Peak Load Reduction Device

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Abstract—This paper reports the conceptual design of a Peak Load Reduction (PLR) Device meant to cycle on/off air conditioners, swimming pool pumps, water heaters and compressors. It presents the impact of the proliferation of such devices on the local marginal cost of electric energy and the effect on indoor temperature. Finally the result of a survey of a sample of homeowners, questioned to determine their reaction to the installation of PLR Devices, is summarized.

Index Terms—Community Survey, Load Management, Peak Demand Reduction, Power System Economics.

I. INTRODUCTION

THE concept of load management and PLR (peak load reduction) during hours of unusually high demand, characteristic to very hot summer days, is not new [1], [2]. Recently, a new approach meant to reduce the load of residential central air conditioners started to gain acceptance in South-West Connecticut [3]. This method is based on the remote control of the contactors that energize central air conditioning units, or any high energy using devices such as swimming pool pumps or water heaters. The control is wireless and is managed by Comverge [4]. A prototype device with the same purpose but with additional features is presented in this report.

In case of extreme demand the controlled units are cyclically turned off/on; on for τ_1 minutes and off for τ_2 minutes. The process of load cycling starts ΔT min after the detection of excessive demand conditions; however, the delay time ΔT is different for each unit. In this way synchronous cycling is avoided and the ideal overall load reduction is proportional to $\tau_1/(\tau_1 + \tau_2)$.

An additional feature presented in this report is the ability of the PLR device to sense brownout conditions and to start the on/off cycling when the peak or the rms voltage decreases below a pre-established value.

The prototype designed for this work incorporates both features; the cycling process can be initiated by a remote generated signal (wireless), or as a function of the line voltage.

The paper consists of four sections:

- Description of the PLR Device,
- A brief economics evaluation,
- The PLR Device effect on home temperature,
- Consumer response; a survey.

II. PLR DEVICE DESIGN

The PLR Device is a microprocessor controlled contactor connected between a large load (an air conditioner, a pump, or a compressor) and its 120/240 V ac supply. The on/off cycling process starts when a voltage sensor detects a drop in its supply voltage exceeding a pre-established threshold that corresponds to brownout conditions, or when an input signal transmitted at a specific radio frequency is received. The proposed device has a simplified schematic shown in Fig.1.

A 120/24 V step-down transformer supplies a bridge rectifier that in turn supplies a 5 V regulated buck converter needed to power the microprocessor and the RF receiver. The microprocessor activates a 5 V relay K1, that in turn energizes the 30 A contactor K2 that controls the load.

Three potentiometers, supplied from the regulated 5 V bus help adjust the following input values: 1) The cycling time $\tau_1 + \tau_2$; 2) The duty cycle $\tau_2 / (\tau_1 + \tau_2)$; 3) The threshold voltage.

The basic code algorithm is explained with the help of Fig. 2. The initialization procedure in the code is fairly simple. It sets the variables in the microprocessor to their starting values, disables unnecessary features of the microprocessor, activates the analog to digital conversion module, and sets up the proper pins for input and output. This initialization subroutine only occurs at the startup of the microprocessor or in the case of a reset; all the other subroutines are in a perpetual loop.

The input acquisition subroutine utilizes the analog to digital conversion module to obtain values related to the line voltage, a constant voltage for comparison, total on-off time, and duty cycle. The analog to digital converter produces a 10 bit binary number for each of the inputs, resulting in a resolution of about 0.12 V per step (relative to the full system input of approximately 120 V ac). Within each of these conversion loops there is also a test for an RF signal. This is done so that if the device only sees an RF input briefly, it will still proceed with the RF loop once it reaches that point in the code. If the constant comparison voltage was previously below the line voltage, a small value will be added to the comparison voltage in order to prevent erratic control of the device if these voltages are very close to each other.

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Fig. 1. PLR Device: (a) Simplified Schematic.



Fig. 2. Basic Code Algorithm.

The voltage information is usable at this point, but the timing results are not usable without some modification to their values. A subroutine performs this function: the four most significant bits of both timing inputs are used as the four least significant bits of the actual timing variables. This provides the total amount of time and the amount of off time. The on time is determined by subtracting the off time from a constant value. As a result, if the off time is set to be short, the on time will be long, and vice versa. A check is also performed to ensure that none of these times are set to 0, since due to certain details of the operation of this microprocessor a zero value in a timing loop actually results in a timing loop that runs much longer than desired. If by chance one of the values at the output of this subroutine is found to be 0, it is changed to 1, thus fixing this problem.

