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Pacific Northwest National Laboratory

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End-Use Load Control for Power System Dynamic Stability Enhancement

J. E. Dagle
D. W. Winiarski
M. K. Donnelly

February 1997

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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Summary

Faced with the prospect of increasing utilization of the transmission and distribution infrastructure without significant upgrade, the domestic electric power utility industry is investing heavily in technologies to improve network dynamic performance through a program loosely referred to as Flexible AC Transmission System (FACTS). Devices exploiting recent advances in power electronics are being installed in the power system to offset the need to construct new transmission lines. These devices collectively represent investment potential of several billion dollars over the next decade.

A similar development, designed to curtail the peak loads and thus defer new transmission, distribution, and generation investment, falls under a category of technologies referred to as demand side management (DSM). A subset of broader conservation measures, DSM acts directly on the load to reduce peak consumption. DSM techniques include direct load control, in which a utility has the ability to curtail specific loads as conditions warrant. This is a rapidly emerging new area, representing substantial investment by the utility industry.

A novel approach has been conceived by Pacific Northwest National Laboratory (PNNL) to combine the objectives of FACTS and the technologies inherent in DSM to provide a distributed power system dynamic controller. This technology has the potential to dramatically offset major investments in FACTS devices by using direct load control to achieve dynamic stability objectives.

The deployment of distributed load control devices, such as smart controls for end-use equipment, could enhance the dynamic stability of the western U.S. power grid. The potential value of distributed versus centralized grid modulation has been examined by simulating the western power grid under extreme loading conditions. In these simulations, a scenario is analyzed in which active grid stabilization enables power imports into the southern California region to be increased several hundred megawatts beyond present limitations. Modeling results show distributed load control is up to 30 percent more effective than traditional centralized control schemes in achieving grid stability.

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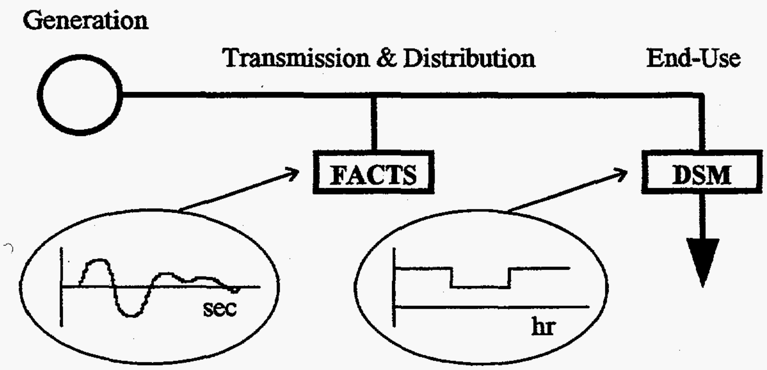
Introduction

Most electric power utilities are capacity constrained. While they have plenty of energy to sell (limited primarily by fuel), it is meeting peak load (seasonal and daily) that requires huge investment in generation, transmission, and distribution infrastructure. Most utilities, therefore, provide incentives for consumers to curtail power usage during these peak periods (as evidenced by demand charges and time-of-use rate structures). Another method available to utilities for peak load control is demand side management (DSM). An example of DSM technology is fitting specific loads with special controls, which the utility can operate when load curtailment is needed. A common example is domestic hot water heating. This is practical because the consumer would generally not feel the impact of having this load turned off briefly from time-to-time. These DSM measures have been implemented by utilities throughout the country, and are expected to dramatically increase as utilities are driven into a more competitive environment. Incentives offered to consumers to provide interruptible load can be much cheaper than the capital cost required to upgrade the system to meet peak demand.

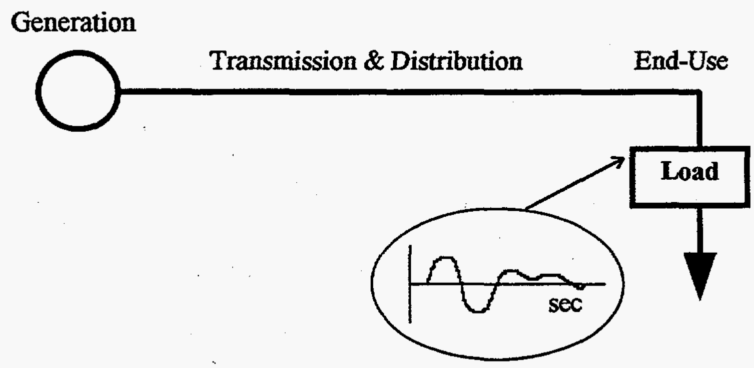
Many bulk-power transmission corridors are stability constrained. In these cases, there may be ample steady-state, or thermal capacity of the lines serving an area, but because of the need to prevent transient, oscillatory or voltage instability following credible foreseen contingencies (e.g., the loss of a major line or generation), the system is constrained to operate within more restrictive stability limits. FACTS devices, such as static-var compensation (SVC) and thyristor-controlled series capacitors (TCSC), are designed to provide stability enhancement to these transmission facilities, allowing them to be loaded to or near their ultimate thermal capacity. By either supplying reactive power for voltage support or providing modulation to damp electromechanical oscillations, these devices are typically large multi-million dollar investments. Many utilities are adding FACTS devices lieu of more expensive (and restrictive) options, such as constructing new transmission lines.

The technologies described above can be combined to provide a distributed dynamic power system control. A novel approach has been conceived by Pacific Northwest National Laboratory (PNNL) to use distributed load control for power system dynamic stability enhancement. Many devices deployed throughout the grid, acting to provide a coherent response, can achieve the same objectives as FACTS devices with potentially much less investment. For example, if hot water heaters in a region were fitted with this control scheme, they could modulate together to enhance stability on the bulk power transmission system. A schematic of this concept, and how it contrasts with the conventional approach, are given in Figure 1.

A primary distinction between the end-use load control for stability enhancement and conventional DSM is that for stability enhancement, the load would only need to be turned on and off for a second or two several times over a few minutes on perhaps a few occasions per year. Such control action would be transparent to the consumer, and could provide significant benefit to wide-area dynamics. It is envisioned that several classes of end-use load could be similarly controlled using this technology, particularly thermostatically-controlled loads.



(a) Conventional Approach



(b) End-Use Load Control for Dynamic Stability Enhancement

Figure 1. Distributed Dynamic Controller Implementation Schematic

Implementation of distributed dynamic control can take several forms. For instance, either a centralized or decentralized architecture can be adopted. In a centralized approach, a master control unit determines appropriate control action and communicates this information to the remote distributed loads. A decentralized concept measures local signals (e.g., voltage and frequency) to determine appropriate control action. The later approach eliminates the need for extensive communication infrastructure, but may not effectively capture other benefits associated with direct load control.

Distributed dynamic control can either be embedded into the controls of specific end-use appliances and equipment, or inserted external to the actual end-use equipment (such as a master load control for a building or a circuit breaker). It is anticipated that as direct load control DSM measures are adopted, many of the same innovative concepts currently envisioned for DSM deployment are equally appropriate for instituting end-use load control for stability enhancement.

Stability Enhancement and Modeling

In power systems that are transient stability limited, real or reactive power modulation based on fault-dependent control schemes can provide considerable power transfer enhancement. The amount of power required for transient stability enhancement is highly system dependent. A power-swing damper uses feedback through a compensating controller to modulate real power, reactive power, or a combination of real and reactive power. The design of the modulation control requires a detailed understanding of the stability characteristics of the system and how these characteristics are affected by the modulation.

The modulation was modeled in the Extended Transient/Midterm Stability Package (ETMSP), developed by the Electric Power Research Institute (EPRI). A time-domain transient simulation software package, ETMSP has unique user-defined capability enabling special stability controls to be modeled in detail. Real or reactive power injection at a given bus is controlled by a series of user-defined control blocks, in which the modulation controller is implemented. A variety of measured signals are available for input to the modulation controller, as described later in this report.

Study System

The western North American interconnected power system, embodied within the Western Systems Coordinating Council (WSCC) region, covers all or part of 14 western states, the Canadian provinces of Alberta and British Columbia, and the northern portion of Mexico. The State of California imports considerable amounts of energy from the Arizona/New Mexico area and from the Northwest. Transient and oscillatory stability places limits on the simultaneous power imports from these areas. Loss of critical transmission facilities can result in undamped power oscillations when the transfers from Arizona to California are high.

In an interconnected power system, all generators are synchronized at 60 Hz, and operate as a single system. When a change in operating condition occurs, such as the sudden unexpected loss of a key transmission line, the system converges on a new operating state. In the process of changing to the new operating state, the electromechanical characteristics associated with these generators can result in oscillatory behavior. Inertia associated with these generators and their turbines resists instantaneous change, while the electrical balance between load and generation must be maintained. The electrical characteristics of the transmission network play an integral role in system response.

As it applies to limiting power imports into southern California, one of the critical disturbances producing electromechanical oscillations is a three-phase fault at a key 500-kV bus, followed by the loss of a principal transmission line between Arizona and southern California. This specific occurrence is one of the primary limiting factors when determining southern California import capability in transmission planning studies. This contingency is used in this study to determine the ability of distributed end-use load control to increase southern California import capability.

Consistent with standard transmission planning practices applied by the utility industry, the simulation and analysis in this study uses a full model representation of the western North American power system. Developed by WSCC member utilities, it represents heavy loading conditions and infrastructure projected to be in place near the turn of the century. In addition to a detailed representation of the transmission and sub-transmission system, nearly all large generating facilities are modeled in detail. The model is comprised of over 5000 individual nodes (called buses). The distribution system is not represented, however, and all system load is aggregated at buses representing actual substations in the power system.

Based on the results of these planning studies, stability constraints that limit the amount of power that can be safely imported into southern California are defined by a nomogram. This nomogram defines maximum allowable power transfers as a function of key transmission corridor loadings and other important system operating characteristics. In a similar fashion, this study determines maximum power imports by loading specific transmission lines to their maximum allowable limits. Transient simulations are performed for several loading conditions to evaluate stability. As the loadings on the transmission infrastructure are increased, the oscillations become less damped.

This stability-constrained transmission limit is determined when the system responds with marginally-damped oscillations following the critical contingency. Marginal damping is defined as the stable case with loading incrementally reduced from a case that is unstable. The response from the marginally-damped case, and a case with 50-MW of additional power imports, is shown in Figure 2.

The marginally damped case exhibits a strong 0.5-Hz oscillatory mode in response to the critical contingency. Detailed simulation and modal analysis reveals that, for this mode, machines in southern California oscillate against those in the Arizona area. As expected, the oscillations occur heavily in the real-power flows and bus voltage angles. Also, 0.5-Hz swings occur heavily in the reactive line flows and bus voltage magnitudes because the system has high reactive loading. A second dominant mode is observed at about 0.25 Hz, and is predominately a North-South mode in which Arizona and southern California oscillate in phase.

The 0.5-Hz mode described above is characteristic of the 0.67-Hz East-West mode associated with the present-day power system and associated planning models. Similarly, the 0.25-Hz North-South mode appears to correspond with the 0.3-Hz mode of the contemporary system. It is presumed that these frequency shifts are the result of heavy loading conditions and high system inertia in the model used in this study.

