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Study on Smart Manufacturing using Control and Optimization

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ABSTRACT

Energy management has become a major concern in the past two decades with the increasing energy prices, overutilization of natural resources and increased carbon emissions. According to the department of Energy the industrial sector solely consumes 22.4% of the energy produced in the country [1]. This calls for an urgent need for the industries to design and implement energy efficient practices by analyzing the energy consumption, electricity data and making use of energy efficient equipment. Although, utility companies are providing incentives to consumer participating in Demand Response programs, there isn't an active implementation of energy management principles from the consumer's side. Technological advancements in controls, automation, optimization and big data can be harnessed to achieve this which in other words is referred to as "Smart Manufacturing". In this research energy management techniques have been designed for two SEU (Significant Energy Use) equipment HVAC systems, Compressors and load shifting in manufacturing environments using control and optimization. The addressed energy management techniques associated with each of the SEUs are very generic in nature which make them applicable for most of the industries. Firstly, the loads or the energy consuming equipment has been categorized into flexible and non-flexible loads based on their priority level and flexibility in running schedule. For the flexible loads, an optimal load scheduler has been modelled using Mixed Integer Linear Programming (MILP) method that find carries out load shifting by using the predicted demand of the rest of the plant and scheduling the loads during the low demand periods. The cases of interruptible loads and non-interruptible have been solved to demonstrate load shifting. This essentially resulted in lowering the peak demand and hence cost savings for both "Time-of-Use" and Demand based price schemes. The compressor load sharing problem was next considered for optimal distribution of loads among VFD equipped compressors running in parallel to meet the demand. The model is based on MILP problem and case studies was carried out for heavy duty (>10HP) and light duty compressors (<=10HP). Using the compressor scheduler, there was about 16% energy and cost saving for the light duty compressors and 14.6% for the heavy-duty compressors. HVAC systems being one of the major energy consumers in manufacturing industries was modelled using the generic lumped parameter method.

INTRODUCTION

With the growing population and incessant demands, energy management and conservation has become a major challenge in the smart grid. Demand side management programs are being initiated around the globe so as to reduce the overall energy load and emissions that pose a threat to the non-renewable forms of energy and environment respectively. As a result, in the recent years, there has been an exponential increase in the interest for energy management research. According to energy.gov, the Department of Energy of United States spends approximately $5.9 on energy research for clean and better utilization of energy resources. Besides the United States, South Korea and Germany have been actively implementing "smart" manufacturing techniques to optimize production, energy consumption and cost in response to this activity [2]. Process and other energy intensive industries have already resorted to smart systems to run plants in an economical and productive manner. The purpose of this thesis is to investigate and implement the potential overlooked energy saving practices for major energy consuming systems in manufacturing industry using optimization and control.

Smart Manufacturing

Smart manufacturing is a type of manufacturing where the optimized techniques and processes are used to obtain maximum yield while keeping the energy footprint and costs low. This is made possible with the advanced modelling, controls, optimization, and big data that has been on rise in the past decade. In fact, smart manufacturing is regarded as the industrial revolution 4.0 as a result of this. According to The National Institute of Standards and Technology (NIST) [3], Smart Manufacturing systems are fully integrated, collaborated manufacturing systems that 2 respond in real time to meet changing demands and conditions in the factory in the supply network and customer needs. This is exactly what this thesis is attempts to achieve by using tapping the energy management techniques using control and optimization

Demand Side Management

Demand Side Management refers to the energy measures taken from the demand side (consumer) to reduce the electricity bills and utility infrastructure costs. This is usually done by shifting or scheduling the consumption of energy from high demand periods to low demand ones. For example, costumers could use renewable resources or energy storage devices like batteries for their energy needs during the high demand periods. Another simple yet effective way would be to prioritize the energy needs and schedule the low priority energy needs during the off-peak periods. DSM can also be implemented at subsystem level by carrying out energy audits to find out potential energy saving methods, installing energy efficient equipment like VFDs, improving the schedule of machines, upgrading the control systems of the energy demanding systems such as the HVAC. The following figure shows how load shifting can be used to smoothen the peak demand and hence the demand-based charges which is one of the most commonly used DSM techniques.

