An MILP Formulation for Load-Side Demand Control

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Abstract

This paper presents a mixed integer linear programming formulation for load-side control of electrical energy demand. The formulation utilizes demand prediction to determine if control actions are necessary, and it schedules both shedding and restoration times based on an optimization model that minimizes the net cost of load shedding. Operational constraints are satisfied through the use of minimum/maximum uptimes/downtimes, which depend upon the current state of the system. The algorithm is evaluated using a simulation model of an underground coal mining operation where, (i) its performance is compared with a traditional static, priority-based, load-shedding schedule, and, (ii) its potential is established for producing net savings through demand control.

1. Introduction

Electricity charges for industrial customers are generally based on total energy consumption, power factor, and maximum demand. The demand component is determined from the maximum average power flow during short, fixed-duration time intervals, typically 15, 30, or 60 minutes, and it is measured in kVA, kW, or other suitable units. This demand charge is levied primarily because of the cost of peaking generation required for occasions when the utility experiences high coincident demand; and it is a large component of the customer’s total bill (a demand charge of 25% of the total is typical for most industrial users, Pongia and Battish).

Accordingly, a very effective means of reducing utility bills is through control of the demand component, especially for customers with large, uneven loading patterns that make their operations prone to high demand charges. In fact, demand control has been used in residential power systems (Gustafson; Hsu and Su), manufacturing systems (Pongia and Battish; Su, et al), coal mines (Croyle, et al), and even the utility companies themselves (Cohen and Wang; Halevi and Kottick). These applications show that demand control can not only reduce costs, but also increase the productivity and the life of equipment (Pongia and Battish; Effler and Wagner; Hsu and Su).

Demand control is likely to become of greater importance in the future as the gap between electrical demand and supply decreases. For example, utilities are currently offering large industrial customers interruptible rates (which allows the utility to shed customers on short notice during periods of high coincident demand). In addition, utilities are also moving towards shorter demand intervals, e.g., five minutes, and even rolling demand intervals.

* These authors contributed equally to the preparation of this paper.
1.1. Supply-side Versus Load-side Demand Control

Demand control systems can be divided functionally into supply-side and load-side control/management systems. Supply-side demand management systems, implemented by the utilities, choose between maintaining the demand below a certain level, or permitting an increase in the demand level, in which the choice depends on the current generating costs. If demand is to be limited, most systems attempt to determine the best strategies to shed customer load groups during peak periods. Customers participating in such an arrangement are usually given special rates.

Load-side management systems are used by power consumers and are motivated by a desire to reduce the demand component of their power bills. Control objectives are to minimize the electric demand charges by switching loads off and on while minimizing production losses caused by load shedding. Load shedding schedules are established according to the structure of the demand charge, operational priorities of each load, and power consumption of each load. Control decisions should also consider load operational status, guard against equipment damage from frequent switching, and prevent safety hazards caused by automatic load switching.

In this paper, we present a new load-side demand management approach using a linear integer programming formulation of load scheduling alternatives that results in more effective control decisions than earlier approaches, briefly described below.

2. Prior Work on Load-side Demand Control Systems

There are three major types of load-side demand control systems. Jorge, et al (1993) discussed and compared these systems in detail, and we only briefly summarize them here.

The first type of system uses the ideal load curve (ILC) algorithm. Control is initiated whenever the energy consumption rate exceeds a pre-defined level called the ideal rate. The load with the lowest priority is shed first, followed by the second lowest priority load, etc., according to a pre-determined shedding schedule. Shed loads are usually restored at the beginning of the next demand interval.

Advantageously, ILC is simple. However, random power fluctuations can trigger frequent and unnecessary shedding operations, which may reduce production and shorten electrical equipment life (Minasiewicz, et al). Note that instantaneous power, not the average demand, triggers shedding actions in this system. Also, the concurrent restoration of loads at the beginning of next demand interval can cause power surges. Some versions of ILC systems allow restoration at other times to avoid this problem.

The second type of control system uses the frequency comparator (FC) algorithm. The major distinction between this algorithm and ILC is that the FC algorithm does not consider the demand interval when restoring loads. Like ILC, control is initiated whenever the power exceeds a pre-defined level, and loads are shed according to a pre-determined shedding schedule. However, loads are restored whenever the power level falls below a second pre-defined value. This control approach is also simple to implement; but, similar to the ILC algorithm, loads may be shed and restored too frequently.

