗個案中次級冷凍水泵的節能率在冬天約69%，在春天為48%，在炎熱的夏天為13%。在整個期間約為38%。在測試期間，前線操作人員沒有接到任何室內環境的負面報告。



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