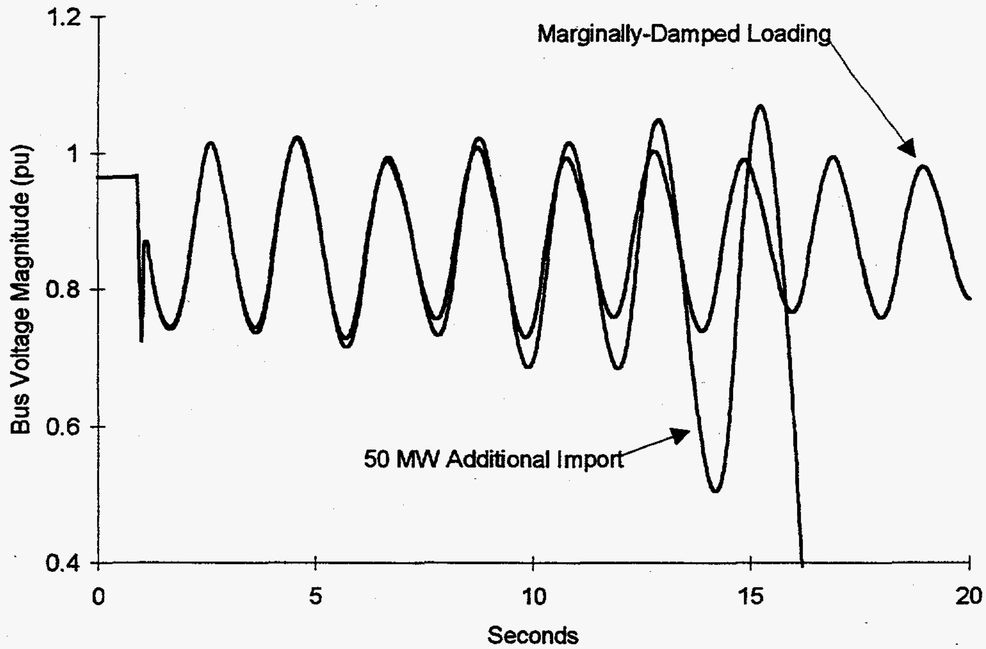


Figure 2. System Response to Critical Contingency

Modulation Design

The design approach for the controller is based on advanced, but well established, small-signal stability control methodologies described in the literature; a recent review is given in Kundur (1994). Three steps are required in the design process: 1) select a location for control actuation; 2) choose feedback signals; and 3) select the compensating parameters. For the purposes of this study, Step 1 is obtained by selecting key buses throughout the southern California area to which active grid stabilization will be applied.

In typical power system planning models for transient stability simulation software, generation and transmission infrastructure is represented with precise detail. All major generators and major bulk power transmission facilities are included. Depending on the level-of-detail of the particular model being used, most models include nearly all of the sub-transmission lines connecting substations within localized areas. Sub-transmission voltages are generally considered to be between 60 and 200 kV. However, these models usually do not represent any distribution system infrastructure beyond individual substations. Therefore, all loads associated with particular substations are aggregated.

Because the primary objective of this analysis is to determine the wide-area transmission benefits resulting from end-use load control and modulation, the aggregated substation-level load can be manipulated to provide a proxy for simulating these effects. A shunt-connected power source at each substation (controlled by compensated feedback modulation) is used to simulate the effects of end-use load control. This shunt power source provides power to simulate load curtailment, and consumes power when additional load is desired.

Step 2 is addressed by investigating the observability of the swing mode in signals that may be used for feedback. Using a feedback signal that contains modal characteristics of the principal oscillation to be controlled (i.e., high observability), the feedback modulation control is more effective at providing positive damping to this mode without adversely impacting other modes that are also present in the system.

Transfer function residues for the 0.5-Hz mode are calculated from each bus location to a common state variable to determine relative controllability of each location (see Pagola et al. (1988) for a discussion on residues and Trudnowski (1994) for a discussion on software used to identify residues). Based on these tests, nearly all 500-kV buses tested in the Los Angeles basin are suitable locations for controlling the 0.5-Hz oscillation using real power modulation.

Two signals were chosen as prime candidates for providing feedback input into the modulation controller: frequency and voltage. While a variety of other signals could provide effective modulation control, these signals have several advantages, particularly related to distributed end-use load control. Both of these signals are derived from the voltage signal, which can be obtained with relatively inexpensive potential transformers and digital transducers. In addition, these signals propagate relatively well throughout local-area power systems. Therefore, voltage or frequency fluctuations seen at a substation would likely be felt throughout the distribution system served by the substation. Both voltage and frequency were selected as feedback signals, depending on the particular application.

Classical design techniques are used to select the controller parameters to provide proper phasing and gain at the modulation frequency (Step 3). The modulation controller has the form shown in Figure 3. Time constant T_W is a washout filter, T_L is a low-pass filter, and T_1 and T_2 are lead-lag time constants. T_W and T_L are adjusted to restrict the bandwidth of the controller, and T_1 and T_2 are adjusted to provide the proper phasing. The objective of the controller is to provide damping to the 0.5-Hz mode while minimally effecting other system modes. Several simulations and root-locus analyses were used to adjust the control parameters to optimum values.

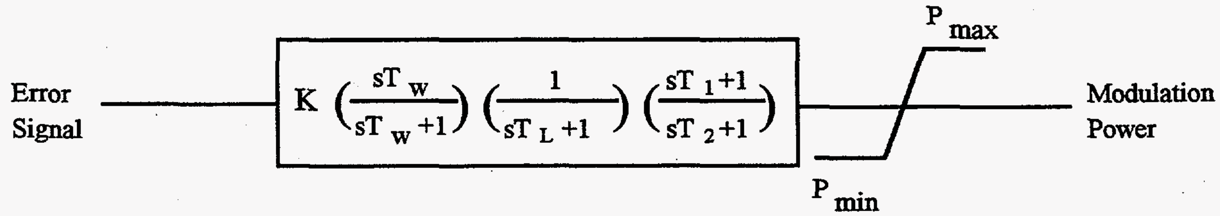


Figure 3. Modulation Control Block Diagram.

Study Results

Transmission stability enhancement is determined by evaluating contingency cases with loading conditions in excess of the benchmark. This study uses a loading case in which southern California imports are increased 400 MW beyond the marginally-damped case with no additional stability controls. With this added load, the system is unstable for the critical contingency. With active grid stabilization included, and appropriately-designed feedback modulation control, the system response is stable provided sufficient modulating power is provided.

Benchmark Comparison

FACTS devices employing power electronics, such as thyristor-controlled series compensation, static-var compensators, high voltage dc, adjustable speed generation, and superconducting energy storage, can provide additional damping to electromechanical power system oscillations (Paserba et al. 1995). Modulation using shunt-connected real or reactive power at a single location is the benchmark to which distributed end-use load control modulation will be compared.

Several simulations were performed with varying modulation limits and gains to determine the minimum size needed to provide stability enhancement. The location and attributes of this actuator are then optimized. A typical result is shown in Figure 4, where ± 450 MW modulation is the minimum power required to stabilize the system, while ± 400 MW was not sufficient. Similar analysis for reactive power modulation at the same location (with a controller tuned to optimize damping with this mode of oscillation) reveals that the minimum modulation is ± 500 MVAR to provide a stable response, as summarized in Table 1.

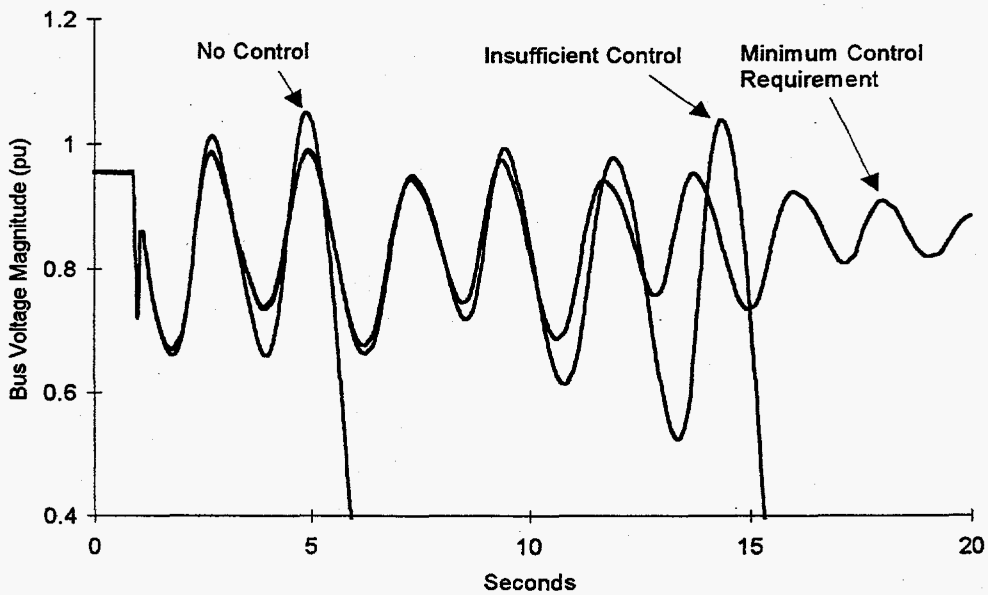


Figure 4. Determining Minimum Control Needed to Stabilize the System

Table 1. Minimum Modulation Power at a Single Location Necessary to Provide 400-MW Transmission Enhancement

Real power modulation	± 450 MW
Reactive power modulation	± 500 MVAR

Reactive power modulation is a very effective means of stabilizing the southern California power system. However, real power modulation, also effective at providing enhanced transmission capacity, is the focus of this study. Direct load control is envisioned to provide greater leverage when manipulating real power loads. Additional leverage may be obtained when the reactive component of certain low power-factor loads is considered, which was beyond the scope of this study.

Asymmetrical Modulation

The modulation described above assumes that modulation is symmetric. Prior to the disturbance, the device is *off*. When the disturbance occurs, feedback compensation control modulates the device to maximize damping, adjusting the output between its maximum and minimum available power ratings, as shown in Figure 5 for the 450-MW case. Simply put, symmetric modulation is when maximum and minimum power have the same magnitude but opposite sign. This is a somewhat typical design approach for traditional FACTS devices.

Using end-use load for distributed control requires that loads are either turned on or off to provide modulation. Positive modulation swings are obtained by interrupting loads turned on prior to the disturbance, while negative modulation swings require turning on loads not previously energized. Because these are mutually exclusive of each other, providing ± 450 MW of modulating power requires access to 900 MW of controllable end-use loads, exactly half of which must be off prior to the disturbance and vice versa.

To alleviate this constraint, it is possible to provide asymmetrical modulation to dampen the oscillations, whereby the positive and negative swings are not the same. Several simulations were performed with different positive and negative modulation limits to demonstrate the impact of asymmetrical modulation. These cases are shown in Figure 6, which indicate that 600 MW of modulating power is necessary if only positive modulation is used to stabilize the system (i.e., no negative power swings).

Some degree of both positive and negative modulation may be possible with end-use load control. Because end-use load modulation is envisioned to be combined with traditional DSM, in which some load may be curtailed during periods of peak consumption, those loads that happen to be curtailed would be available during the negative modulation swings. However, for the purposes of this study, this possibility was not explored in detail, with subsequent analysis focusing solely on momentary load curtailment to provide modulation.