The third type of control system employs demand prediction. Control action is initiated whenever the predicted energy consumption in the current demand interval exceeds the specified maximum value. Like ILC and FC, loads are shed according to a pre-determined order. Moreover, loads are restored whenever the predicted demand drops below the maximum value, and loads with the highest priorities are considered first for restoration. Because prediction provides information about the possible level of demand before the interval ends, it gives the controller an opportunity to consider alternative control policies. In some modified schemes, specific time parameters, e.g., minimum on time and maximum off time, have been used to condition shedding/restoration actions.
2.1. Limitations of Prior Approaches

First, as noted above, ILC and FC systems determine shedding actions on the basis of the instantaneous power level instead of the expected demand. A decision to take action based on an indirect measure of the variable being controlled, especially one subject to substantial random fluctuations, has high potential to result in spurious control actions.

Second, emphasis has focused on controlling auxiliary equipment, e.g., air conditioners and heaters. However, when the demand reaches a certain level, production equipment might also be shed to satisfy the maximum demand limitation, since the cost of demand may exceed the value of the productive work performed by a particular machine. Thus, there is a trade-off between production losses and cost of energy usage, which has not been fully considered in prior work.

Third, many loads have special operational requirements constraining shedding and restoring actions, such as maximum downtime (i.e., maximum duration that the machine can be *off*) and minimum uptime (i.e., the minimum duration that the machine can be *on*). For example, an air conditioner cannot be shut down for long periods of time, nor can it be restarted immediately after it is shut off, or the compressor could be damaged. A control algorithm should consider all these factors before a control decision is made.

Finally, instead of simply shedding loads when forecasts predict demand limits will be exceeded and restoring them when forecasts predict the situation has been corrected, it makes more sense to schedule load shedding and restoration over the entire demand interval. Through careful scheduling, strategies can be devised which meet demand limits with minimum loss of production, while satisfying the noted operational constraints.

The new approach discussed below attempts to overcome these limitations of existing demand control systems.

3. Motivating Application

An electric load simulation model of a typical underground coal mine was created to assist in evaluating the new demand control strategy. This particular application was selected because (1) mining operations are large users of electricity, (2) loading patterns are highly irregular, resulting in relatively high demand charges, and (3) mines are often located in remote areas where power delivery during periods of high coincident demand is problematic.

In the model, five continuous-miner sections are simulated. Each operating section includes one continuous miner, three shuttle cars, two roof bolters, one feeder, and one section conveyor belt. (The location of each production section and conveyor belt are shown on Figure 1.) Other important loads in the mine include conveyor belts, drainage pumps, and ventilating fans. We begin with a brief description of the production operations that have been simulated.

The continuous miner (CM) extracts coal from the face and loads the shuttle car that is positioned directly behind the CM. Once loaded, the shuttle car trams (i.e., travels) to the belt feeder. Each shuttle car has a unique path from the miner to the feeder except for that portion of the path in close proximity to the CM and feeder, referred to, respectively, as the miner path and feeder path, which must be shared by the shuttle cars. If a shuttle car is occupying the feeder (or miner) path when another shuttle car approaches it, the second shuttle car must switch into an intersection at the end of the path (i.e., the change point) and wait until the first shuttle car clears the path. Once the shuttle car reaches the feeder, it immediately discharges its load and returns to the continuous miner. The feeder smooths the flow of coal onto the section conveyor belt which transports coal to the section gathering belts that, in turn feed downstream belts that eventually transport the coal out of the mine.
This process of cutting, loading, and hauling continues until a specific distance is mined, at which time the continuous miner must vacate the cut so that the newly exposed roof can be supported. Roof support consists of a roof bolting crew drilling the roof and installing roof bolts.

Significant auxiliary operations performed include dewatering and ventilation of the mine. Water is generally collected into several sumps and periodically pumped to the surface by sump pumps. One or more ventilating fans are located on the surface and are used to create an air pressure difference that causes air to flow throughout the mine. Within the mine, static devices (e.g., doors, walls, and curtains) usually control airflow. In addition to these major auxiliary operations, there are additional loads such as lights, welders, battery chargers, and so forth.