Many points in the code check for an RF signal so that the microprocessor will know if a signal is only detected briefly. If a signal has been detected, the microprocessor will wait until the signal is no longer detected. It will then wait for a bit longer before turning the load off. This amount of time is staggered between devices based on how many times the microprocessors have gone through the main code loop and is ideally random between devices. This is done to stagger the device operation between multiple devices and thus to prevent synchronous cycling. The microprocessor will cycle the load on and off until another RF signal is detected or until it goes through a predetermined maximum number of cycles. The microprocessor will then resume normal operation.

After checking for an RF signal, the microprocessor compares the constant voltage (plus a small value, if the



Fig. 3. Demonstration Board. Side View

constant voltage was higher on the last pass through this subroutine) to the relative line household voltage. The value of the constant voltage is determined by the setting of one of the potentiometers. If the constant voltage is higher, the microprocessor will turn the load off for a period of time, then on for a period of time. These times are based on the potentiometer settings (for a demonstration unit), or on a preset value in the code in a production version of the circuit. After all these steps are completed, the code will loop back to the beginning and go through the steps again.

After checking for an RF signal, the microprocessor compares the constant voltage (plus a small value, if the constant voltage was higher on the last pass through this subroutine) to the relative household voltage. The value of the constant voltage is determined by the setting of one of the potentiometers on the demonstration circuit. If the constant voltage is higher, the microprocessor will turn the load off for a period of time, then on for a period of time. These times are based on the potentiometer settings in the demonstration circuit or on a preset value in the code in a production version of the circuit. After all these steps are completed, the code will loop back to the beginning and go through the steps again.

The PLR Device was designed with the following priority concept in mind: When the device receives an RF input, it will continue in turning the connected load off and on periodically until another RF input is received or a pre-set maximum number of cycles (sets of on and off times) is reached; during this process, the voltage seen by the microprocessor has no effect. This essentially gives the utility, or other controlling entity, a priority over the device's local control so that the device will not keep the load on if the utility wishes for it to keep cycling on and off. Setting a maximum number of cycles is a precaution in the case that it receives the first RF input (to tell it to start cycling) but does not receive the second input (to tell it to return to normal operation), thus preventing a perpetual on-off loop. A photograph of the device build as a demonstration board device is given in Fig. 3.

III. LOCATIONAL MARGINAL PRICE REDUCTION

The total hourly demand in MW for New England on August 2, 2006 - a day where the demand was near the maximum that could be served – and on August 3, 2006 – where the demand was lower – are presented in Fig.4. The horizontal axis for these graphs is a time axis, representing the end of the hour during which the corresponding values were determined. The time variations of the Locational Marginal Price (LMP) – essentially the cost of electricity at a given location in the electric grid – averaged for all nodes in New England in MWh, for August 2 and 3, 2006 are shown in Fig. 5. The information used in these Figures was obtained from ISO New England's publicly available records [5].



Fig. 4. Demand 0n 08/02/2006 and 08/03/2006



100

0 -

From these data it was possible to extract the points that

Fig. 5. Average LMP versus time

2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 Hour Ending in LMP on 8/2 LMP on 8/3



The total savings for implementing any load reduction program can be quantified by comparing the total cost of electricity on a high-demand day to the expected total cost with the load reduction program in place. The total cost of electricity on a given day can be estimated by finding the product of the values of the average LMP and total demand for each hour and then summing all of these results for the hours during which the load reduction program would be activated. This sum can then be compared to the result of the same calculation performed with the total demand and average LMP reduced according to the amount of demand reduction which the program in question would provide.



Fig. 7. Total savings versus the Demand Reduction

Estimation of LMP for daily demand curves obtained from the interpolation between the data extracted from August 2 and August 3, 2006, enabled the computation of savings in millions of dollars per day versus the demand reduction. 5,819,932 housing units were reported in New England in the 2005 census [6]. Assuming that only 25% of the houses have air conditioning and the average unit consumes 2 kW, results that the installed power commanded by all the air conditioners in New England is about 2910 MW. Thus, a well proliferated PLR technology may lead in New England to power demand reductions as high as 1000 MW.