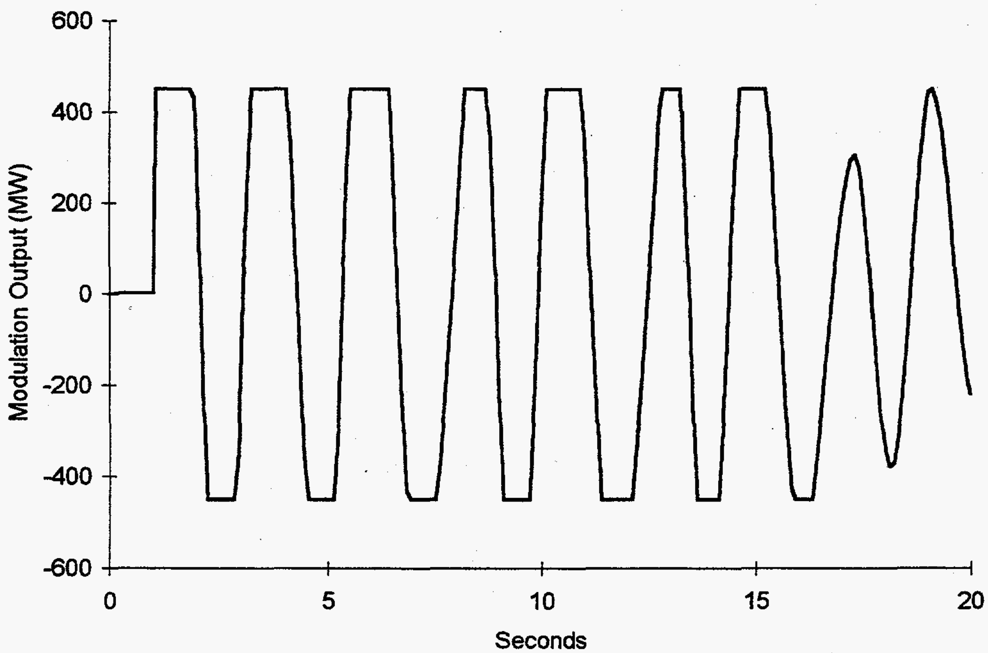


Figure 5. Typical Modulation Power Output

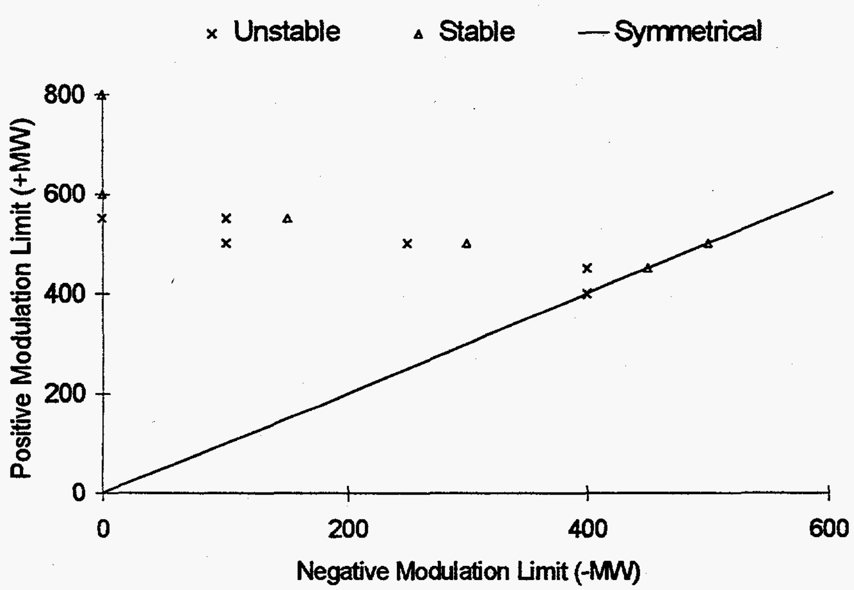


Figure 6. Asymmetrical Modulation Simulation Results

Distributed Modulation

A case was developed in which 10 modulation devices were deployed at key sites throughout southern California. The sites were selected to distribute the overall control power throughout the region at individual sites with sufficient transmission capacity to the bulk power system. Therefore, most sites had multiple high voltage lines (230 kV or equivalent) connecting them to other sites, and were usually near 500-kV bulk power substations.

Following the methodology described above, appropriate feedback signals were chosen and the controller was tuned. Tuning the controller requires several steps, and involves the use of modal analysis tools and classical feedback-control design techniques. After an initial controller is designed, several simulations are performed to optimize its performance (selecting sufficient gain, for instance, which is difficult to predict when simulating highly complex, non-linear dynamics). When the properly tuned and optimized controller has been tested, a suite of simulations are performed with progressively smaller limits to determine the minimum modulation power needed to result in a marginally-stable response to the critical contingency.

It was shown that the case with 10 devices providing 43 MW of modulating power (positive swings only) was sufficient to provide a stable result. With an aggregate combined capacity of 430 MW, this was a 30% improvement over the 600 MW needed for the single modulating device. Another set of simulations with 100 control points yielded similar results.

Centralized Versus Distributed Feedback

The study also included an assessment of centralized versus distributed feedback control. Centralized feedback uses the same measured signal at a given location as the input to all of the individual modulation controllers. While not difficult to simulate, this approach assumes extensive communication capability is present, because this signal must be broadcast (in real time) to each of the individual end-use controllers. While it may be possible and desirable to achieve this degree of supervised end-point control, it may not be necessary to provide transmission stability enhancement. As previously described, both voltage and frequency variations that might be used as input to an end-use modulation controller are present at the individual end-use site. Therefore, it may be possible to achieve similar results using truly distributed modulation control feedback.

A series of simulations were performed to compare centralized and distributed feedback modulation control. The results of this simulation indicate that both approaches require similar controller deployment to achieve the same transmission capacity enhancement. Therefore, the selection criteria of one approach over the other becomes solely economic. The centralized control approach will be more expensive because of the extensive communication infrastructure it requires, but would also provide additional benefit that could not be obtained with the distributed control approach. It is also possible that this communication system could be integrated into enhanced utility-customer information interface systems likely to be deployed in the near future.

Economic Analysis

Evaluating the specific benefit of increasing imports into southern California by 400 MW can be performed by 1) evaluating the foregone revenue potential of inadequate transmission capacity during peak periods, or 2) selecting the least-cost approach among various alternative technologies to achieve a similar increase in the stability limit. These are described below.

Assuming that in a typical year the transmission infrastructure reaches its peak capacity 500 hours per year, and that on-average, $20/MWh of lost revenue occurs while the system is constrained, this results in a net present benefit of $55 million if system capacity can be reliably raised by 400 MW (life-cycle cost assumptions are a 6% real interest rate and 30-year amortization period).

An alternate method of estimating this benefit is considering the cost of a traditional means for providing stability enhancement. Assuming that SVC modulation is the most cost-effective means presently available for providing this modulation (with turnkey cost of about $100/kVAR), providing 500 MVAR of modulation necessary to increase the stability limit by 400 MW represents a capital cost of about $50 million.

Therefore, if the total cost of the distributed control system (which enhances southern California transmission capacity by 400 MW) is less than $50 million, it is competitive with alternate methods of achieving the same result. Because this analysis indicates 430 MW of distributed load control is needed to achieve this goal, the target break-even cost is $116/kW.

A detailed assessment of end-use control potential in southern and northern California is provided in Appendix A. Based on this analysis, for example, household refrigerators contribute about 1210 MW to the southern California regional peak load; each one on average contributing 0.17 kW (taking into account demand and diversity factors). Therefore, to achieve the 430 MW of distributed load control described previously using only residential refrigerators, about 35% of all refrigerators would need to be equipped with control hardware. If the per-unit cost were less than about $20, this control implementation would be cost competitive.

Another example is residential central air conditioning, which contributes 3752 MW to the regional southern California peak demand between 3:00 and 5:00 p.m. On average, each unit contributes 2 kW. In this example, the distributed load control target can be achieved with only 11.5% penetration, and each individual controller can cost $230 and meet the break-even target.

It is envisioned that distributed dynamic load control could be deployed in conjunction with more conventional load control techniques to meet other objectives (e.g., peak load management). Therefore, hardware and communication cost (if applicable) could be cost-shared with other applications utilizing similar technology. Perhaps an additional set of algorithms within the controller would represent the incremental cost incurred deploying this technique for stability enhancement, which represents negligible added cost.

Customer incentives to allow fairly rapid cycling of their equipment (in the form of discounted rates or rebates) would also need to be factored into the target break-even cost estimates provided above. Therefore, the refrigerator end-use, with a projected break-even target cost of $20, is not likely to provide enough benefit to enable its utilization. Other end-uses, such as air conditioning equipment, have much better economic leverage. For example, it may be possible to provide consumer incentives (in addition to the controller costs) while still meeting the target break-even cost.

Other classes of end-use loads may be highly desirable for end-use load control for stability enhancement. All thermostatically-controlled loads are appropriate, because their momentary curtailment will not be noticed by the consumer. Other types of interruptible load, such as electric vehicle recharging equipment, may be very amenable to distributed load control.

Additional benefits of having controllers deployed in the system further reinforce their cost-effectiveness. Some ancillary services include automatic generator control, frequency and tie-line regulation, spinning reserve, voltage support, cold-load pickup and black start capability, augmenting remedial action schemes, and providing power quality and reliability enhancement. In addition to these benefits, distributed end-use load control can also be used to offset peak load (along the lines of traditional DSM). A detailed assessment of these benefits was beyond the scope of this study.

Hardware Design and Testing

The distributed end-use load control concept was tested experimentally in a laboratory setting at PNNL. An unmodified household refrigerator was chosen as the subject appliance. The refrigerator was fitted with a relay switch to facilitate the cycling of the distributed controller. In this experimental setup, the power to the entire appliance was switched. The voltage and current supplied to the refrigerator were then instrumented and monitored. The experimental setup is illustrated in Figure 7. The appliance was run through a series of tests to determine the response characteristics of the load as it applies to power system dynamics.

Experimental results confirmed that appliance load is dropped almost instantaneously as the switch opens in response to a " dump load" command. This part of the appliance response was anticipated. The fast turn-off time is viewed as beneficial to power system transient response. It means that appliances configured in this way can be relied upon to act quickly and predictably to controller commands in severe power system emergencies.

The turn-on characteristics of the appliance were more interesting. The most energy intensive electrical device within a refrigerator is the compressor. Frost-free refrigerators also have high power consumption during the defrost mode, but this occurs relatively infrequently. Another primary electrical subsystem is the circulation fans. The switching characteristics of the refrigerator were highly dependent on which of these subsystems was energized at the time the appliance was cycled on and off. It was observed that when the appliance was turned off with both compressor and fans on, the turn-on characteristics could not be reliably predicted. Sometimes only the fans would turn back on and sometimes both compressor and fans would start when power was restored. Because of its infrequent nature, the defrost system was not considered part of the refrigerator's switching characteristics as it relates to this study.

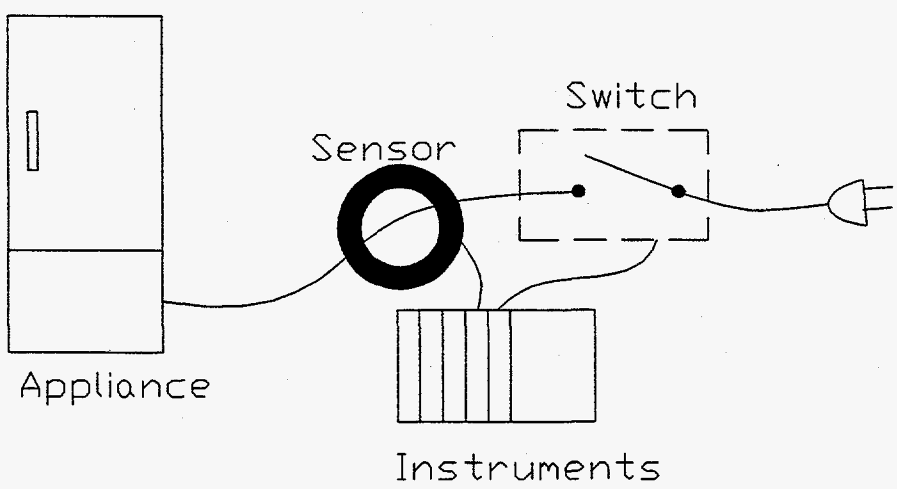


Figure 7. Experimental Setup

The time constant for the fan restart was considered to be adequate to damp slow power system oscillations. However, a full compressor restart is likely to be too slow to be used as an oscillation damping controller when installed as shown in Figure 7. Other control schemes for refrigerant systems were also investigated as part of this project. These configurations may cause less stress on the refrigerant system while still having a faster response time.