4. A New Demand Control Approach

In our proposed demand control approach, demand prediction is utilized; however, in making decisions to shed or restore loads, an optimization formulation is solved. In this formulation, shedding and restoration are scheduled to minimize production losses while satisfying equipment operational constraints through the use of minimum and maximum downtimes and minimum and maximum uptimes for each controllable load. Note that these minimum/maximum uptimes/downtimes are also not always static values, but may depend on the current state of the system.

4.1. Mixed-Integer Programming Formulation

The demand control algorithm that we propose is initiated under the following two circumstances. First, when it is predicted that the predetermined demand limits will be violated, load shedding control is initiated to decide which loads to shed, when to shed them, and when to restore them. Particularly, for a load that is on at time \( t \), the control procedure decides whether it needs to be shed, the time to do so, and the time to resume its operation. For a load that is already off, the system will reschedule its restoration time and its next down time. Second, when it is predicted that demand has significantly dropped after shedding actions have been taken, control is initiated, primarily to determine which loads to restore. The same model formulation can be used for both cases.
Like earlier demand prediction control approaches, at time $t$ we use the cumulative energy consumption, from the start of the demand interval, $E(t)$, and the current power, $K(t)$, to predict the energy consumption during the demand interval, $E_{\text{tot}}$, as follows

$$E_{\text{tot}} = E(t) + K(t) \cdot (T-t)$$

where $T$ is the time that the current demand interval ends (see Figure 2).

![Figure 2. Demand Prediction.](image)

Assume that the demand forecasting system has just triggered the $n^{th}$ control event at the current time, $t$. $t$ is contained in a particular demand interval, and we desire to keep the demand in that interval below $D_{\text{max}}$. Let $U(t)$ be the set or collection of loads that are up (or on) at time $t$; let $D(t)$ be the set or collection of loads that are down (or off) at time $t$.

We have three decision variables: $t_{\text{down}}^n(i)$, $t_{\text{up}}^n(i)$, and $x(i)$ for each load $i$. $t_{\text{down}}^n(i)$ and $t_{\text{up}}^n(i)$ are defined as the decision times to shed and restore, respectively, load $i$ for the current control event, $n$. Note that for $i \in U(t)$, $t_{\text{down}}^n(i) \leq t_{\text{up}}^n(i)$ and for $i \in D(t)$, $t_{\text{down}}^n(i) \geq t_{\text{up}}^n(i)$. Let $x(i)$ be a binary decision variable with

$$x(i) = \begin{cases} 1 & \text{if load } i \text{ is to be switched on for } i \in D(t), \text{ off for } i \in U(t), \text{ in the demand interval,} \\ 0 & \text{otherwise.} \end{cases}$$

Then, for any load $i$ that is currently up, i.e., $i \in U(t)$, the following inequalities hold to meet the maximum/minimum down time requirements:

$$x(i) \cdot d_{\text{min}}(i) \leq t_{\text{up}}^n(i) - t_{\text{down}}^n(i) \leq x(i) \cdot d_{\text{max}}(i),$$

where $d_{\text{min}}(i)$ and $d_{\text{max}}(i)$ are the minimum/maximum allowable down times for load $i$, respectively. In addition, to meet maximum/minimum up time requirements $t_{\text{down}}^n(i)$ must satisfy...
where $t_{\text{lastup}}(i)$ is the previous restoration time (or up time) for load $i$, and $u_{\text{min}}(i)$ and $u_{\text{max}}(i)$ are the minimum/maximum up times for load $i$, respectively. Note that $t_{\text{lastup}}(i)$ is known. Finally, shedding must occur after the current time, i.e.,

$$t \leq t_{\text{down}}(i).$$

Similarly, for any load $i$ that is down at time $t$, i.e., $i \in D(t)$, the following inequalities should hold to meet the maximum and minimum up time requirements:

$$x(i) \cdot u_{\text{min}}(i) \leq t_{\text{down}}^n (i) - t_{\text{up}}^n (i) \leq x(i) \cdot u_{\text{max}}(i)$$