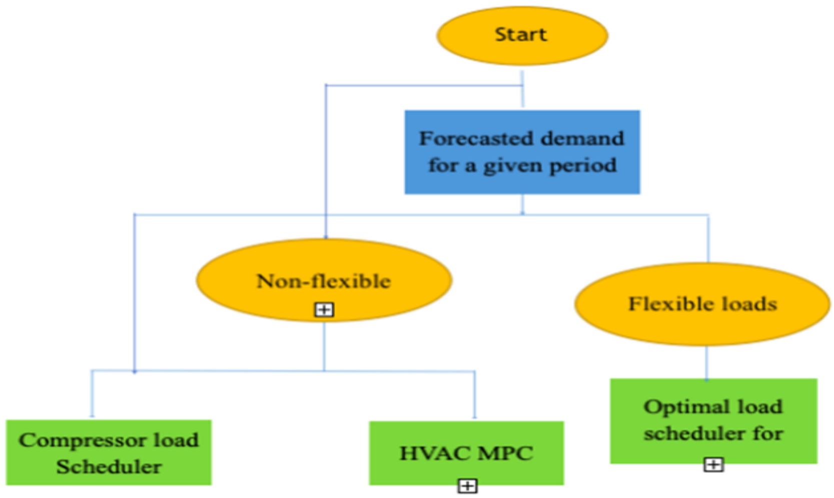
Research Milestones

Problem Statement: The HVAC systems together with the air compressors and electric motors consume more than half of the total energy in the manufacturing sector. This significant share of energy consumption is a result of inefficient energy management practices which in turn strain the utility companies and increase the utility bills and carbon footprint. Hence, there is a dire need of optimizing the energy consumption through energy management and energy efficient control and optimization systems.

Major objectives in this research are,

- Identification and selection of potential energy management techniques and processes to increase energy efficiency and reduce costs
- Development of a mathematical model that can schedule the flexible machines with the help of the Demand Side Management.
- Development of a compressor scheduler that can distribute the loads between compressors so that the demand is satisfied in a cost-effective manner
- Generic modelling of a manufacturing facility using lumped parameter modelling and validation using real data
- Using state-of-the-art MPC to reduce the total energy consumption by the HVAC fans while meeting the temperature requirements of the manufacturing facility.

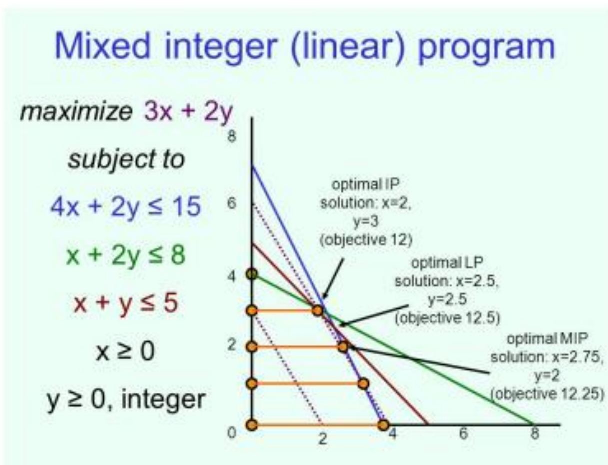
Figure 1.1. Demand side management by load shifting [4]



SCHEDULING PROBLEM

Linear Programming

The purpose of this chapter is to introduce the readers to the concept of scheduling. In a typical scheduling problem, the goal is to find a set of assignments to machines so that a given objective is minimized or maximized. This is a common problem that is solved in the field of Computer Science and is referred to as Job Shop Scheduling (JSP). In such a problem, there are "m" jobs that need to be completed by "n" machines of different processing times and powers. The objective is the assignment of these jobs to the machines such that the jobs are completed in the least amount of time and effort (power consumption).There can be variations in the LP problem such as Integer Programming and Mixed Integer Programming. As the name suggests, integer programming is a LP problem with variables that can take only integer values and the MILP problem is one where the variables can be integers of variables. Figure 2.1 shows the feasible solution space for the given problem and the optimum solution for MIP, LP and IP problems.



Brand and Bound Algorithm

The complexity of solving MILP problems is NP-hard which means that they cannot be solved by any known algorithm in polynomial time and the complexity of the problem increases exponentially with time [27]. This type of problems are mostly solved using Branch and Bound which searches for the solution by dividing the relaxed problem it into smaller sets of problems and without actually enumerating all the possible solutions which significantly reduces the time complexity of the problem. This algorithm is similar to how decision trees that have nodes and branches work. The algorithm starts with an initial computation of the relaxed solution (solution with only equalities) at the root node. From the root node, more nodes (or sub problems) are branched out (or explored) by increasing or decreasing the value of the decision variables. Whenever, a node is found to lead to an unfeasible solution (less optimal than parent node) or violate the bounds of the decision variables, that node is fathomed (the children nodes of that node are not explored and other adjacent nodes is explored).