Conclusions

This report presents the results of a feasibility scoping study evaluating end-use load control as a means of increasing power transfer on selected transmission paths in the southwestern United States power system. Power modulation to stabilize electromechanical power swings is shown to provide increased transmission capability, enabling increased power imports into southern California.

Analysis by computer simulation reveals that a case with 10 strategically-deployed devices each providing 43 MW of modulating power was equivalent to a single device providing 600 MW modulation power. A similar case with 100 controllers yielded similar results. Distributed modulation, therefore, represents 30% better leverage than is possible from centralized modulation. Various analyses were performed to document the performance of centralized verses distributed feedback, asymmetrical modulation (different positive and negative modulation power limits), and a cursory investigation was performed to determine target break-even costs. Simple proof-of-principle hardware testing was performed for an unmodified household refrigerator.

An investigation of northern and southern California residential and commercial end-use loads, and their applicability to short-term load interruption for dynamic stability enhancement is provided in Appendix A. The results of this investigation indicate that while traditional DSM load types, such as electric hot water heating, may not be abundant (most hot water is natural gas in these regions), many other types of end-use loads could provide ample load control potential.

Other regions, while not expressly investigated in this study, could similarly benefit from end-use load control. Wherever stability constraints limit power transfer capability, this approach could benefit the system by providing appropriate dynamic response to various limiting contingencies. These other regions may also exhibit high penetrations of particularly attractive end-use loads (such as electric resistance hot water heating) that could be used to provide dynamic stability enhancement using end-use load control.

In addition to stability enhancement, end-use load control can be used to augment remedial action schemes, and is well suited to provide other benefits such as load leveling, automatic generator control (AGC), spinning reserve, and voltage support. The results of this study indicate that highly-leveraged multiple benefits possible with this approach provide strong overall encouragement to investigate the potential of end-use load control as a cost-effective means of enhancing power transmission.

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Appendix A

Electric End-Use Load Reduction Potential in California

Appendix A

Electric End-Use Load Reduction Potential in California

Statistics on the potential for electric peak load reduction by end-use load control in California are described in this appendix. The statistics are broken down separately into northern and southern California regions and for each region, into residential and commercial sectors of the economy. The primary goals of this effort are 1) to identify specific end-uses that show large contributions to the peak electrical demand in California, and 2) identify those end-uses that have a large peak demand contribution on a per-appliance basis. The suitability of controlling specific end-use loads as a means of enhancing the stability of the power grid is also described.

The appendix is broken into two sections, residential and commercial loads. For each, a discussion of the types of electric loads and their magnitudes is given for southern and northern California. For each region, loads are broken down into weather-dependent loads (heating, ventilation and air conditioning) and weather-independent loads (all other end-use loads).

Residential Energy End-Uses

Residential energy use in California is broken into 24 end-use categories by the California Energy Commission (CEC) in their Biannual California Energy Demand Report (CEC 1995). These categories are listed in Table A.1. The California Energy Demand Report breaks California into eight planning areas[1]. For each planning area, electrical demand and energy consumption forecasts are made for residential, commercial, industrial, and agricultural sectors of the economy. Of the residential end-uses listed, most are relatively descriptive of the actual load. Lighting and plug loads not explicitly listed as a separate category are included in the "Miscellaneous" category.

For each of the 24 residential end-use categories in each planning area, the estimated total appliance stock corresponding to that end-use is reported in the California Energy Demand Report, and based upon the estimated total housing stock in that planning area, the CEC reports an appliance saturation fraction. The average appliance annual Unit Energy Consumption (UEC) is reported for each end-use category. This value is calculated based on either statistical or engineering models of the end-use. In addition, a marginal UEC is also reported for purchases of new appliances satisfying each end-use. Finally from the appliance stock and UEC, the CEC calculates a total annual energy consumption for each planning area.

The California Energy Demand Report was used to determine saturation of electrical appliances in these end-use areas and provide typical annual consumption to calibrate a demand model. For the purpose of this analysis, the utility planning areas were aggregated into southern and northern California regions. Northern California utilities consisted primarily of Pacific Gas and Electric (PG&E) and Sacramento Municipal Utility Department (SMUD). Southern California utilities consisted of Southern California Edison (SCE); San Diego Gas & Electric (SDG&E); Los Angeles Department of Water and Power (LADWP); Burbank, Glendale and Pasadena (BGP) municipalities; and the Imperial Irrigation District (IID).

Table A.1. California Energy Commission Residential Energy Use Categories

Central air conditioners	Furnace fans	Room air conditioners
Clothes washer motors	Hot water for clothes washing	Solar water heaters
Clothes dryers	Hot water for dish washing	Pumps on solar water heaters
Color TV	Miscellaneous	Space heaters
Cooking (stoves)	Pool pump	Hot tub pumps
Dishwasher motors	Pool pumps for solar water heating	Water heating for hot tubs
Evaporative air conditioning	Pool water heating	Water heating for waterbeds
Freezers	Refrigerators	Water heating for domestic uses not otherwise covered

[1] These planning areas are BGP, IID, LADWP, PG&E, SCE, SDG&E, SMUD, and Other (mostly smaller northern utility districts) for eight planning areas total.

Table A.2 shows the residential electrical consumption summary data aggregated for two northern California utilities, PG&E and SMUD. Their combined service areas comprise over 90% of northern California electric energy consumption. Table A.3 shows these categories aggregated across four major southern California utilities (SDG&E, SCE, LADWP, BGP). Only the data for the most recent year, 1993, is shown. The end-use categories are broken into weather-dependent and weather-independent categories.

Table A.2. Residential Electrical Summary Data for Northern California

End-Use	Year	Housing Stock	Appliance Stock	Appliance Saturation	Average Appliance UEC (kWh/yr)	Marginal Appliance UEC (kWh/yr)	Total Energy Used (GWh)
Weather-Dependent Loads							
Central A/C	1993	4,446,435	1,325,976	0.298	1271.8	1064.7	1686.3
Room A/C	1993	4,446,437	410,748	0.092	401.6	368.3	165.0
Evaporative A/C	1993	4,446,437	368,592	0.083	607.5	607.5	224.0
Space heat	1993	4,446,435	455,299	0.102	3829.8	2380.3	1743.7
Furnace fan	1993	4,446,437	2,242,258	0.504	312.1	0.0	699.9
Weather-Independent Loads							
Hot water (dishwas)	1993	4,446,438	343,470	0.077	864.6	0.0	297.1
Hot water (clthwas)	1993	4,446,438	484,810	0.109	970.7	0.0	470.6
Hot water (basic)	1993	4,446,438	523,819	0.118	1989.8	1844.4	1042.2
Refrigerator	1993	4,446,438	5,279,520	1.187	1036.4	728.8	5472.8
Freezer	1993	4,446,438	1,003,235	0.226	1022.8	779.4	1026.0
Color TV	1993	4,446,438	4,341,188	0.976	289.6	276.2	1258.1
Cooking	1993	4,446,438	2,814,553	0.633	630.3	630.3	1774.2
Dishwasher motor	1993	4,446,438	2,764,838	0.622	236.9	228.8	655.4
Clothes dryer	1993	4,446,438	2,862,734	0.644	988.9	988.9	2830.9
Solar water heat	1993	4,177,955	16,191	0.004	478.1	456.3	7.7
Solar watrht pmp	1993	4,177,955	56,399	0.013	399.9	396.1	22.5
Cloth wash motor	1993	4,446,438	3,952,961	0.889	63.0	63.0	248.2
Waterbed heater	1993	4,446,438	823,197	0.185	1196.8	1174.0	985.2
Miscellaneous	1993	4,446,438	4,446,438	1.000	1528.9	0.0	6797.1
Pool pump	1993	4,446,438	321,263	0.072	2578.7	2218.2	828.4
Pool water heater	1993	4,446,438	11,121	0.003	2584.4	2584.4	28.7
Pool pump (solar)	1993	4,446,437	81,217	0.018	0.0	0.0	0.0
Tub pump	1993	2,943,870	275,532	0.094	881.7	881.7	243.0
Tub water heater	1993	2,943,870	105,271	0.036	440.8	440.8	46.5

Table A.3. Residential Electrical Summary Data for Southern California

End-Use	Year	Housing Stock	Appliance Stock	Appliance Saturation	Average Appliance UEC (kWh/yr)	Marginal Appliance UEC (kWh/yr)	Total Energy Used (GWh)
Weather-Dependent Loads							
Central A/C	1993	6,171,935	1,874,048	0.304	1265.7	1065.1	2371.9
Room A/C	1993	6,171,931	995,124	0.161	446.9	409.5	444.7
Evaporative A/C	1993	6,171,931	360,426	0.058	672.3	672.3	242.3
Space heat	1993	6,171,935	907,577	0.147	2261.7	1453.6	2052.7
Furnace fan	1993	6,171,931	1,794,141	0.291	277.9	0.0	498.6
Weather-Independent Loads							
Hot water (dishwas)	1993	6,171,931	403,811	0.065	971.8	0.0	392.4
Hot water (clthwas)	1993	6,171,931	550,145	0.089	1166.5	0.0	641.8
Hot water (basic)	1993	6,171,931	631,847	0.102	2496.8	2347.1	1577.6
Refrigerator	1993	6,171,931	7,110,473	1.152	1446.0	1012.3	10282.0
Freezer	1993	6,171,931	1,131,042	0.183	1340.0	1021.2	1515.7
Color TV	1993	6,171,931	6,017,834	0.975	385.4	364.2	2319.2
Cooking	1993	6,171,931	1,846,268	0.299	868.4	868.4	1603.2
Dishwasher motor	1993	6,171,931	3,877,826	0.628	333.5	321.4	1293.4
Clothes dryer	1993	6,171,931	1,865,435	0.302	1344.7	1344.7	2508.5
Solar water heat	1993	5,905,014	28,745	0.005	458.4	438.7	13.2
Solar waterht pmp	1993	5,905,014	175,772	0.030	495.6	488.8	87.1
Cloth wash motor	1993	6,171,931	5,411,331	0.877	89.5	89.5	484.4
Waterbed heater	1993	6,171,931	639,934	0.104	1572.7	1545.5	1006.4
Miscellaneous	1993	6,171,931	6,171,931	1.000	2219.0	0.0	13695.7
Pool pump	1993	6,171,931	668,447	0.108	3548.6	3216.4	2372.1
Pool water heater	1993	6,171,931	12,041	0.002	3024.9	3024.9	36.4
Pool pump (solar)	1993	6,171,930	134,374	0.022	0.0	0.0	0.0
Tub pump	1993	3,734,693	660,430	0.177	539.5	539.5	356.3
Tub water heater	1993	3,734,693	184,602	0.049	332.2	326.2	61.3

Each end-use category is made up of equipment that uses electricity through various physical means. Identifying these various physical means of electrical use determines the strategies necessary to shed the load for that end-use category. The various physical uses of electricity can be broken down into lighting technologies (primarily electric resistance, gas excitation), motors (primarily characterized by the subcategories of fans, water pumps, and refrigerant compressors), electric resistance heating, electronics and controls, and system losses (lighting ballast losses are a good example). Issues associated with interrupting the load for these types of end-uses are discussed as follows.