And similarly, to meet the maximum and minimum down time requirements, they must satisfy,

$$d_{\text{min}}(i) \leq t_{\text{up}}^n (i) - t_{\text{lastdown}}(i) \leq d_{\text{max}}(i),$$

where, $t_{\text{lastdown}}(i)$ is the last time load $i$ was switched off (and its value is known). And, finally, the rescheduled up time must be greater than the current time, i.e.,

$$t \leq t_{\text{up}}^n (i).$$

Note that for both $i \in U(t)$ and $i \in D(t)$, if $x(i) = 0$, i.e., the load is not scheduled to be switched during the remainder of the current demand interval, then from (1) and (4), it follows that $t_{\text{up}}^n (i) = t_{\text{down}}^n (i)$ implying that these loads are indeed not switched. This implies that load $i$ is to remain up for the rest of the interval for $i \in U(t)$, and that load $i$ is to remain down for the rest of the interval for $i \in D(t)$.

Let $P_i$ denote the average power consumption of load $i$ and let $T$ be the time that the current demand interval ends. After a control action is taken on a load, the contribution of that action to the change in the demand level for the current demand interval is

$$-P_i \cdot (\min[T, t_{\text{up}}^n (i)] - \min[T, t_{\text{down}}^n (i)]) \quad \text{if} \quad i \in U(t)$$

and

$$P_i \cdot (\min[T, t_{\text{down}}^n (i)] - \min[T, t_{\text{up}}^n (i)]) \quad \text{if} \quad i \in D(t).$$

The resulting energy consumption for the current interval, after shedding, must be below the maximum value, $E_{\text{max}} = D_{\text{max}} \cdot L$, where $L$ is the length of the demand interval, to keep the demand below the prescribed limit, $D_{\text{max}}$. That is,

$$E(t) + K(t) \cdot (T - t) - \sum_{i \in U(t)} P_i \cdot (\min[T, t_{\text{up}}^n (i)] - \min[T, t_{\text{down}}^n (i)])$$

$$+ \sum_{i \in D(t)} P_i \cdot (\min[T, t_{\text{down}}^n (i)] - \min[T, t_{\text{up}}^n (i)]) \leq E_{\text{max}}$$

Finally, the objective of the control system is to minimize the net costs caused by the production loss due to load shedding, specifically,

$$\min_{t_{\text{up}}^n (i), t_{\text{down}}^n (i), x(i)} \sum_{i} (t_{\text{up}}^n (i) - t_{\text{down}}^n (i)) \cdot C_i.$$
We assume that the production losses are proportional to the duration of the downtime interval, but the proportionality constants, $C_i$, may differ from load to load and may be state dependent. Practical considerations for specifying the $C_i$ are outlined in subsequent sections.

### 4.2. Linear Mixed Integer Programming Formulation

The model to this point is a mixed integer formulation with one constraint that is non-linear, specifically, (8). In order to use existing mixed integer linear programming (MILP) algorithms to solve the problem, we will now transform it to a linear form.

Consider adding another binary decision variable, $y(i)$, which takes the value of 1 if and only if the second control action (i.e., switching off for down loads, and on for up loads) is taken within the current demand interval. Then clearly, we may require that

$$ y(i) \leq x(i),$$

which states that the second control action is taken only if the load is switched to begin with.

In addition, let $t_1(i)$ and $t_2(i)$ be two auxiliary variables where,

$$ 0 \leq t_1(i) \leq y(i) \cdot M $$

and

$$ 0 \leq t_2(i) \leq (1 - y(i)) \cdot M $$

where $M$ is a large, positive real number. Note that either $t_1(i)$ or $t_2(i)$ must be zero at any time. With the two auxiliary variables, the second stage decision variables, $t_{\text{up}}^n(i)$ and $t_{\text{down}}^n(i)$, can be written as:

