Time Programmable Smart Devices for Peak Demand Reduction of Smart Homes in a Microgrid

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***Abstract* – Increasing electricity access through Microgrids for rural areas is often faced with the challenge of increased peak demand through increased electricity demand as more electronic devices will be acquired by the consumers and more small businesses will spring up in the community. If not taken care of, this leads to additional cost of incurring higher peaker plants to meet the peak demand, and the burden of the cost of peaker plants are consequentially transferred to the consumers. Since this load is generated by the consumers, it is most desirable to control the peak demand from the consumers' side. Therefore, a method of Time Programmable Smart Devices (TPSD) with an efficient Electricity Use Plan (EUP) is proposed in this paper by introducing appliance working knowledge and improving load shifting technique of Demand Side Management for peak demand reduction in a rural Microgrid. This method yielded lower morning and evening peaks, a lower peak-to-peak difference than those available in literature, and a peak period shift from the traditional peak period to traditional off-peak period. These lead to financial savings, reduced cost of peaker plants and a safer environment from less greenhouse gases emissions.**

Key words – Time Programmable Smart Device (TPSD); Smart Home; Peak Demand; Peaker Plants; Microgrid.

I. INTRODUCTION

The increasing demand for electricity cannot be over-emphasized with the increasing number of devices that needs to be electrically powered. This has led to a lot of research in power systems, information and communication technologies to give birth to the future grid, also called smart grid. The future grid is expected to be an intelligent Macrogrid comprising of many Microgrids with both centralized and distributed energy sources capabilities. Smart grid is motivated by economic, political, environmental, social and technical factors for energy reliability, efficiency, security and saving. Advanced Metering Infrastructure (AMI) system is a fundamental aspect of the smart grid and it comprises of technologies and applications such as smart meters, Wide Area Communications Infrastructure, operational gateways, Meter Data Management Systems (MDMS) and Home Area Networks (HANs) [1]. The HAN is responsible for the two-way communication between smart meters and controllable household electrical loads. Among its energy management functions include in-home displays, responsiveness to price signals based on consumer-centred preferences, setting limits for utility or local control actions to a consumer specified band, security monitoring, control of loads without continuing consumer involvement and consumer over-ride capability [2][3]. HAN could exist in both Macrogrid-connected and Microgrid-connected homes.

Microgrids shall form a very strong part of the future grid for its contribution to energy reliability, savings and sustainability especially in areas far from the grid utility. Electric access to rural areas often leads to increase in electricity demand by the consumers in the long run. More electronics devices will be acquired by the individuals and more small businesses and government facilities would also spring up leading to increased demand of electricity as illustrated in Fig. 1 showing initial load profile (LP) at the onset of the Microgrid implementation and an unregulated load profile (Unreg. LP) due to increased electricity demand. In a traditional unregulated use of electric power by households, the morning and evening peaks could be very high, and utilities would have to procure higher power rating peaker plants. Peaker plants are generating sets acquired by utilities to cater for the periods of high peak demand from consumers. The cost of acquiring these peaker plants falls back on the consumers that generated this peak load through higher electricity tariffs. Most often, Microgrid peaker plants have unclean energy sources such as coal, diesel or gas [4]. In South Africa, over 90% of total electrical energy production comes from coal [5]. Hence, it is essential to introduce Demand Side Management (DSM) technique into rural Microgrid designs for their sustainability, affordability and reliability.

Households are known to usually have two peak demand periods in a day - morning peak demand and evening peak demand. The morning peak (05:00 - 09:00 hours) is often due to the use of appliances such as lights, heaters, toasters, stoves, fans, electric kettle, radio, phone chargers, laptop chargers etc. Whereas, the evening peak (17:00 – 21:00 hours) is often due to the use of more devices and appliances such as lights, heaters, stoves, fans, electric kettles, televisions, radios, computers, microwave, dishwashers, blenders, washing machines, DVD players, laptop chargers, phone chargers etc.