Lighting

Interruption of primary lighting inside a residence could be inconvenient and possibly a safety hazard for interruptions of a second or more. Repeated interruptions of lighting circuits (as might be required for end-use load control) would definitely be noticed by the customer and cannot be recommended. However in certain multiple-bulb appliances, interruption of some bulbs may be less of an issue (assuming all lights are functioning at the time of interruption). Interruption of lighting outside a residence would be less of an issue. Indeed, exterior lighting may represent a sizable load control potential. Frequent interruption of lighting circuits may be detrimental to bulb life in incandescent lighting systems. Degradation in lamp life will be less of an issue in ballast based lighting systems, although controlling lamp restart may be difficult.

Electric Resistance Heating

Presently there are two large uses of electric resistance heating in residences, space heating (either electric furnace, baseboard, or heat pump backup) and hot water heating. Hot water heating can be broken down further into batch heating processes (examples include a typical electric hot water tank, hot tub, pool, waterbed) or instantaneous hot water heat (such as a faucet hot water tap and instantaneous heaters built into appliances like dishwashers). Often the instantaneous hot water heater is actually an electric booster heater for water that has already been heated in a batch-type tank water heater.

Space Heat

Electric space heat represents about 3.86 % of the annual residential electric use in southern California and 5.39% of the annual residential electric use in northern California. This value is fairly small because of the predominant use of natural gas for space heating and the typically mild climate. The actual electric load is highly seasonally dependent, with strong daily variations. Although the peak load created by one furnace may be high, the relative infrequency of use makes this an unlikely candidate for load shedding technologies.

Water Heat

The fraction of water heating that can be attributed to electric resistance heat is moderate. 8.10% of the annual southern California residential electric energy consumption is attributable to water heating. This is primarily because of the frequent use of natural gas for water heating in that section of the state. The value is 9.94% in northern California, where electricity is generally cheaper. However, there is still significant value to analyzing batch water heating processes because these represent an easily curtailable load. Any loss of water temperature will not be noticed immediately by the user. Similarly, in appliances that use an electric resistance heater as a temperature booster, brief electric power interruptions may not be noticed. One subcategory of water heat that is always electric is waterbed heating. The CEC data suggests that waterbeds make up 28.3% of the total electric energy used for heating water in southern California. This also represents an easily interruptible load with little or no negative impact on the consumer resulting from brief power interruptions.

Motors

Motors in residential use occur widely in three categories: compressors (space conditioning and refrigeration), fans (space conditioning primarily), and pumps (primarily for swimming pool, Jacuzzi or hot tub use and possibly irrigation).

Motors used for space conditioning and water pumps represent a large potential resource for end-use load control. Generally, space conditioning equipment can be shut off repeatedly for short periods with no noticeable effect on the end-use. The same is true for swimming pool pumps used for sanitation purposes. (Jacuzzi or hot tub pumps used for aeration and rapid cycling would be noticed). Irrigation pump cycling would likely be noticed, but would have little impact on the end-use.

However, the difficulty with cycling motors is the impact on the motor itself. Rapid on/off cycling of motors will have a deleterious impact on motor windings because they are subject to a high initial inrush of current that generates heat in the motor windings. This initial inrush current is often five to seven times the full load current and may range from a few seconds to several minutes in the case of heavy loads (Nadel et al. 1991). At the same time, ventilation fans are turning slowly at startup and will not quickly remove heat. This combination can lead to high initial winding temperatures, which can reduce insulation life.

The total heat developed during startup is a function of the time required to reach the motor's rated speed. The higher the required torque during startup, the longer period of time will be needed to reach rated speed and more heat buildup will result. For certain motor application (fans and pumps primarily), the motor load is a function of the motor speed. Thus, the initial motor starting condition is the zero load condition and the increase in motor torque during startup is gradual. These motor applications represent a relatively easy target for end-use load control, which require cycling of motor systems. For certain applications, particularly fan systems, the estimated period of off-time in a load-control cycle can be considerably shorter than the time for the fan to reach zero speed after being shut off. For these systems the motor never actually stops turning and the time required to reach full speed is shortened considerably, thus reducing any damage to the motor as compared to the zero speed startup. The incorporation of electronic "soft-start" controls could help to relieve this problem significantly, at the expense of slower startup times.

For compressor systems, the differential pressure of the gases will generally stop the compressor almost immediately once the power to the motor is cut. These systems have relatively high starting torque requirements, particularly if there is very little time between cycles for the refrigerant pressure on the high side to subside. For this reason, both motors and compressors may be negatively impacted by rapid system cycling. This is particularly true of reciprocating compressor equipment.

NEMA Standard MG 1-12-50 and MG 10 discuss successive motor starts and make recommendations on the total number of successive starts that can be made on an hourly basis without causing significant motor damage. Nadel et al. (1991) shows an excerpt of the NEMA recommendations in tabular form. Examination of the table (which assumes torque equal to the square of motor speed, like with a pump or fan) shows the suggested maximum number of motor starts per hour, maximum number of starts times rated load, and minimum time between starts for Design A and B motors as a function of motor size and number of poles. For even the smallest motors listed (1 hp), rapid cycling of motors at intervals of less than 75 seconds is anticipated to result in motor damage.

End-Use Load Control Potential: Residential End-Uses

The potential demand reduction for residential appliances was analyzed using regional electrical energy use data from the California Energy Commission California Energy Demand Report, end-use electric demand profiles from the Bonneville Power Administration's End-Use Load and Consumer Assessment Program (ELCAP) (Cahill et al. 1992), and from SCE's 1994 Residential Appliance End-Use Study (RAEUS) (SCE 1995). Generally ELCAP demand profiles were used for most end-uses that were deemed non-climate dependent. Because climates in most of California differ significantly from that of the Pacific Northwest, the RAEUS data was used for climate-dependent end-use demand profiles and for certain end-uses not separately defined in ELCAP.

Determination of the demand reduction potential for each end-use was as follows: The CEC data set was used to establish the regional energy use on an annual basis for each end-use. Using the CEC estimates for saturation of each end-use, the annual energy use per appliance was then calculated. Next appropriate usage profiles extracted from either ELCAP or RAEUS were used to develop daily average profiles for electrical energy use at both a regional and a per unit level. For weather-dependent (primarily HVAC equipment) or strongly day-of-week dependent electrical profiles, the ratio of the hourly load during a peak period to the hourly load during the average period was used to determine expected peak loads during peak use periods. The expected load during the peak energy consumption period for the end-use, and the expected load during the anticipated system peak demand period (3:00 to 5:00 p.m. weekdays), was then calculated on both a regional and a per unit basis.

A synopsis of residential demand reduction potential in northern and southern California by end-use follows.

Residential Demand: Southern California Region, Non-Weather-Dependent Loads

Figures A.1 and A.2 illustrate the regional and the per unit demand expected for the non-weather dependent residential end-uses. Those end-uses envisioned to be most appropriate for load control are described in detail below.

Electric Resistance Hot Water Heat

Electric resistance hot water heaters have a total curtailment potential of at least 312 MW during the hours of 8:00 to 9:00 a.m. because of "basic" hot water usage. Basic use does not include energy use by dishwashers and clothes washers. An additional 100+ MW is likely

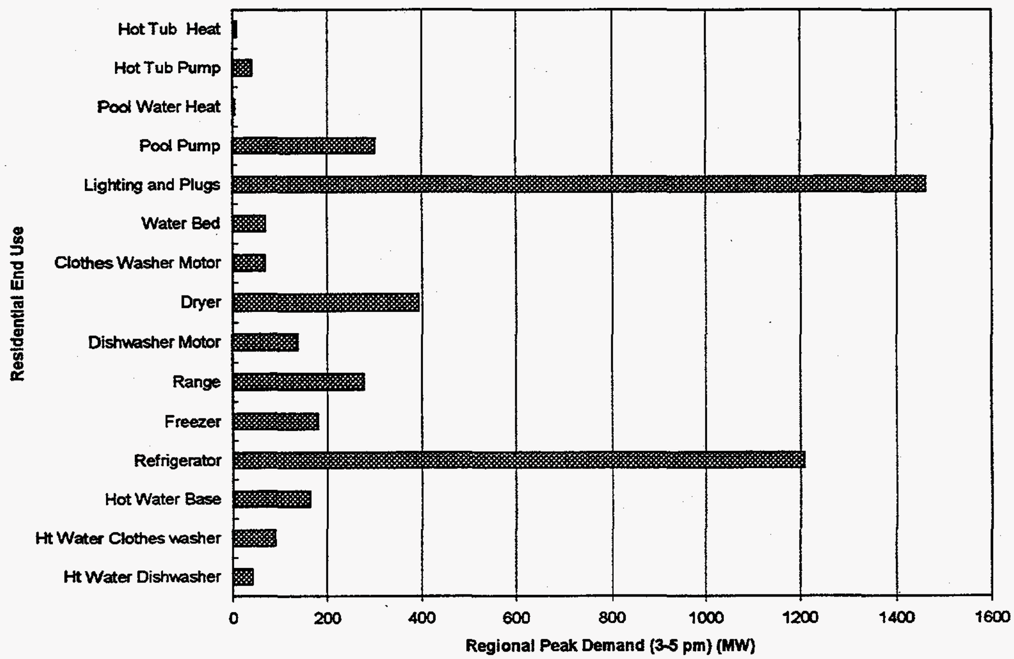

Figure A.1. Residential non-weather dependent peak demand (3:00 to 5:00 p.m.) for southern California by end-use.

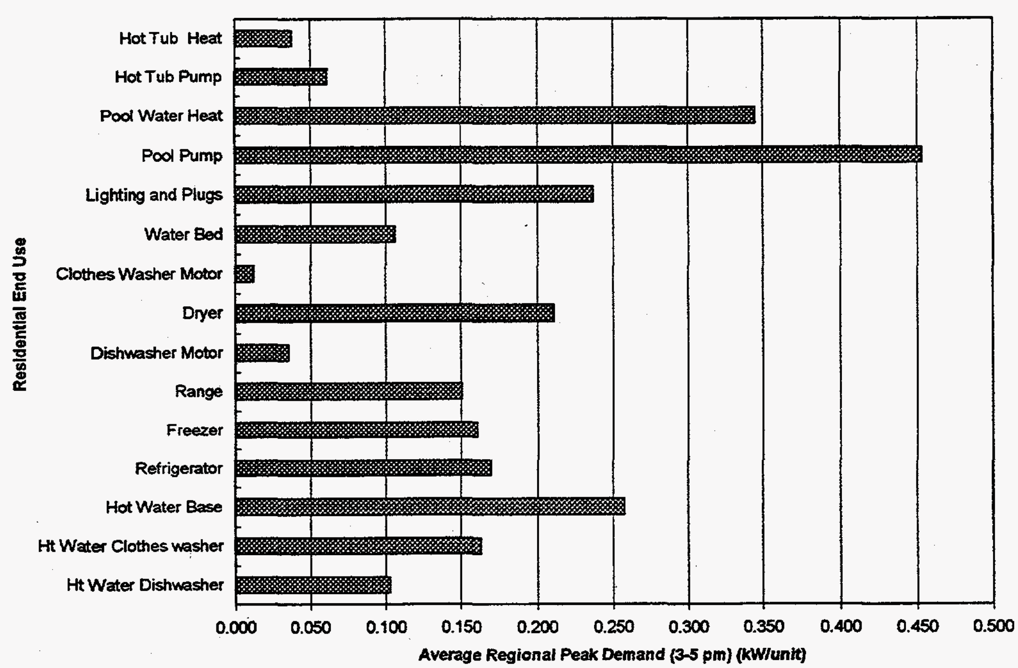

Figure A.2. Residential non-weather dependent per unit peak demand (3:00 to 5:00 p.m.) for southern California by end-use.

attributable to the latter two categories during the same 8:00 to 9:00 a.m. time period. During the hours between 3:00 and 5:00 p.m., the total curtailable usage for all three categories combined is on the order of 300 MW.