$$ t_{\text{up}}^n(i) = T - t_1(i) + t_2(i), \quad \text{for } i \in U(t), $$

and

$$ t_{\text{down}}^n(i) = T - t_1(i) + t_2(i), \quad \text{for } i \in D(t). $$

As illustrated in Figure 3.a, if $t_{\text{up}}^n(i)$ for $i \in U(t)$ precedes $T$, (or $t_{\text{down}}^n(i)$ precedes $T$ for $i \in D(t)$), then $y(i)=1$, $t_1(i)$ is the amount of time by which this value precedes $T$, and $t_2(i)=0$. As illustrated in Figure 3.b, if $t_{\text{up}}^n(i)$ for $i \in U(t)$ exceeds $T$ (or $t_{\text{down}}^n(i)$ exceeds $T$ for $i \in D(t)$), then $y(i)=0$, $t_2(i)$ is the amount of time by which this value exceeds $T$, and $t_1(i)=0$.

Now, by Eqs. (11)-(13), for $i \in U(t)$, we see that

$$ T - t_1(i) - t_{\text{down}}^n(i) = \begin{cases} t_{\text{up}}^n(i) - t_{\text{down}}^n(i), & t_{\text{up}}^n(i) \leq T \\ T - t_{\text{down}}^n(i), & t_{\text{up}}^n > T \end{cases} $$

If the load is switched, i.e., $x(i)=1$, then $y(i)$ may be 0 or 1, and both cases on the right hand side of (15) are possible. If the load is not switched, i.e., $x(i)=0$, we showed earlier that $t_{\text{up}}^n(i) = t_{\text{down}}^n(i)$. Hence, if we add the constraint

$$ t_{\text{down}}^n(i) \leq T, \quad i \in U(t), $$

the right hand side of (15) must be zero when the load is not switched. Also, by (11), (12), and (14), for $i \in D(t)$, we see that
3.a. $t_{up}^n(i)$ Precedes $T$.

Figure 3. Diagram Illustrating $y(i)$, $t_1(i)$, $t_2(i)$, for $i \in U(t)$.

3.b. $t_{up}^n(i)$ Exceeds $T$.

\[ T - t_1(i) - t_{up}^n(i) = \begin{cases} \frac{t_{down}^n(i) - t_{up}^n(i)}{T - t_{up}^n(i)}, & t_{down}^n(i) \leq T \\ \frac{t_{down}^n(i)}{T - t_{up}^n(i)}, & t_{down}^n(i) > T \end{cases} \]  

(17)

Applying an argument analogous to the case for $i \in U(t)$, both cases on the right hand side are possible when load $i$ is switched. Adding the constraint

\[ t_{up}^n(i) \leq T, \quad i \in D(t) \]  

(18)

forces the right hand side of (17) to zero when load $i$ is not switched.

Thus, the maximum demand constraint, (8) can be rewritten in a linear form as

\[ E(t) + K(t) \cdot (T - t) - \sum_{i \in U(t)} P_i \cdot (T - t_1(i) - t_{down}^n(i)) + \sum_{i \in D(t)} P_i \cdot (T - t_1(i) - t_{up}^n(i)) \leq E_{max} \]

With this reformulation of (8), and the additional constraints (10-14), demand control decisions may be obtained as the solution of an MILP.
5. Implementation Considerations in a Practical Demand Control System

5.1. Demand Prediction

Power consumption is assumed to be monitored at all times, and demand intervals are synchronized with the utility demand intervals. Also, the slope, $K(t)$, is estimated using the average value of power consumption for a certain length of time, $\delta$, so that a reliable and stable estimate can be obtained. (The particular value of $\delta$ can vary according to different applications.) The magnitude of $K(t)$ is particularly important at the beginning of the demand interval because it has the greatest influence on the demand prediction at this time. Near the end of the interval, the forecast is dominated by $E(t)$, which is known precisely.

5.2. Specifying Minimum/Maximum Uptimes/Downtimes

In virtually every application of demand control, it is necessary to limit the frequency of load shedding and restoration actions in order to minimize operational disruptions and prevent equipment damage. Of special concern is the prevention of motor heating from frequent starting. In other situations, there are operational constraints that control minimum/maximum uptimes/downtimes. For example, a dewatering station has a limited-capacity sump and the maximum pump downtime will vary with time, based on the current sump level, water inflow rate, and pump discharge rate, which are all deterministic. Many similar situations can be envisioned, for example, minimum downtime of climate controls to maintain conditions within acceptable limits.