If consumers are able to regulate their use of home appliances especially at peak times, there will be three-dimensional savings from such action. Firstly, there will be financial savings for the individual consumers without trading off their comfort. Secondly, there will be energy and financial savings for the utility providers. Lastly, there will be

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environmental savings as lesser greenhouse gas emissions will be generated from peaker plants.

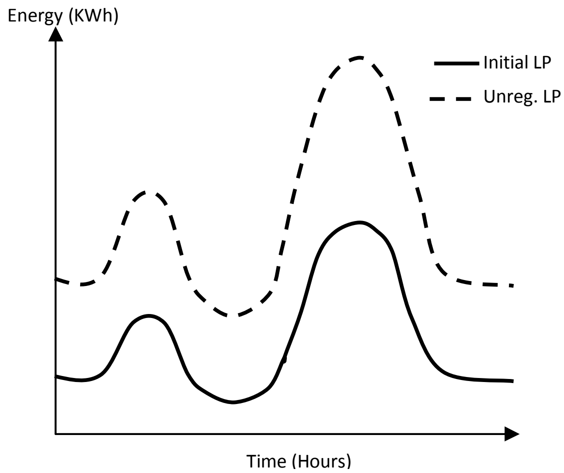

Fig. 1. Initial and Unregulated Load Profiles

Therefore, using Time Programmable Smart Devices (TPSD) method for the reduction of peak demand in Smart Homes of a Microgrid is proposed in this paper. It is a unique method providing an efficient Electricity Use Plan (EUP) for smart homes by introducing device working knowledge and improving load shifting technique of Demand Side Management for peak demand reduction in a rural Microgrid. This method produced lower morning and evening peaks and a lower peak-to-peak difference than those available in literature. This proposal can be applicable to both urban and rural smart homes.

The rest of the paper is organized as follows. Demand Side Management techniques are presented in Section II while the proposed Time Programmable Smart Devices (TPSD) peak demand reduction technique is presented in Section III. Section IV contains simulation graphical results and discussions and the Conclusion is presented in Section V.

II. DEMAND SIDE MANAGEMENT TECHNIQUES

The term, Demand Side Management (DSM) was coined following the 1973 and 1979 energy crises, but was publicly introduced by Electric Power Research Institute (EPRI) in the 1980s [6]. Demand Side Management (DSM), a very important aspect of load management, has been mentioned as an effective tool for transformation of traditional grid to smart grid, liberalization of electricity market, enhancement of control management, electricity infrastructure construction cost reduction, reducing electricity demand and energy consumption, balance of electricity demand and supply in real time and increasing the feasibility of decentralized energy resources and electric vehicles [7].

The future (smart) electricity grid is transforming DSM from being only utility driven to also being consumer-driven and environmental policies-driven. DSM aims on using power saving technologies, electricity tariffs, monetary incentives, and government policies to mitigate the peak load demand instead of enlarging the generation capacity or reinforcing the transmission and distribution network [8].

Modification of consumers' load profiles has been used for classifying DSM techniques [8] into load shifting, peak clipping, conservation, load building, valley filling and flexible load. These techniques are illustrated in Fig. 2.

Load shifting technique applies the fact that loads are time independent and therefore, shifts loads from peak time to off-peak time. It is widely used in most current distribution networks for effective load management.