The saturation of electric water heaters in southern California housing is 10.2%. The curtailable potential for each electric water heater for base water consumption is 0.494 kW during the hours of 8:00 to 9:00 a.m. or 0.257 kW between the hours of 3:00 to 5:00 p.m. The addition of dishwashers and clothes washers could raise these up to as much as 0.706 kW during the hours of 8:00 to 9:00 a.m. or 0.466 kW during the hours of 3:00 to 5:00 p.m. (depending on the fraction of these appliances that use instantaneous electric heat).

Pool Pumps

A "typical" profile for swimming pool pumps was extracted from the RAEUS data. This study developed typical profiles based on metering of 59 swimming pool pumps. Very little difference was seen based on the magnitude of the weekend versus weekday load profiles. Normalized winter versus summer profiles were also similar, although the winter energy use was about 60% of the summer energy use. For this reason, only one normalized profile was used, averaging weekday summer and winter profiles. Based on the CEC's annual energy consumption for this end-use in southern California and the SCE's demand profile, a maximum curtailable demand of 820 MW was calculated for this end-use, occurring between 12:00 and 2:00 p.m. An average curtailable demand of 303 MW was seen during the hours between 3:00 to 5:00 p.m. With a saturation of 10.8% in southern California housing, this results in a curtailable potential for each pool pump of 0.453 kW between 3:00 and 5:00 p.m. daily or 1.227 kW between the hours of 12:00 and 2:00 p.m.

Waterbed Electric Heat

A "typical" profile for waterbed electric heat is unknown; however, a constant "regional demand" profile was assumed for this analysis. Based on the CEC's annual energy consumption for this end-use in southern California and a constant 24-hour demand profile, a curtailable demand of 115 MW was calculated for this end-use (any time during the day). With a saturation of 10.4% in southern California housing, this results in a curtailable potential for each waterbed of 0.180 kW.

The demand profile for waterbeds is a strong function of climate and house temperatures - particularly residences that allow for daytime room temperature float. Other external factors can dramatically impact consumption profiles, which were not quantified for this study.

Applying the normalized average of the summer and winter weekday profiles from the RAEUS data resulted in a peak curtailable demand of 476 MW at 11:00 a.m. and an average of 67 MW between 3:00 and 5:00 p.m. Thus, in this study, the curtailable demand for each waterbed was approximately 0.736 kW for 11:00 a.m. and 0.104 kW for the hours between 3:00 to 5:00 p.m.

Clothes Dryers (Electric Heat and Motors)

Electric resistance heaters and motors in residential clothes dryers account for a total curtailment potential of 394 MW during the hours of 3:00 to 5:00 p.m. With a saturation of 30.2% in residential housing, this end-use has an average curtailable demand of 0.211 kW per clothes dryer during this period. Further equipment research should break this down into motor energy use and electric resistance energy use because the electric resistance load may be larger and more easily controlled.

Refrigerators (and Combination Refrigerator/Freezer Units)

Residential refrigerators account for a total curtailment potential of 1210 MW during the hours of 3:00 to 5:00 p.m. With a saturation of 115% in residential housing, this end-use has an average curtailable demand of 0.170 kW per refrigerator during this period.

Freezers (Separate Units)

Residential freezers account for a total curtailment potential of 182 MW during the hours of 3:00 to 5:00 p.m. With a saturation of 18.3% in residential housing, this end-use has an average curtailable demand of 0.161 kW per freezer during this period.

Cooking (Electric Range and Stoves)

Electric ranges account for a total curtailment potential of 278 MW during the hours of 3:00 to 5:00 p.m. With a saturation of 29.9% in residential housing, this end-use has an average curtailable demand of 0.151 kW per electric range during this period. Electric ranges use significantly more energy later in the evening. Between the hours of 5:00 to 6:00 p.m., this end-use has an average curtailable demand of 0.342 kW.

Southern California Region: Weather-Dependent Loads (HVAC)

Space Conditioning - Cooling Equipment

Residential air conditioning loads in southern California are met chiefly by central air conditioning equipment (including heat pumps), room air conditioners, or evaporative systems. Estimated market saturation of each technology, appliance UEC, and total energy use during a typical year, as reported in the California Energy Demand Report, are shown in Table A.4.

To ascertain the peak loads for air conditioning in southern California, detailed metering data from RAEUS was used. The RAEUS data provided 15-minute metered data for all three of these residential air conditioning appliances. Average equipment loads were provided for SCE's summer (June through September) and winter (October through May) schedule periods. In addition, average equipment load on the peak summer day metered, provided separately in this study, was converted to hourly values to create an annual average air conditioning end-use profile. In addition, average summer peak day air conditioning load profiles were also created.

Table A.4. Residential HVAC Energy Use - Southern California

End-Use	Central AC	Room AC	Evaporative AC	Furnace Fan
Energy Using Component(s)	Motor/ Compressor	Motor/ Compressor	Motor/Fan	Motor/Fan
Saturation (%)	30.4%	16.1%	5.8%	29.1%
Regional Energy Consumption (GWh/yr)	2372	445	242	499
Unit Energy Consumption (UEC) (kWh/yr)	1266	447	672	278

The annual air conditioning energy use was then applied to the average daily profile from the RAEUS data to get average daily profiles of air conditioning energy use on both regional and per unit equipment bases. Summer peak energy use was then developed by multiplying the annual hourly energy use values for the year by the ratio of the magnitude of the summer peak profile values to the annual average hourly profile values on an hour by hour basis. This exercise was repeated using the summer average profiles instead of the peak profiles. The results are shown in Table A.5.

Space Conditioning - Heating Equipment

Heating loads in southern California are typically met by either natural gas or electric resistance heat or heat pumps. The saturation of electrically fueled heating appliances (electric resistance furnaces, electric resistance baseboards, or heat pumps) is 14.7%, with the average

Table A.5. Residential HVAC Peak Energy Use - Southern California

End-Use	Central AC	Room AC	Evaporative AC	Furnace Fan
Regional Demand Peak (MW) (annual/summer average)	3928 / 1843	1076 / 337	221 / 130	317 / 172
Regional Load Factor (based on annual peak)	0.07	0.04	0.14	0.15
Peak Period (hour of day)	16	15	13	15
Regional 3:00 to 5:00 p.m. Demand Peak (MW)	3752 / 1798	923 / 243	203 / 128	315 / 111
Average Unit Demand Peak (kW) (peak / summer average)	2.096 / 0.984	1.081 / 0.338	0.613 / 0.360	0.177 / 0.096
Average Unit 3:00 to 5:00 p.m. Demand Peak (kW) (peak / summer average)	2.002 / 0.959	0.928 / 0.244	0.564 / 0.356	0.176 / 0.06

heating appliance consuming 2262 kWh/yr. The marginal unit energy consumption for new electric heating equipment (for 1993) is 1454 kWh/yr. This is likely attributable to the more frequent use of heat pumps in place of electric resistance in new heating systems.

Peak space heating loads were not addressed in this study because of lack of appropriate data on peak space heating energy use. This was not considered a significant issue because the need for end-use load control is tied to the peak electrical energy requirements of the region, which for both northern and southern California is not coincident with space heating energy use.

Residential Demand: Northern California Region, Non-Weather-Dependent Loads

Figures A.3 and A.4 illustrate the regional and the per unit demand expected for the non-weather dependent residential end-uses. Those end-uses envisioned to be most appropriate for load control in northern California are described in detail below.

Electric Resistance Hot Water Heaters

Electric resistance hot water heaters have a total curtailment potential of at least 206 MW during the hours of 8:00 to 9:00 a.m. due to "basic" hot water usage. Basic use does not include energy use of dishwashers and clothes washers. An additional 100+ MW is likely attributable to the latter two categories during the same 8:00 to 9:00 a.m. time period. During the hours between 3:00 and 5:00 p.m., the total curtailable usage for all three categories combined is on the order of 205 MW.

The saturation of electric water heaters in northern California housing is 11.8%. The curtailable potential for each electric water heater for base water consumption is 0.394 kW during the hours of 8:00 and 9:00 a.m. or 0.205 kW between the hours of 3:00 and 5:00 p.m. The addition of dishwashers and clothes washers could raise these up to as much as 0.625 kW during the hours of 8:00 and 9:00 a.m. or 0.391 kW during the hours of 3:00 and 5:00 p.m. (depending on the fraction of these appliances that use instantaneous electric heat).

Pool Pumps

A "typical" profile for swimming pool pumps was extracted from the RAEUS report. This study developed typical profiles based on metering of 59 swimming pool pumps. Very little difference was seen based on the magnitude of the weekend versus weekday load profiles. Normalized winter versus summer profiles were also similar, although the winter energy use was about 60% of the summer energy use. For this reason, only one normalized profile was used, averaging weekday summer and winter profiles. Based on the CEC's annual energy consumption for this end-use in northern California and the SCE demand profile, a maximum curtailable demand of 285 MW was calculated for this end-use, occurring at 12:00 to 2:00 p.m. An average curtailable demand of 105 MW was seen during the hours between 3:00 to 5:00 p.m. With a saturation of 7.2% in northern California housing, this results in a curtailable potential for each pool pump of 0.328 kW between 3:00 to 5:00 p.m. daily or 0.888 kW between the hours of 12:00 and 2:00 p.m.

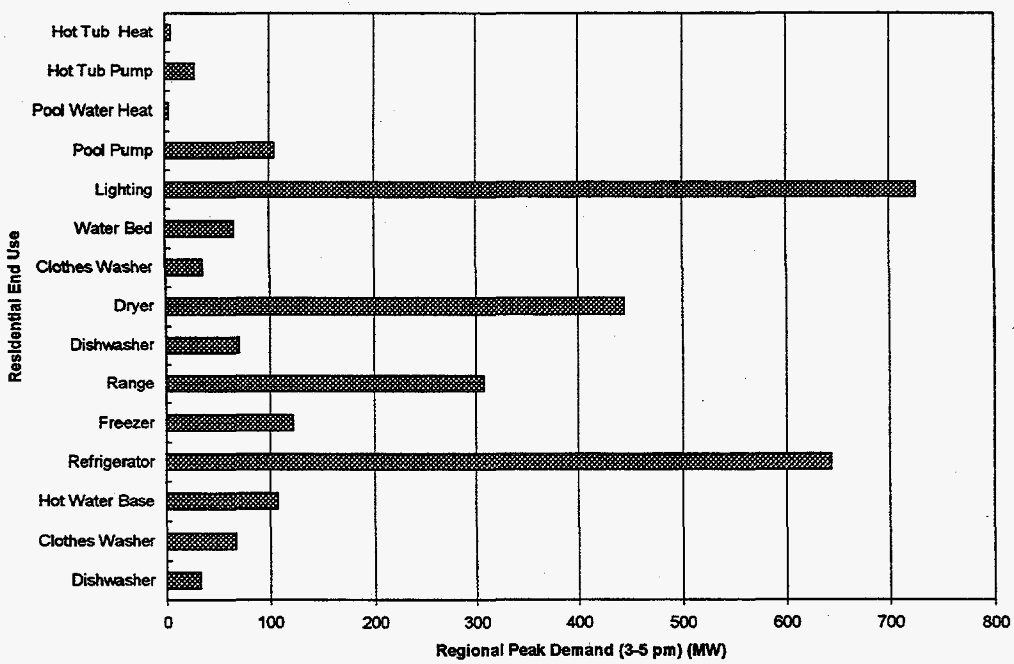

Figure A.3. Residential non-weather dependent peak demand (3:00 to 5:00 p.m.) for northern California by end-use.