Finally, minimum/maximum uptimes/downtimes need to be considered for making accurate energy-consumption forecasts for loads that have highly variable power flows during their operational cycle. For example, in our application the power flow of a continuous miner varies widely during each cutting cycle. Therefore, if a decision is made to shed this load, it should be shed for a length of time equal to at least one full operational cycle (and preferably for an integer number of cycles for additional load-shedding requirements) in order to accurately forecast the energy reduction from the shedding action.

5.3. Specifying Cost Coefficients Used in the Objective Function

For many industrial loads, cost coefficients are proportional to the reduction in output due to shedding a particular load. For example, in our application, shedding a continuous miner results in stopping all production at one operating section. The cost coefficient should be proportional to the lost production, and might be determined from the average production for that particular section. Alternatively, shedding one shuttle car will result in reducing a section’s output; however, production will not be reduced by one-third since the two remaining shuttle cars will experience different delay times from switching into a change point to clear the path for the other shuttle car. Therefore, because of the difficulties in determining cost coefficients in processes where there is a complex interaction of production equipment, there is a need to use production models, e.g., simulation, to determine the impact on production and establish cost coefficients.

In addition to equipment directly related to production, there will frequently be loads that can be deferred for a limited time at no cost. For example, dewatering actions at a pumping station can be deferred at zero cost until the storage sump is full, at which point the pumping action must begin. Therefore, a non-zero cost coefficient is inappropriate; instead, pump shedding/restoration action and energy-reduction forecasts are determined by specification of dynamic minimum/maximum uptimes/downtimes as previously described.
6. A Simulation Study to Assess Performance of the Control Algorithm

The event scheduling method (Law and Kelton) was used in the power system simulation model (which is modeled as a discrete event process). As a representative example, the event diagram for shuttle cars is shown in Figure 4. On this diagram, each node corresponds to an event where state variables may change. Arcs connect each node to other nodes representing events that may be scheduled upon occurrence of the event in question. Any conditions that must exist for scheduling the subsequent event are shown in brackets and the time duration until the event occurs is shown on the arc. These time durations are random and based on typical distributions observed in the field. The load levels for each major piece of equipment are state variables, as is the total load of the mine. These values are updated upon occurrence of the various events in the simulation run.

Power estimates for continuous miners, roof bolters, shuttle cars, and feeders were based on measurements made at operating mines (Sottile, et al, 1994, 1996). Conveyor belt power flows were estimated from a simplification of standard formulas used for belt sizing. This procedure
requires only belt dimensions of length and width, change in elevation, from tail (receiving end) to head (discharge end), friction factors, belt speed, and amount of material currently on the conveyor. (In the simulation, representative values were assumed.) Power estimates were computed dynamically from the loading history produced by the simulations. Pumping cycles were developed from typical sump capacities, inflow rates, and pumping rates, and the simulation model tracks the sump level and pump status for each pumping station to determine opportunities for demand reduction. Ventilating fans and lighting represent relatively constant-power loads. In addition, fans also represent uncontrollable loads because they are essential for worker safety. The model is equivalent in detail to widely used production simulators such as CONSIM (Topuz and Ramachandran) and CMBCS (Thompson and Adler). Details can be found in Luo (1995). (Table A.1. in the Appendix provides a summary of essential equipment operating characteristics for each load type.)

7. Performance Evaluation of the Demand Control Algorithm

Based on demand prediction, the demand control procedure determines which loads to shed, when to shed them, and when to restore them. However, because of PC memory constraints posed by the extensiveness of the simulation model, controllable loads were limited to two shuttle cars (one in each of two sections), four roof bolters, three pumps, and two entire sections (i.e., both roof bolters, three shuttle cars, and the continuous miner for two production sections). In order to compare the control procedure to earlier approaches, a priority-based demand control system was also constructed for comparison, with the following priority schedule (from high to low): pumps, roof bolters, continuous miner sections, shuttle cars. This priority schedule was, necessarily, devised from safety considerations rather than impact on production. Both systems used the demand prediction algorithm previously described to trigger control actions.