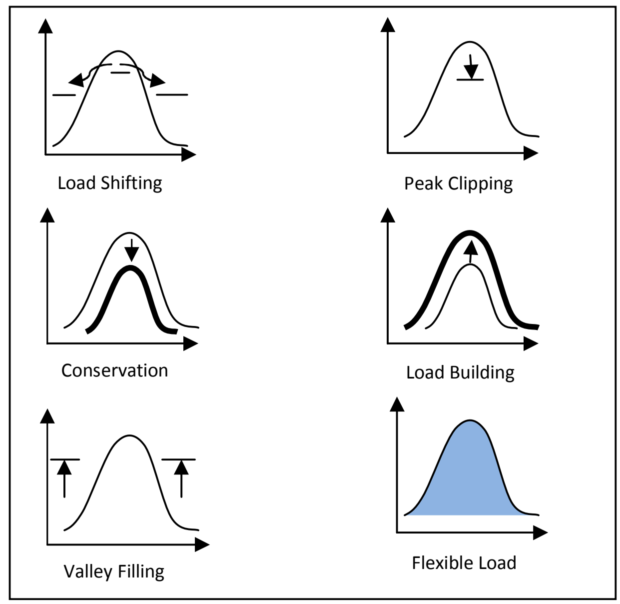

Fig. 2. Demand side management techniques.

Peak clipping technique is a direct load control technique that aims at peak reduction of consumers load profile at specific periods. It can be done by direct control on equipment or through tariff.

Conservation technique is used to achieve load shape optimization through application of demand reduction methods at customer premises, although this may have a long term effect on network planning and operation.

Load building technique is based on increasing the market share of loads supported by energy conversion and storage systems or distributed energy resources. It optimizes the daily response in case of large demand introduction beyond the valley filling technique.

Valley filling technique is used to reduce the valley load levels by constructing the off-peak demand through direct load control.

Lastly, flexible load technique offers reliability to the smart grid by identifying customers with flexible loads who are willing to be controlled during critical periods in exchange for various incentives.

Several methods have been proposed in literatures for DSM. Some are system specific [10, 11], some are based on linear programming [12] and some on dynamic programming [13]. The authors in [14] proposed an optimal load demand schedule method using water heater and Binary Particle Swarm Optimization (BPSO) for minimizing the peak load demand while maximizing customer comfort level. Also, a control and scheduling strategy approach called lazy scheduling was proposed in [15]. Some also studied the demand response of modifying the elastic load components of common household appliances by decreasing their instantaneous power drawn at the expense of increasing their duration of operation with no impact on the appliance's lifetime [16]. In [17], the authors presented a domestic hot water heater model to be used in a demand side management program. Many users of programmable timers in the home often set EUP that is not informed by appliance working principle and as such do not get optimum financial and energy savings.

All the methods proposed in literature did not yield a very high peak demand reduction as the TPSD method to be presented in this paper. In the next section, we shall see how load shifting DSM technique and device working knowledge were used to develop an efficient Electricity Use Plan (EUP) for peak demand reduction and consumers' comfort.

III. PROPOSED TIME PROGRAMMABLE SMART DEVICE (TPSD) PEAK DEMAND REDUCTION TECHNIQUE

In this paper, Time Programmable Smart Device (TPSD) technique is proposed for peak demand reduction. The technique presents a model with an efficient EUP for peak demand reduction in a rural Microgrid based on appliance working principle and improvement on DSM load shifting technique. The knowledge of an appliance working principle was used to programme its ON/OFF working states. Therefore, the ON/OFF working states of three shiftable devices (refrigerator, water heater and room heater) were considered from the sample residential load profile of a rural Microgrid in uMhlabuyalingana Local Municipality (ULM) of Kwazulu-Natal Province of South Africa [18]. Shiftable devices are devices whose time-of-use can be adjusted for short periods of time without affecting the end user's comfort.

The TPSD is expected to be a smart home appliance with built-in capacity for programmable times of operation as desired by the customer. The on-state and off-state of the TPSD is determined by the consumer. A display unit is incorporated into the device from which the customer can set the desired on-state and off-state periods. This model is simulated in Matlab and Microsoft Excel.

The TPSD technique does not require the customers to daily set the appliances, but the devices rather switch ON/OFF according to their programmed time table. Since it is an automated switching operation, there would be no issues of human inadequacies such as forgetting to switch device ON/OFF or absence from home.