Energy Oriented Control

This chapter serves to provide a basic understanding about optimal control and the Model Predictive Control that has been used for the energy efficient control of HVAC systems in manufacturing industries. There are several control techniques that are used in industries such as the Programmable Logic Control (PLC), Proportional Integral Derivative (PID) Control and ON/OFF controller. Although these control techniques satisfy the performance requirements but they are not the most optimum input to the actuators. In case of ON/OFF controller, the input goes from zero to full and keeps running the machine until the set point is reached. Although this type of control has its roots from optimal control, the response is oscillatory about the dead band which is undesirable and it starts and stops the machine quite frequently. As for the PID control, it may be able to continuous adapt and follow the set point, however it cannot handle Multi Input Multi Output System (MIMO) and constraints and is susceptible to integral windup. PLC control is purely based on logic for very simple systems like valves and cannot be used for complex systems altogether. Optimal control techniques like the MPC provide the best possible input to the system with respect to the objective function. If the objective function requires minimum energy effort, then the inputs provided by the MPC is energy efficient.

Model Validation

The purpose of this chapter is to prove that the proposed modelling generic technique for the HVAC system is realizable and applicable. This has been done by modelling a real manufacturing facility using the modelling technique and validating it with the input and output data collected at the actual facility. Since the Optimal Load Shifter and the Compressor Load Scheduler are just mathematical formulations rather than models they have been directly tested using the case studies (Results Chapter).

HVAC Model Validation

To represent small scale manufacturing industries, a company named Electro-Spec that specializes in Electroplating, Passivation and Heat-treating services [33] has been chosen. To validate the model, the inputs (HVAC mass flow rate and disturbances) and output (Temperature in the plant) of the actual plant were logged for 5 days. Table 5.1 shows the details of the sensor and loggers that were used to log the input and output parameters for model validation. For heating and cooling purposes, Electro spec uses 3 Rooftop Units and 2 Packaged that are based on On/OFF control with a maximum Volumetric flow rate of 47m3/s and minimum volumetric flow rate of 4.7m3/s. Since the actual plant has numerous disturbances affecting the temperature, at least the major temperature disturbances had to be accounted for model validation accuracy. This includes the 1500 T5s light bulbs that are rated 35 W each and are about 10% efficient (90% of the power consumed is dissipated as heat), an oven that releases exhaust gases at 116◦F (46.67◦C) and 40 different chemical tanks (of similar dimensions) that keep releasing heat at an average temperature of 150◦F (65.56◦C). Since the material properties of the chemicals in the tanks were not available, these tanks were approximate

#	Sensor	Qty	Purpose	Placement	Specifications	Sampling rate
1	Temperature Sensor and Datalogger	8	Measure and log surrounding rooms temperatures	Close to the thermostat in the room	-40° to 122° F(-40 ° C to 50 ° C) ± 0.45° F from 32° to 122° F (± 0.25° C from 0° to 50° C)	1 sample/min
2	Temperature Sensor and Datalogger	5	Measure average plant temperature	Close to the thermostats in the plant	-40° to 122° F(-40 ° C to 50 ° C) ± 0.45° F from 32° to 122° F (± 0.25° C from 0° to 50° C)	1 sample/min
3	Current Sensor	5	Measure the 3 phase current of the HVAC blower fans	Hooked to the one of the 3 phase wires of the HVAC blower fans	10-100Amps ± 4.5% of full scale	1 sample/min

CONCLUSIONS

In this thesis, the potential energy saving strategies have been explored for the SEU systems which are the HVAC, Compressors and machines driven by electrical motors. The proposed energy management techniques have been proved to be effective in reducing the energy and costs. The OLS was used to achieve load shifting and valley filling which resulted in lower peak demand and costs. The CLS was used to distribute loads among compressors such that all the compressor run in their most efficient conditions for energy efficiency. The lumped parameter HVAC model was used to model a manufacturing facility and the MPC was implemented as the HVAC control for the validated model to improve the energy savings. In case of the optimal shifter, there is potential for cost saving even though the energy consumption is same due to the load shifting that reduces the peak demand. This is usefully manufacturing industries that are located in regions with utilities that have TOU and Peak Demand schemes. The Compressor scheduler was able to reduce the energy and cost for both the heavy and light duty compressors and this is a generic formulation that can be used regardless of the compressor type as long as the compressor is VFD type and works with other compressor in parallel configuration. The MPC pertaining to its optimal nature was able to reduce the overall energy consumption by running the fan only when needed. The total framework when implement has a potential of saving upto 40% of energy and costs as summarized in the below table. Table 7.1 summarizes the cost and energy savings of the proposed energy management framework.

Estimated energy savings with the proposed framework

#	Energy Management Technique	Type	Savings
1	Optimal Load Shifter	Optimization	27.6% Energy and Cost saving
2	Compressor Scheduler	Optimization	14.6% (Heavy duty) and 16% (Light duty)Energy and Cost saving
3	HVAC MPC	Control System	Cost Savings depending on the peak demand price or TOU price

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