Cost coefficients were determined from estimates of lost opportunity costs due to shedding a particular load. In addition, the costs are dynamically adjusted as a function of the state of the system (e.g., there is no cost associated with shedding a roof bolter provided that the next working face is currently available for the continuous miner, and, of course, no safety hazard is created). Benefits are determined from reduced demand charges resulting from load shedding actions compared with demand charges for the uncontrolled simulations.

The first task in evaluating the new demand control strategy was to compare its performance with the static control procedure. Comparisons were made by computing shedding costs for a series of specified maximum demand limits. For this analysis, shedding costs were assumed to be $13 per ton of lost coal production.

In all cases that were simulated, the new control procedure maintained the maximum demand below the defined limits at a lower shedding cost compared with the static control procedure. Figure 5 illustrates a representative result, in which the demand is limited to 4800 kW, based on five-minute demand intervals. This figure illustrates that the new control strategy results in a significant reduction in shedding costs compared with the static control strategy.

Subsequently, potential for savings through demand control was evaluated by computing the difference between savings realized by load shedding and the cost of lost production caused by enforcing demand limits. Lost production costs were assumed to be $13 per ton; the utility demand and energy charges were $12.00 per kW and $0.035 per kWh, respectively.

Table 1 presents a summary of simulation results for mine production and energy consumption for a typical one-month billing cycle for seven different demand settings, using five-minute demand intervals. The uncontrolled maximum demand was 5256 kW. Figure 6 is a plot of the net savings at each demand setting above 4800 kW. These results indicate that a demand limit of approximately 4980 kW could save over $2000 per month.
Figure 5. Load-shedding Cost Comparison of Proposed Control Strategy with Static Shedding Schedule.

Table 1. Production and Energy Use For Different Maximum Demand Settings.

<table>
<thead>
<tr>
<th>Maximum Demand (kW)</th>
<th>Mean Production (tons)</th>
<th>Mean Energy Use (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4560</td>
<td>691,560</td>
<td>2,058,967</td>
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<tr>
<td>4680</td>
<td>695,630</td>
<td>2,067,452</td>
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<tr>
<td>4800</td>
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<td>5040</td>
<td>707,170</td>
<td>2,124,215</td>
</tr>
<tr>
<td>5160</td>
<td>707,250</td>
<td>2,125,175</td>
</tr>
</tbody>
</table>

(Production before Control: 707,250 tons. Energy Use before Control: 2,125,175 kWh. Demand Interval: 5 Minutes. Maximum Demand without Control: 5256 kW.)

Figure 6. Net Cost Reduction as a Function of Maximum Demand Setting. (5 minute demand)
The control routine was also applied to a billing schedule using 15-minute demand intervals. Table 2 and Figure 7 present a summary of results. As with the 5-minute interval, a lost opportunity cost of $13.00 per ton of coal was used; the utility demand charge was $12.00 per kW, and the energy charge was $0.035 per kWh. These results show that the control algorithm was able to produce a net saving of approximately $1000 per month by maintaining demand below 4640 kW.

Table 2. Production and Energy Use for Different Maximum Demand Settings.

<table>
<thead>
<tr>
<th>Maximum Demand (kW)</th>
<th>Mean Production (tons)</th>
<th>Mean Energy Use (kWh)</th>
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</thead>
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<td>4600</td>
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<td>4752</td>
<td>707,250</td>
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</tbody>
</table>

(Production Before Control: 707,250 tons. Energy Use before Control: 2,125,175 kWh. Demand Interval: 15 Minutes. Maximum Demand Without Control: 4752 kW.)

These results illustrate that the proposed demand control strategy can be effective in achieving savings through demand control. In addition, we believe that the results are very conservative, for several reasons. First, because of computing limitations (i.e., simultaneously simulating a large mine and determining control actions on a PC) the number of controllable loads was kept quite small. With the ability to include all controllable loads, we believe that the strategy could have met lower demand limits with less of an impact on production. Second, this particular mine simulation model had a very extensive conveyor belt system which reduced power fluctuations due to the long retention time of material on the conveyor network. In many operating mines, especially newer ones, the conveyor networks represent a smaller fraction of the total load and power fluctuations are larger. Finally, because this simulation did not include surface facilities of underground mines, a group of controllable loads, e.g., heaters, air conditioners, and so forth, were not available for shedding. Because many of these loads are not directly related to production, including them would have provided more flexibility in meeting demand limits with less of an impact on production.
REFERENCES
### Appendix – Simulation Model Parameters

Table A.1. Parameter Settings for Simulation Model.