A. Classification of Household Devices

The common household devices and appliances in a rural Microgrid as earlier designed for uMhlabuyalingana Local Municipality (ULM) [18] were grouped under shiftable loads and non-shiftable loads. Unit Records data obtained from [19] presented statistics of access to mains electricity for lighting, income and expenditure levels of households and the type of basic home electrical appliances owned or accessed by households in all the provinces of the nation. This data was used to predict the type of appliances to be considered for ULM based on their income level. The shiftable loads in the TPSD load profile simulation were the refrigerator, water heater and room heater. The non-shiftable loads were other loads such as radio, television, electric stove, phone, bulbs, electric iron, electric kettle and fan. The total energy consumed, E_T by a household is given as:

$$E_T = \sum_{i=1}^{m} nP_iT_i = E_1 + E_2 + E_3 + ...E_m \quad (1)$$

Where n is the total number of the appliance i in use in a household, P_i is the power rating of appliance i and T_i is the duration of appliance i usage per household as shown in (1).

B. Refrigerator Time Programmable Smart Device

A refrigerator is a common household appliance used to keep food items cool and preserved till when they will be consumed. Most refrigerated food items can remain safe for 2 hours or even 4 hours if the refrigerator doors were not opened, after a power outage [20]. Therefore, a consumer smart refrigerator TPSD was modelled with this understanding and the ON/OFF working states timing of the refrigerator was done without any negative impact on the comfort of either the consumers or the food items in the refrigerator. Some consumers like to leave their refrigerators switched ON for 24 hours, although this is not really necessary for the preservation of the food items kept in it. Leaving a refrigerator in an ON-state for 24 hours a day yields a higher electricity bill at month end than if its usage were regulated as a TPSD. Therefore, the consumers' smart refrigerators (TPSDs) for 100 households connected to the ULM Microgrid were simulated to be switched OFF for 3 hours in the night (22:00 - 01:00 hours), 1.5 hours in the morning (07:00 – 08:30 hours) and 1.5 hours in the evening (18:30 – 20:00 hours). This EUP for the smart TPSD refrigerator contributed to a reduced and shifted morning and evening peaks from conventional peak periods to non-peak periods and a reduced overall load profile.

C. Heater Time Programmable Smart Device

A heater is a household appliance that falls under the group called Heating, Ventilating, and Air-Conditioning (HVAC) devices. The heating load in a household comes basically from the water heating and room heating loads. The water heater is often responsible for 30% - 50% of a consumer's household electricity consumption [21]. Therefore, a smart reduction of these figures will lead to energy and great financial savings for the consumers. For instance, a 3 kW 150 litre water heater (geyser) requires 2 hours 40 minutes to heat up water from 20^oC – 65^oC. If the water heater is switched OFF and it stores the water at thermostat set point, the water temperature will only drop by 10°C over 24 hours [21]. Therefore, the smart water heater (a TPSD) was modelled to be switched ON for a maximum of 4 hours daily. The EUP schedule was 21:30 – 23:30 hours for evening bath and 03:30 – 05:30 hours preceding morning bath. Also, the room heater (a TPSD) was modelled with EUP to be switched ON for 7 hours (22:00 – 05:00 hours) per day during the winter months, but with reduced or sparing usage during autumn months. Results also showed that this EUP model for TPSDs yielded reduced and shifted morning and evening peaks from conventional peak periods to non-peak periods and a reduced overall load profile.

A total of one hundred (100) households were considered. It was assumed in the model that same devices and number of devices were owned by all households under consideration. The electricity consumption for a typical household in the model both for traditional Normal Devices (ND) LP and TPSD LP is shown in Table I.