In Fig. 7 are summarized the predicted potential daily savings for New England, on a day identical to August 2, 2006, versus the demand reduction. It was learned that even a modest demand reduction of 200MW, during a high demand/high energy priceday, translates in into potentially significant LMP savings, \$41,000,000 in this example, due to demand reduction and the corresponding estimated LMP reduction.

IV. PLR DEVICE EFFECT ON AIR CONDITIONER PERFORMANCE

This section reports the indoor temperature, obtained by means of theoretical simulations, of a typical house with an equivalent cooling surface of 220 m². The heat transfer conditions are governed by two major parameters: 1) the equivalent thermal time constant of the house and 2) the air conditioner's power. The thermal time constant τ_{TH} , is a function of the walls and attic insulation, the type of windows and doors, as well as weather conditions. τ_{TH} was assumed in the range of 5h $< \tau_{TH} < 20$ h. The air conditioner power was

reflected in power density p, measured in W/m². This parameter enables the extrapolation of the results to different home geometries and sizes. Due to limited space this paper reports only the case of the house with the thermostat set at

75 o F when the outdoors temperature is 100 o F.

In Fig.8 is presented the indoor temperature variation for the house with $\tau_{TH} = 20$ h, p = 25 W/m² cooling power density, and a PLR Device that operates with $\tau_1 = \tau_2 = 30$ min.

The initial temperature was assumed 90 o F. Once the air conditioner is turned on the temperature decreases to 74 o F and the thermostat helps maintain the temperature at 75 ± 1 o F. After 30 min the PLR Device turns off the air conditioner for the next 30 min. During this time the temperature increases to 86 o F. The percent energy saved due to the PLR Device is about 30%. This is less than the expected 50%. The reason for this reduction in energy saving stems from the fact that additional energy is needed to lower the temperature from 86 o F to 74 o F.



Fig. 8. Typical indoors temperature variation when a PLR Device controls an air conditioner.

Simulations were performed for $\tau_1 = \tau_2$ in the range of 5 to 30 min. The indoor temperature extremes were obtained for $\tau_{TH} = 5$, 10 and 20 h and are shown in Fig. 9.

From these results it is learned that the smaller the cycle $\tau_1 + \tau_2$, the shorter the temperature excursion between maximum and minimum; accordingly, more comfortable conditions are obtained by using smaller values of $\tau_1 + \tau_2$. The best result, an excursion of 74 °F to 81 °F, was obtained with the strongest air conditioner, p = 50 W/m², and $\tau_1 = \tau_2 = 5$ min. When the power density is p = 6.25 W/m² the minimum temperature exceeds 74 °F. This means the thermostat is not activated, and the air conditioner is cycled on/off by the PLR Device. In this case a perfect 50% reduction in energy consumption is obtained, but the indoor temperature

may be too high for comfort

In Fig. 10 are shown the percent energy savings versus

 $\tau_1 = \tau_2$, when the power density is the parameter and τ_{TH} =5h.



Fig. 9. Extreme indoors temperatures (a) τ_{TH} =5h. (b) τ_{TH} =10h.

(c) τ_{TH} =20 h.



Fig. 10. Percent energy savings. au_{TH} =5h

Similar results were obtained for τ_{TH} >5h. One will notice a conflict between the need for a short cycle, that ensures a cooler house and low temperature variations, and the amount of energy saved. Satisfactory energy savings require good insulation, τ_{TH} >25 h and cycling with $\tau_1 = \tau_2$ >20 min.

V. COMMUNITY RESPONSE TO PLR DEVICE IMPLEMENTATION: A SURVEY

For PLR devices to have a societal impact technical feasibility is not enough. They must also gain public acceptance and be affordable for regional transmission organizations (RTOs) or other load serving entities to offer. Prior to the present study there was little evidence to suggest how individual homeowners might react to offers to participate in various types of demand reduction (DR) programs. In particular, the values of key behavioral variables necessary for an RTO or load serving entity to determine whether or not to offer a DR program, such as the degree to which consumers might resist giving up full control of their air conditioning system, and the size of financial incentive that would be required to overcome that resistance, have been elusive.