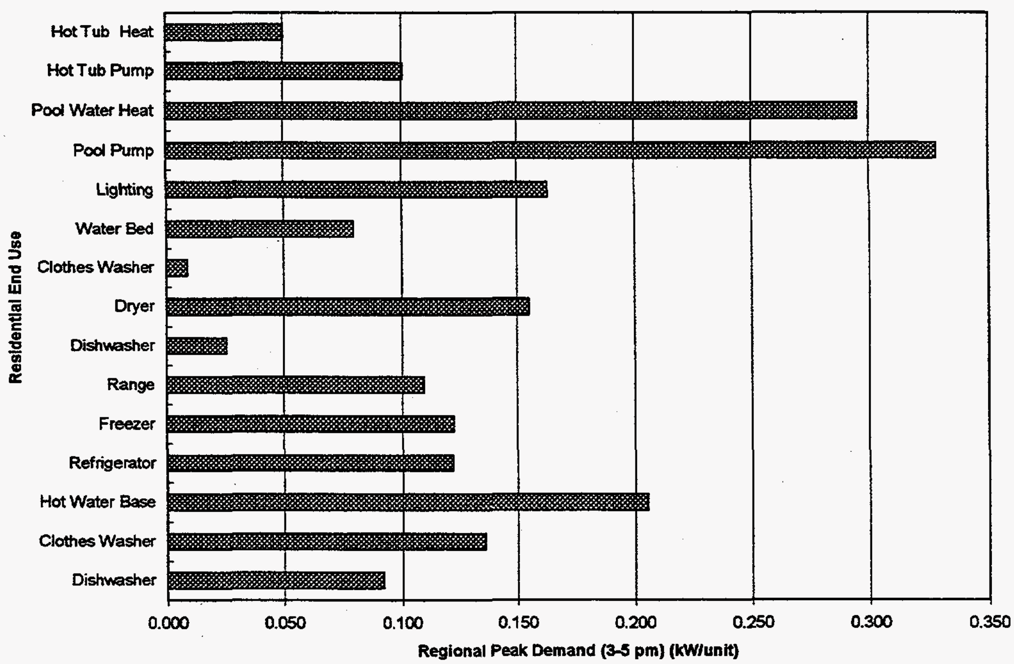

Figure A.4. Residential non-weather dependent per unit peak demand (3:00 to 5:00 p.m.) for northern California by end-use.

Waterbed Electric Heat

A "typical" profile for waterbed electric heat is unknown, however a constant "regional demand" profile was assumed for this analysis. Based on the CEC's annual energy consumption for this end-use in northern California and the constant demand profile, a curtailable demand of 112 MW was calculated for this end-use, occurring at any time during the day. With a saturation of 18.5% in northern California housing, this results in a curtailable potential for each waterbed of 0.137 kW. The demand profile for waterbeds may be a strong function of climate and house temperatures - particularly residences which allow for daytime room temperature float. Curiously, the annual UEC reported by the CEC is less in northern California than in southern California.

Applying the normalized average of the summer and winter weekday profiles from the RAEUS study resulted in a peak curtailable demand of 461 MW at 11:00 a.m. and an average of 65 MW between 3:00 and 5:00 p.m. Thus the curtailable demand for each waterbed is about 0.560 kW for the hour of 11:00 a.m. or 0.079 kW for the hours between 3:00 to 5:00 p.m.

Clothes Dryers (Electric Heat and Motors)

Electric resistance heaters and motors in residential clothes dryers account for a total curtailment potential of 444 MW during the hours of 3:00 to 5:00 p.m. With a saturation of 64.4% in residential housing, this end-use has an average curtailable demand of 0.155 kW per clothes dryer during this period. This should be broken down into motor energy use and electric resistance energy use because the electric resistance load may be larger and more easily controlled.

Refrigerators (and Combination Refrigerator/Freezer Units)

Residential refrigerators account for a total curtailment potential of 644 MW during the hours of 3:00 to 5:00 p.m. With a saturation of 119% in residential housing, this end-use has an average curtailable demand of 0.122 kW per refrigerator during this period.

Freezers (Separate Units)

Residential freezers account for a total curtailment potential of 123 MW during the hours of 3:00 to 5:00 p.m. With a saturation of 22.6% in residential housing, this end-use has an average curtailable demand of 0.123 kW per freezer during this period.

Cooking (Electric Range and Stoves)

Electric ranges account for a total curtailment potential of 308 MW during the hours of 3:00 and 5:00 p.m. With a saturation of 63.3% in residential housing, this end-use has an average curtailable demand of 0.109 kW per electric range during this period. Electric ranges use significantly more energy later in the evening. Between the hours of 5:00 and 6:00 p.m., this end-use has an average curtailable demand of 0.25 kW.

Northern California Region: Weather-Dependent Loads (HVAC)

Space Conditioning - Cooling Equipment

Residential air conditioning loads in northern California are met chiefly by central air conditioning equipment (including heat pumps), room air conditioners, or evaporative air conditioners. Estimated market saturation of each technology, appliance UEC, and total energy use during a typical year are shown in Table A.6.

To ascertain the peak loads for air conditioning in northern California, detailed metering data from RAEUS was used. The RAEUS data provided metered end-use electrical load data on 15-minute intervals for all three of the above residential air conditioning appliances. Average equipment loads were provided for SCE's summer (June through September) and winter (October through May) schedule periods. In addition, average equipment load on the peak summer day metered was provided separately in this study. The data was converted to hourly values, and an annual average air conditioning end-use profile was created. In addition, average summer peak day air conditioning load profiles were also created.

The annual air conditioning energy use was then applied to the average daily profile from the RAEUS data to get average daily profiles of air conditioning energy use on both regional and per unit equipment bases. Summer peak energy use was then developed by multiplying the annual hourly energy use values for the year by the ratio of the magnitude of the summer peak profile values to the annual average hourly profile values on an hour by hour basis. This exercise was repeated using the summer average profiles instead of the peak profiles. The results are shown in Table A.7.

Table A.6. Residential HVAC Energy Use - Northern California

End-Use	Central AC	Room AC	Evaporative AC	Furnace Fan
Energy Using Component(s)	Motor/ Compressor	Motor/ Compressor	Motor/Fan	Motor/Fan
Saturation (%)	29.8%	9.2%	8.3%	50.4%
Regional Energy Consumption (GWh/yr)	1686	165	224	700
Appliance Unit Energy Consumption (UEC) (kWh/yr)	1272	402	608	312

Table A.7. Residential HVAC Peak Energy Use - Northern California

End-Use	Central AC	Room AC	Evaporative AC	Furnace Fan
Regional Demand Peak (MW) (annual / summer average)	2793 / 1311	399 /125	204 / 120	445 /241
Regional Load Factor (based on annual peak)	0.07	0.05	0.13	0.18
Peak Period (hour of day)	16	16	16	17
Regional 3:00 to 5:00 p.m. Demand Peak (MW)	2668 / 1278	342 /90	188 / 119	443 / 156
Average Unit Demand Peak (kW) (peak / summer average)	2.106 / 0.988	0.971 / 0.304	0.554 / 0.325	0.198 / 0.107
Average Unit 3:00 to 5:00 p.m. Demand Peak (kW) (peak / summer average)	2.012 / 0.964	0.834 / 0.220	0.510 / 0.322	0.197 / 0.069

Space Conditioning - Heating Equipment

Heating loads in northern California are typically met by either natural gas or electric resistance heaters or heat pumps. The saturation of electrically fueled heating appliances (electric resistance furnaces, electric resistance baseboards, or heat pumps) is 10.2%, with the average heating appliance consuming 3823 kWh/yr. The marginal unit energy consumption for new electric heating equipment (for 1993) is 2380 kWh/yr. This is likely attributable to the more frequent use of heat pumps in place of electric resistance in new heating systems. Peak heating loads were not addressed in this study because of a lack of appropriate data on peak space heating energy use. This was not considered significant because the need for end-use load control is tied to the peak electrical energy requirements of the region, which for both northern and southern California is not coincident with the likely peak space heating energy usage.

Commercial End-Uses

Annual end-use energy consumption estimates for 1993 were extracted from CEC (1995). The following end-uses were examined: building ventilation, water heating, cooking and food preparation, refrigeration, interior lighting, exterior lighting, office equipment, and other (electrical end-uses that do not fit into the above categories).

Demand profiles were taken from two different sources. For office buildings, retail buildings, restaurants, and warehouses, load profiles available from ELCAP were used for interior lighting, exterior lighting, refrigeration, cooking, and water heating end-uses. All other end-use profiles were taken from the input decks used in the present CEC demand forecast model. These input decks were developed by Lawrence Berkeley Laboratory and other consulting firms for the CEC, and the demand profiles represent their estimates for California buildings. All 12 different building type categories from the CEC work were considered separately in this analysis.

The demand profiles used in this analysis are combined weekday and weekend average. Where the weekday and weekend profiles differed significantly, it is noted for each end-use.

The CEC Demand Report provides regional forecasts of annual end-use energy consumption. These forecasts were aggregated into northern and southern California energy use, northern California being dominated by PG&E and SMUD, southern California dominated by SDG&E, SCE, LADWP, with separate consideration given to the municipalities of Burbank, Glendale, and Pasadena.

Unlike the residential sector, the commercial sector CEC Demand Report does not produce estimates of per unit energy consumption during the year. No attempt was made to develop these estimates in this study. However, future analysis into typical shipping sizes for commercial equipment discussed in this report may be used to develop estimates of the unit energy consumption and unit electrical demand in each end-use category.

Figures A.5 and A.6 show the impact of eight commercial end-use loads on the regional peak demands of southern and northern California. The following sections describe the methodology used to develop these values.

Commercial Demand: Southern California Region, Non-Weather-Dependent Loads

Ventilation

Building ventilation accounts for 12.7% of all non heating/cooling electric energy use in commercial buildings in southern California. For all building types combined, this end-use has a peak demand of 932 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 897 MW.