TABLE I. HOUSEHOLD ELECTRICAL LOAD

Load	Power, P (KW)	Qty, n	Load type	Usage, T (hours)		Electricity Consumption, E (KWh)	
				ND LP	TPSD LP	ND LP	TPSD LP
Radio	0.015	1	NS	10	10	0.15	0.15
Television	0.040	1	NS	6	6	0.24	0.24
Stove	1.000	1	NS	3	3	3	3
Phone	0.010	2	NS	2	2	0.04	0.04
Bulbs (inside and outside)	0.010	4	NS	12	12	0.48	0.48
Iron	1.000	1	NS	1	1	1	1
Kettle	1.000	1	NS	2	2	2	2
Fan*	0.080	1	NS	9	9	0.72	0.72
Refrigerator	0.035	1	S	24	15	0.84	0.525
Water heater	3.000	1	S	15	5	45	15
Room heater*	1.000	1	S	15	8	15	8

*Seasonal loads NS – Non-shiftable load S – Shiftable load

IV. RESULTS AND DISCUSSION

After simulating the proposed TPSD model for smart homes in a Microgrid, the results obtained showed greater reduction in peaks than those recorded in literature. The comparative seasonal load profiles of 100 households connected to the Microgrid using normal devices (ND) under traditional usage and TPSD refrigerators and heaters are presented in Figs. 3, 4, 5 and 6 for summer, spring, winter and autumn load profiles respectively. The proposed TPSD model and EUP also achieved the shifting of morning and evening peak demand times from their usual times in traditional load profiles to traditional off-peak times. Also, the proposed TPSD technique does not only produce a reduced peak demand, but also resulted in lower peak-to-peak difference as shown in Fig. 7. This will further lead to lower capital cost to incur peaker plants by the utility provider, more financial savings for the consumers and better environmental safety. Energy savings, Em_s in terms of morning peak demands, *PDm* is given as:

$$Em_s = PDm_{ND} - PDm_{TPSD} \quad (2)$$

Where, PDm_{ND} is morning peak demand with normal devices and PDm_{TPSD} is morning peak demand with TPSDs included load. While Energy savings, Ee_s in terms of evening peak demands, *PDe* is given as:

$$Ee_s = PDe_{ND} - PDe_{TPSD} \quad (3)$$

Where, PDe_{ND} is the evening peak demand with normal devices and PDe_{TPSD} is evening peak demand with TPSDs included load.

The peak-to-peak differences for TPSD LP model are 8.5 KWh, 6.0 KWh, 16.5 KWh and 11.5 KWh compared to 194 KWh, 172.5 KWh, 289.5 KWh and 213.5 KWh for ND LP in summer, spring, winter and autumn seasons respectively. This is a lot of savings indeed as shown in Fig. 7.

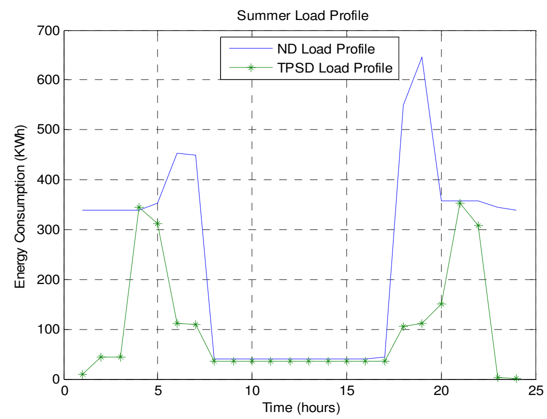

Fig. 3. Summer Load Profiles for Normal Devices (ND) and Time-Programmed Smart Devices (TPSD)

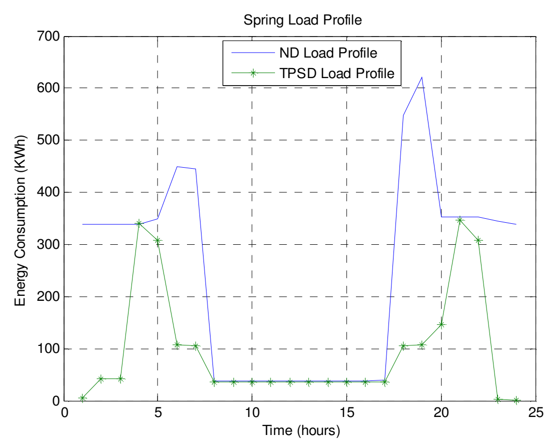

Fig. 4. Spring Load Profiles for Normal Devices (ND) and Time-Programmed Smart Devices (TPSD)

A summary of the morning and evening peaks for the load profiles of the Microgrid using normal devices (ND) load and TPSD refrigerators and heaters included load is shown in Table II.