In order to begin to address these questions, in January 2007 a mail survey was distributed to a representative sample of 915 homeowners in the Greater Boston Metropolitan Area. Two hundred fifty responses were received, yielding a response rate of 27%. Topics covered on the survey included experience with electricity interruptions and outages, electricity and air conditioning usage habits, standard demographic information, and attitudes and toward and economic evaluation of DR programs. Two hypothetical DR scenarios were presented: one in which consumers would be asked to adjust their thermostat on their own after receiving a request from the RTO or local utility and one in which a PLR device would be installed and fully controlled by the RTO, local utility or other controlling entity. The survey also included a brief explanation of DR programs and their benefits to individual consumers and society as a whole.

The survey results indicated a substantial amount of reluctance on the part of homeowners to yield control of their air conditioners, with about ³⁄₄ of respondents being slightly or strongly opposed to the idea. This reluctance was further reflected by a 2 to 1 preference for the homeowner-controlled versus PLR-controlled DR program. The minimum financial incentives respondents suggest would be required for them to participate in the proposed DR programs are shown in Fig. 11 for the homeowner-controlled option and Fig. 12 for the PLR device-controlled option.

Although the incentives required are slightly lower, on average, for the homeowner-controlled program, the pattern is similar in both cases. Around half of respondents say they would require a very large incentive of \$50 per month or higher; these individuals are likely not interested in participating in a DR program under any reasonable incentive scheme. Between 30 and 40% of respondents say they would require a more modest, but still substantial incentive between \$15 and \$45 per month; it may be possible to persuade some of this group of individuals to participate if efforts are made to educate them regarding appropriate incentive rates, but they clearly expect to be compensated for their participation. Finally, between 10 and 15% of respondents indicate they would participate with no incentive required at all; these individuals are apparently motivated more by the societal benefits of the program versus any personal benefit.



Fig. 11. Financial incentive required by respondents for participation in homeowner-controlled DR program.



Fig. 12. Financial incentive required by respondents for participation in PLR device-controlled DR program.

In order to better understand the factors that predict incentives required, several demographic and behavioral variables were entered as predictors of incentives in a multiple regression model. Two significant predictors were identified, the strongest being summer thermostat temperature. As thermostat setting increased, incentive required increased, all else being equal. It is likely that higher summer thermostat settings indicate the respondent is predisposed to conserve energy and hence likely to have a favorable attitude toward DR programs. The other significant predictor was summer electric bill. As the monthly bill increased, the incentive required increased. It may be that respondents are calculating their incentive required as a percentage of their monthly bill. Unfortunately, this finding indicates that the largest summer electricity users, whose participation would help the most, are likely to be the hardest to recruit to a DR program.

It should be emphasized that the incentive required figures described were obtained through survey responses to hypothetical scenarios. Responses to a real offer to participate in a DR program might vary if details of the program are different than those described.

Furthermore, the survey responses were obtained after only a brief introduction to DR programs. How people might respond after additional efforts to inform and educate them on DR and PLR devices is unknown and awaits future research. However, the basic pattern of the results is clear:

- 1. There is substantial resistance to PLR devices among about half of the sample population.
- 2. The great majority of the sample population would require a substantial incentive to participate in a DR program.
- 3. The sample population does not have a good understanding of what size incentive is appropriate.

For a homeowner demand response program to succeed in the Greater Boston Metropolitan Area, beyond the level of 10-15% participation, either financial incentives substantially larger than those currently contemplated would be required or significant, sustained efforts would be needed to raise public awareness and increase public knowledge about DR programs.

VI. CONCLUSIONS

The PLR Device has a relatively simple construction and today's modern industry can mass-produce it without major difficulties. Such devices are effective peak demand reducers and enable large scale energy management.

For a well thermally insulated house the use of PLR Devices may lead to 30% energy savings, without a major deterioration in the comfort of the residents. For pumps and water heaters 50% savings or more are possible.

A survey of 250 homeowners in Greater Boston Metropolitan Area indicates that the majority of homeowners are not yet ready to accept PDR Devices. An effective education program that promotes energy management is needed if PDR Devices are to proliferate.

VII. ACKNOWLEDGMENT

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