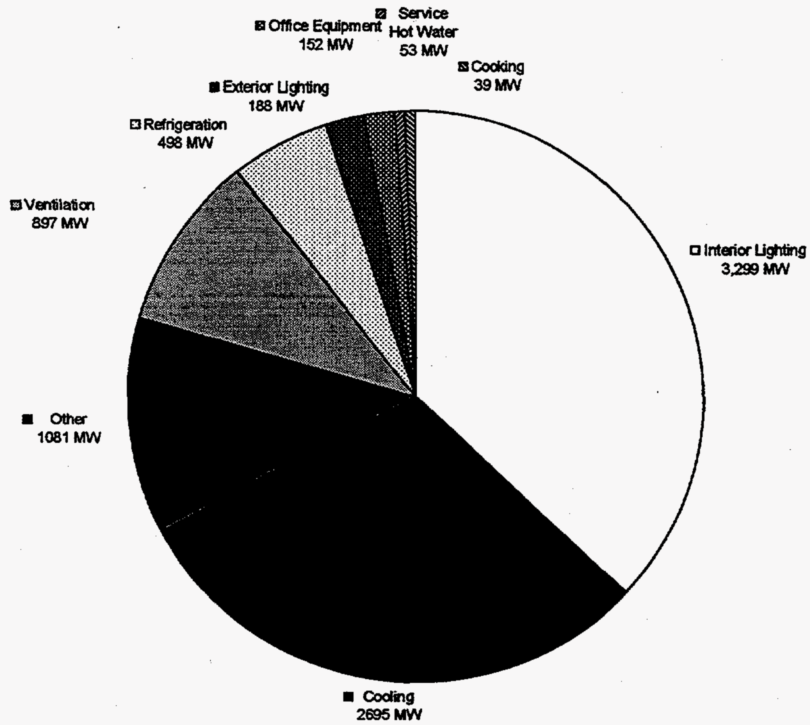

Figure A.5. Commercial end-use contribution to southern California peak demand.

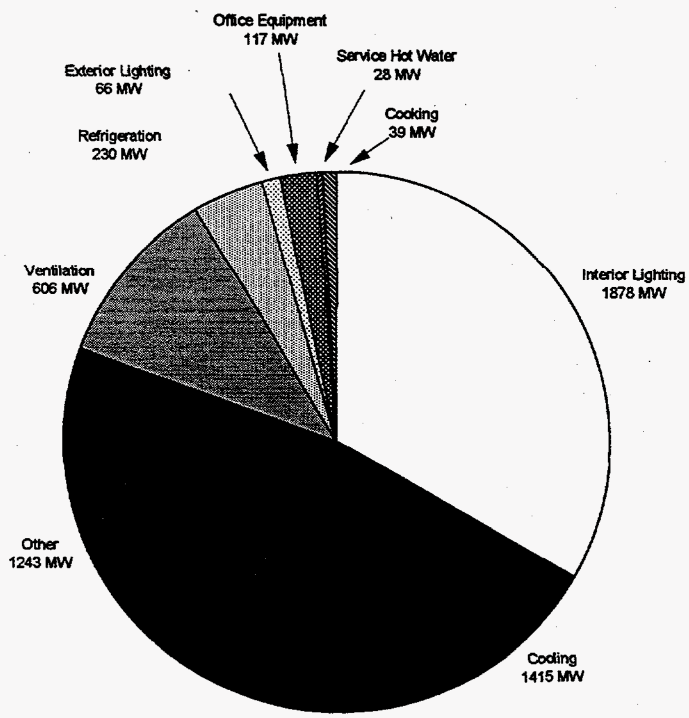

Figure A.6. Commercial end-use contribution to northern California peak demand.

Service Hot Water

Building service hot water accounts for 0.6% of all non heating/cooling electric energy use in commercial buildings in southern California. Because of the predominance of other fuels, mainly natural gas, total curtailable peak load is about 50 to 60 MW.

Cooking

Cooking end-use accounts for 0.7% of all non heating/cooling electric energy use in commercial buildings in southern California. For all building types combined, this end-use has a peak demand of 62 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 43 MW.

Refrigeration

Refrigeration accounts for 10.7% of all non heating/cooling electric energy use in commercial buildings in southern California. For all building types combined, this end-use has a peak demand of 471 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 498 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Interior Lighting

Interior lighting accounts for 46.4% of all non heating/cooling electric energy use in commercial buildings in southern California. For all building types combined, this end-use has a peak demand of 2993 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 3299 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Other

The "other" end-use category used by the CEC accounts for 17.7% of all non heating/cooling electric energy use in commercial buildings in southern California. For all building types combined, this end-use has a peak demand of 1026 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 1081 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Office Equipment

Office equipment accounts for 2.5% of all non heating/cooling electric energy use in commercial buildings in southern California. For all building types combined, this end-use has a peak demand of 142 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 152 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Exterior Lighting

Exterior lighting accounts for 8.7% of all non heating/cooling electric energy use in commercial buildings in southern California. For all building types combined, this end-use has a peak demand of 604 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 188 MW.

Commercial Demand: Southern California Region, Weather-Dependent Loads

For this study, only cooling loads were looked at for weather-dependent loads. Cooling loads were assessed using the CEC's demand Report and the End-Use Metered Data for Commercial Buildings Annual Report 1992-1993 (SCE 1993). This report provides information on commercial building energy end-use and demand profiles, showing demand profiles developed from end-use metering of seven building types: office, retail, fast-food restaurant, sit-down restaurant, grocery stores, warehouses, and health facilities. A total of 87 buildings were monitored in this study, with the resultant load profiles averaged together for like building types.

Using the data described above allowed development of hourly air conditioning demand profiles for five building types that corresponded with like descriptions in the CEC database. Summer and winter demand profiles were developed based on SCE's summer and winter rate periods for both weekend and weekday profiles. Summer and winter peak air conditioning demand profiles were also developed using this data.

The summer and winter weekend and weekday rates were all weighted together into an annual average air conditioning demand profile for each building type. Table A.8 shows the pertinent data from each load profile.

The ratio of measured peak load to average cooling load was multiplied by the estimated average regional cooling load (calculated by dividing the CEC's estimated regional cooling energy use by 8760 hr./yr), giving an estimate for the regional peak cooling loads. For the five building types, the average ratio of summer peak cooling load was 3.32, with a maximum of 3.76 for restaurants and a minimum of 2.83 for retail buildings. For CEC building types that were not represented, the average of the ratios for the five building types represented was used to estimate regional peak loads.

The peak electrical demand for a single commercial cooling unit can be estimated based on the full load electrical demand for that unit. If one assumes that most commercial HVAC systems are sized appropriately for their load, and the size is supplemented with a typical safety margin of 25%, the peak hourly energy demand for a given commercial HVAC system is conservatively estimated to be approximately 75% of full load electrical demand of the piece of equipment. This provides a first estimate of the load control potential on a unit by unit basis.

Table A.8. Average and Peak Cooling Electric Loads in Southern California on a Building and Regional Basis

Building Type	Estimated Regional Energy Use (GWh/yr)	Average Yearly Load (W/ft^2)	Summer Peak Load (W/ft^2)	Time of Peak Load	Summer Peak 3-5 p.m. Load (W/ft^2)	Regional Summer Peak Load (MW)	Regional Summer 3-5 p.m. Peak (MW)
Office	2527.7[a]	0.590	1.829	4:00 p.m.	1.794	895	879
Retail	817.6	0.606	1.716	5:00 p.m.	1.684	264	259
Restaurant	435.2	1.017	3.824	3:00 p.m.	3.741	187	183
Warehouse	66.3[b]	0.096	0.317	4:00 p.m.	0.311	25	25
Health Facilities	922.4	0.171	0.628	4:00 p.m.	0.620	386	382
Elementary Schools	245.5	0.496	1.662	NA	1.630	93	92
Food Storage	79.9	0.496	1.662	NA	1.630	30	30
Hotel/Motel	425.8	0.496	1.662	NA	1.630	162	159
Miscellaneous	1440.9	0.496	1.662	NA	1.630	548	538
College	401.6	0.496	1.662	NA	1.630	153	150
Total	7362.9					2743	2695

[a] Regional energy use combined for small and large office buildings.
[b] Regional energy use combined for refrigerated and non-refrigerated warehouse

Commercial Demand: Northern California Region, Non-Weather-Dependent Loads

Ventilation

Building Ventilation accounts for 12.2% of all non heating/cooling electric energy use in commercial buildings in northern California. For all building types combined, this end-use has a peak demand of 611 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 606 MW.

Service Hot Water

Building service hot water accounts for 0.6% of all non heating/cooling electric energy use in commercial buildings in northern California. . Because of the predominance of other fuels, mainly natural gas, total curtailable peak load is about 28 MW.

Cooking

Cooking end-use accounts for 1.0% of all non heating/cooling electric energy use in commercial buildings in northern California. For all building types combined, this end-use has a peak demand of 52 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 39 MW.

Refrigeration

Refrigeration accounts for 7.4% of all non heating/cooling electric energy use in commercial buildings in northern California. For all building types combined, this end-use has a peak demand of 217 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 230 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Interior Lighting

Interior lighting accounts for 40.1% of all non heating/cooling electric energy use in commercial buildings in northern California. For all building types combined, this end-use has a peak demand of 1699 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 1878 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Other

The "other" end-use category used by the CEC accounts for 31.5% of all non heating/cooling electric energy use in commercial buildings in northern California. For all building types combined, this end-use has a peak demand of 1180 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 1243 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Office Equipment

Office equipment accounts for 2.9% of all non heating/cooling electric energy use in commercial buildings in northern California. For all building types combined, this end-use has a peak demand of 110 MW. The 3:00 to 5:00 p.m. weekday average peak demand is 117 MW. Results are averages over all days and averages for weekdays only (weekday peaks are higher for most categories).

Exterior Lighting

Exterior lighting accounts for 4.4% of all non heating/cooling electric energy use in commercial buildings in northern California. For all building types combined, this end-use has a peak demand of 195 MW. The 3:00 p.m. to 5:00 p.m. weekday average peak demand is 66 MW.

Commercial Demand: Northern California Region, Weather-Dependent Loads

For this study, only cooling loads were looked at under the category of weather-dependent loads. As with the southern California region, cooling loads were assessed using the CEC's Demand Report and the End-Use Metered Data for Commercial Buildings Annual Report 1992-1993 (SCE 1993). The methodology used was identical to that used to estimate peak electrical loads caused by space cooling in commercial buildings in southern California.

Table A.9 shows the pertinent data from this study and estimates of the regional peak electric demand due to space cooling. Note that cooling loads profiles in northern and southern California regions will not be identical in real life. However, it is unclear how the profile would change. It is recommend that in a future study, building energy use simulation be used to assess the relative changes in cooling load profile between the two regions and adjust the northern California results accordingly. The same building model could be used to weather-normalize the data and to provide better peak load information.

Table A.9 Average and Peak Cooling Electric Loads in Northern California on a Building and Regional Basis

Building Type	Est. Region Energy Use (GWh/yr)	Avg. Annual Load (W/ft^2)	Summer Peak Load (W/ft^2)	Time of Peak Load	Summer 3-5p.m. Load (W/ft^2)	Regional Peak Load (MW)	Regional 3-5 p.m. Load (MW)
Office	1598.5	0.590	1.829	4:00 p.m.	1.794	586	555
Retail	264.9	0.606	1.716	5:00 p.m.	1.684	86	84
Restaurant	192.3	1.017	3.824	3:00 p.m.	3.741	83	81
Warehouse	106.2	0.096	0.317	4:00 p.m.	0.311	40	39
Health Facilities	693.9	0.171	0.628	4:00 p.m.	0.620	290	287
Elementary Schools	24.3	0.496	1.662	NA	1.630	9	9
Food Storage	347.1	0.496	1.662	NA	1.630	132	130
Hotel/Motel	40.6	0.496	1.662	NA	1.630	15	15
Miscellaneous	438.9	0.496	1.662	NA	1.630	167	164
College	135.2	0.496	1.662	NA	1.630	51	51
Total	3842.8					1440	1415

[a] Regional energy use combined for small and large office buildings.
[b] Regional energy use combined for refrigerated and non-refrigerated warehouse

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