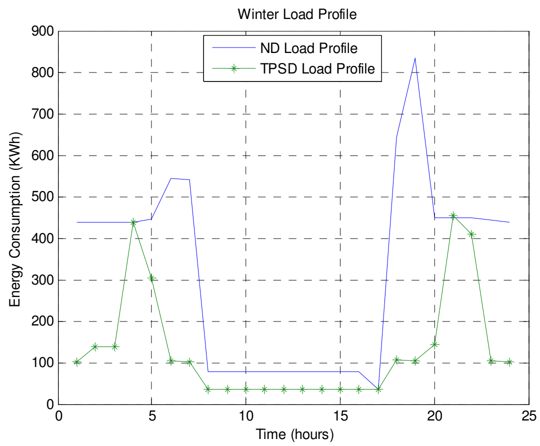

Fig. 5. Winter Load Profiles for Normal Devices (ND) and Time-Programmed Smart Devices (TPSD)

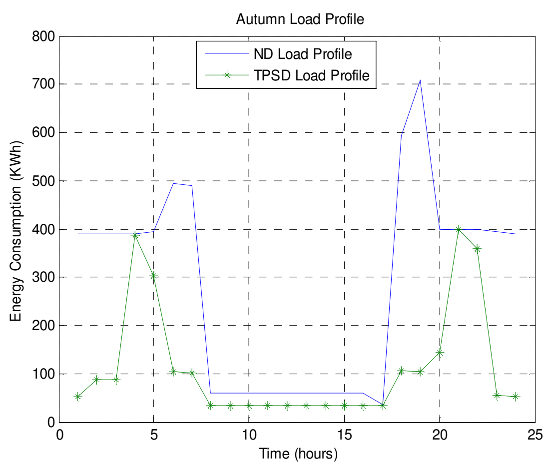

Fig. 6. Autumn Load Profiles for Normal Devices (ND) and Time-Programmed Smart Devices (TPSD)

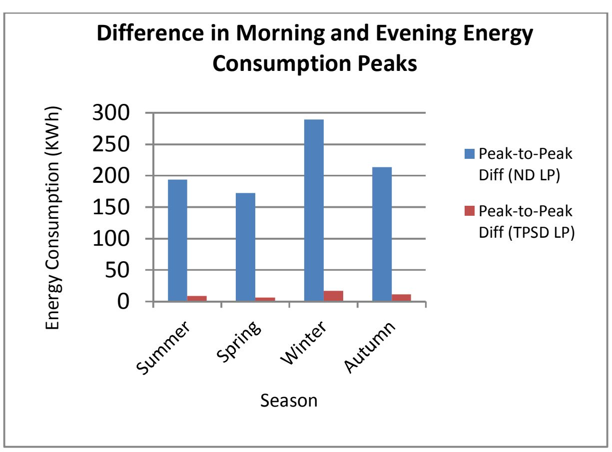

Fig. 7. Difference in Morning and Evening Energy Demand Peaks

TABLE II. SUMMARY OF MORNING AND EVENING ELECTRICITY PEAK DEMANDS

Season	**Morning peak (KWh)**		**Evening peak (KWh)**	
	PDm_{ND}	PDm_{TPSD}	PDe_{ND}	PDe_{TPSD}
Summer	452.5	345.0	646.5	353.5
Spring	448.5	341.0	621.0	347.0
Winter	544.5	437.0	834.0	453.5
Autumn	494.5	387.0	708.0	398.5

If the households were to have different sets of appliances, the results wouldn't be too significantly different as long as the above model by extension is applied to determine the devices' working states (on-state and off-state) periods. The little differences may be just due to the power rating of the appliance, quantity of the appliance in the house and the time that the appliance is in on-state. The consumer must know if they are shiftable or non-shiftable loads and also have a good knowledge of the device working principle so as to rightly inform the EUP to be set for the appliances. Then, the shiftable loads will be programmed for off-state at peak times and on-state at off-peak times without jeopardising consumer's comfort.