<table>
<thead>
<tr>
<th>Item</th>
<th>Power</th>
<th>Other Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Miners</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loading: 400 kW, between SCs: 50 kW, trammimg: 40 kW</td>
<td>Loading time: 1.0 min, trammimg time: 10.0 min, 20 SCs per cut</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shuttle cars</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Being loaded: 20 kW, trammimg loaded: 35 kW, trammimg empty: 30 kW, discharge: 20 kW, waiting: 2 kW</td>
<td>Trammimg loaded: 250 ft/min, trammimg empty: 275 ft/min, discharge time: 0.55 min</td>
</tr>
<tr>
<td><strong>Roof bolters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Feeders</strong></td>
<td>Discharging: 100 kW, empty: 30 kW</td>
<td>Discharge time: 75 sec</td>
</tr>
<tr>
<td><strong>Pump 1</strong></td>
<td>25 kW</td>
<td>In-flow: 60gpm, out-flow: 300gpm, max level: 30kgal, min level: 1.2kgal</td>
</tr>
<tr>
<td><strong>Pump 2</strong></td>
<td>40 kW</td>
<td>In-flow: 100gpm, out-flow: 500gpm, max level: 30kgal, min level: 6kgal</td>
</tr>
<tr>
<td><strong>Pump 3</strong></td>
<td>60 kW</td>
<td>In-flow: 140 gpm, out-flow: 580gpm, max level: 15kgal, min level: 3kgal</td>
</tr>
<tr>
<td><strong>Miner path</strong></td>
<td></td>
<td>Length: 100 ft</td>
</tr>
<tr>
<td><strong>Feeder path</strong></td>
<td></td>
<td>Length: 100 ft</td>
</tr>
<tr>
<td><strong>SC haulage path</strong></td>
<td></td>
<td>For sections 1 to 5: 350/200/270/300/250 ft</td>
</tr>
<tr>
<td><strong>Section belt 1</strong></td>
<td>Empty power: 113 kW</td>
<td>Length: 5000ft, width: 48 in., elevation change: 75 ft, speed: 550 fpm</td>
</tr>
<tr>
<td><strong>Section belt 2</strong></td>
<td>Empty power: 90 kW</td>
<td>Length: 4000ft, width: 48 in., elevation change: 40 ft, speed: 550 fpm</td>
</tr>
<tr>
<td><strong>Section belt 3</strong></td>
<td>Empty power: 90 kW</td>
<td>Length: 4000ft, width: 48 in., elevation change: 150 ft, speed: 550 fpm</td>
</tr>
<tr>
<td><strong>Section belt 4</strong></td>
<td>Empty power: 45 kW</td>
<td>Length: 2000ft, width: 48 in., elevation change: 20 ft, speed: 550 fpm</td>
</tr>
<tr>
<td><strong>Section belt 5</strong></td>
<td>Empty power: 67.7 kW</td>
<td>Length: 3000ft, width: 48 in., elevation change: 10 ft, speed: 550 fpm</td>
</tr>
<tr>
<td><strong>Main belt 1</strong></td>
<td>Empty power: 215 kW</td>
<td>Length: 7000ft, width: 60 in., elevation change: 200 ft, speed: 600 fpm</td>
</tr>
<tr>
<td><strong>Main belt 2</strong></td>
<td>Empty power: 154 kW</td>
<td>Length: 5000ft, width: 60 in., elevation change: 100 ft, speed: 600 fpm</td>
</tr>
<tr>
<td><strong>Main belt 3</strong></td>
<td>Empty power: 154 kW</td>
<td>Length: 5000ft, width: 60 in., elevation change: 100 ft, speed: 600 fpm</td>
</tr>
<tr>
<td><strong>Main belt 4</strong></td>
<td>Empty power: 49 kW</td>
<td>Length: 1600ft, width: 60 in., elevation change: 500 ft, speed: 600 fpm</td>
</tr>
</tbody>
</table>