The introduction of the time-of-use (TOU) tariff in the DSM aspect of smart grid indicates that consumers pay more for electricity at peak times than off-peak time. Therefore, since the consumers in this model will be consuming more electricity at off-peak times than at peak times (as seen in Figs. 3, 4, 5 and 6), the monthly electricity bill of the consumers will be significantly reduced and they can feel the change in their pockets.

This proposed method would give room for the energy valley in the TPSD load profile to be used by small businesses (such as hair salons, video and game centres, computer centres/cafe, groceries shops etc) that will spring up in the local municipality as illustrated in Fig. 8.

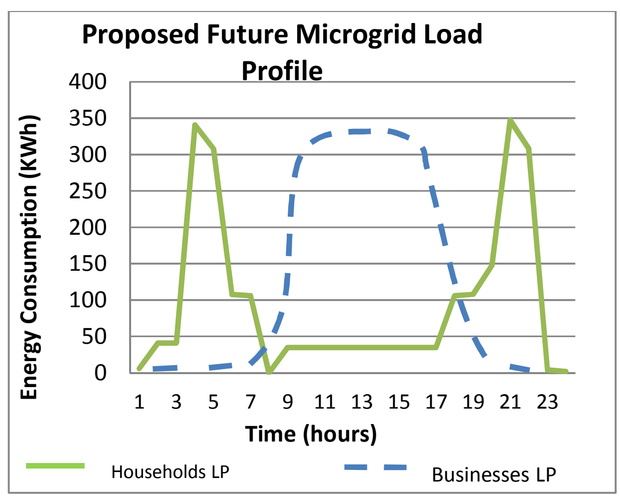

Fig. 8. Proposed Future Microgrid Load Profiles for TPSD Households and Small-scale Businesses

Co-operation from the home owners is expected to be positive towards these devices due to the economic effect it would have on them. Future work includes carrying out these simulations with real life data from a microgrid to prove the reliability of the proposed method.

V. CONCLUSION

The proposed TPSD model in this paper is for peak demand reduction for rural Microgrids. It would be easier to implement, operate and control for rural dwellers that may have more challenges in controlling wireless or wired communications smart homes. The TPSD refrigerator and heaters wouldn't be much costlier than the normal electronic devices since it only involves the little additional cost of the timing control of the ON/OFF working states of the device. The little initial extra cost for purchasing such a device will be gained back in energy and financial savings for the consumers over a few months. The design is also reliable because the user does not have to go and set the time every day as the TPSDs respond automatically to the timing instructions already set by the user. The timing can also be changed if so desired by the customer. Also, this work has shown the importance of knowing a device working principle before programming its usage for financial and energy savings.

Also, the electricity utility (Microgrid) provider would have lesser cost in incurring high peaker plants and the financial and environmental effects of peaker plants would be eliminated from the consumers and the environment.

These types of devices (TPSDs) are not system specific as many DSM models are, but can apply also to consumers in both rural and urban communities; whether connected to the grid or not. Also when the small businesses start up in the community, they will fit into the valley in the TPSD load profile resulting in a near-table load profile. For a rural area like uMhlabuyalingana Local Municipality with a village head, whom the people listens to, the timing (or EUP) advice can be easily passed through him to other residents in the municipality with the benefit of such device, usage and EUP rightly communicated. For an urban application, all the different media means (print, electronics and social) can be explored for effective awareness and communication with the consumers. Since TPSDs will contribute to a sustainable Microgrid, sustainable development of the rural area will also be enhanced. Hence, a better socio-economic life is accessed by ULM residents.

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