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Optimization for energy management in smart grid

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Abstract

Smart Grid is combining the electrical power grid with modern information and communication technologies (ICT). Smart grid is one of the highly uncertain and non-deterministic large scale system. Two-way communication, consumer participation, renewable energies and storage are important features of the smart grid. In the existing power grid, the meter is an end point at consumer for any home/building which gives the information of energy consumption for any utility company. Advances in Internet of Things (IoT) which include wireless sensor networks, machine to machine technologies facilitate the fine grained level of sensing/monitoring and control till the appliance level. In the presence of smart appliances and smart meters, lot of real time data is available which give rise to new optimization problems in this space. The model follows the flow of sensors deployment, sense, communicate the sensor data, collaborate and optimize with the real time data. Optimizations in smart grids are difficult because of uncertainty in the supply and fluctuating demand especially due to penetration of distributed renewable energy sources and active participation from consumers. Even though efforts are on to increase generation capacity, there is significant potential and need to improve the existing power grid infrastructure by utilizing intelligent grid state aware optimal generation, distribution, and loads. Each country has a smart grid vision and the priorities change based on the needs of the country. But managing peak power, integration of renewable energy and demand response programs are few of the common aspects in smart grid vision statements of the countries including developing countries such as India and developed countries such as United Kingdom (UK) and United States of America (USA).

Keywords: Renewable energy, optimal generation, Smart grid (SG) etc.

1. Introductions

For sustainability, Carbon dioxide (CO_2) emissions play a crucial role in atmosphere.350 parts per million (ppm) is the upper safety limit for CO_2 and this number is rising by about 2 ppm every year. Four-fifths of the emissions allowed as per 450 scenario permissible by 2035 are already generated. Power plants, buildings and factories contribute significant portion of it. This forces not to have any additional power plants, factories and other infrastructure unless they are based on renewable and zero-carbon. This raises a flag for sustainable solutions and actions to be taken in the recent years.

2. Energy management (EM)

It is the process of monitoring, controlling and conserving energy in a building or city for judicious and effective use of energy. This includes energy efficiency and demand response activities. Demand Response (DR) is to manage consumer consumption of electricity in response to supply conditions and the demand for the electricity. DR signal indicates a price or a request to modify electricity consumption with peak shifting or valley filling for a limited time period. Energy management models are to be run at each time slot as coordinated activities between utility company and consumers. The techniques which are used to control the energy consumption at the consumer side can be termed as Demand Side Management (DSM). These programs are proposed to control the energy consumption pattern of the consumers with an aim to reduce the peak to average ratio. DR is part of the Demand side management. DSM techniques provide many measures to reduce energy consumption that helps to manage the demand. DSM techniques include direct load control, time of use pricing, frequency regulation, demand bidding, smart metering and appliances. Demand is reduced in the form of load shifting, peak clipping/shaving. Load Shifting involves shifting loads from peak to off-peak hours. This may not change the total energy consumption but reduce the peak load. Peak clipping/shaving also refers to the reduction of energy usage during peak hours but this contributes to reduction in both the peak demand and total energy consumption.

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Valley filling encourages additional energy usage during periods of low system demand/off-peak hours. These strategies are used to flatten the demand over the day or reduce the peak to average ratio.

Matching demand with supply is still a challenge at different levels in the smart grid with sustainability considerations and tremendous increase of demand day by day from consumers. The energy management programs can be more interactive and automatic with near real time response. The utilities can communicate with the consumers in real time using smart meters and consumers can act as prosumers (producers and consumers) using bidirectional communication in the smart grid. The energy conservation is not effective without the participation of consumers. There is an increasing level of awareness in the consumers for the sustainability activities. So, there is a need for solutions that do energy management keeping the individual priorities of consumers and automatically respond to the DR signals from the utility company.

3. Need

- Matching demand with supply from appliance to grid level with fine grained level of monitoring/sensing information.
- Techniques to handle large scale multi objective optimization problems both at utility and consumers by considering price and demand uncertainty.
- Methodologies to make energy management programs more interactive and automatic in smart grid.

The challenges are multi-objective large scale nonlinear optimization problems with real power, reactive power, cost and profit. The summary of identified gaps from literature includes millions of generation and consumption entities, matching of demand with supply from appliance to grid level with finer level of monitoring and sensing information, trade-offs between utility revenue vs. consumer cost, consumer energy vs. comfort, local vs. global energy, consideration of uncertainty in price and demand and limited system observability and controllability. Handling uncertainty is one way of risk assessment but they are not exactly the same. We are unaware of any existing near real time optimal algorithms in literature which address all these issues. We propose hierarchical way of solving the problem to achieve near real time requirements of the problem.

4. Power Balancing

The proposed model objective is power balancing to satisfy demand. In our work, power is taken as a single commodity linear flow and quality of the power is assumed to be same irrespective of their generation source. We consider only real power in our model. Our approach is a decoupled optimization between utility and consumers. To achieve this, the goals are to minimize the energy bill to consumers with energy-comfort trade off in near real time, maximize profit for utility, increase utilization of renewable energy and to increase consumer participation in EM activities in long term. Large scale system is considered with fine grain modeling and limited system observability and controllability. Not many proposals are available in literature which can give mutual benefit for consumers and utility companies. The problem blows up into non-convex optimization problem if we start adding all required constraints of appliances, price, demand and emission. So, we use domain knowledge and convexification techniques while formulating the problem.

5. Appliances

Appliances loading the grid, are modeled at a detailed level including constraints on simultaneous operation of appliances. Appliances such as washing machine and EV chargers cannot be run together, else the peak power becomes very high; computers and routers typically have to be run together etc. Here we are referring to making choices for each appliance to be either fully or partially ON in a time slot, possibly depending on other appliances. The correlations between the operations of appliances are specified by the consumers in a general truth table form. We require an algorithm called as general appliance constraint specification algorithm which gives the capability to specify the constraints at an appliance level into our model. In general appliance constraint specification algorithm, we use the Sum of Products (SoP) expression form to specify correlations from the truth table. SoP is canonical form that is a disjunction (OR) of min-terms. A min-term is a logical expression of variables where each variable appears only once as direct/uncomplemented or complemented along with conjunction operators.

Input

Truth table with validity/invalidity specified

Steps

1. Write the valid combinations from truth table in SoP form.
2. Use Karnaugh-Map (K-Map) [87] / Quine-McCluskey algorithm [88, 89] to mini- mize the Boolean functions.
3. Represent the minimized Boolean SoP in linear form:

n_p = number of product terms in the minimized Boolean SoP form

m_l = number of Boolean variables in the term

z_q represents direct form (value 1 in truth table) and $(1 - z_q)$ represents its complement. It is a binary variable corresponding to scheduling vector x^t

BM is a large constant number as in Big-M method [90].

6. Criteria for fairness

A deal between a consumers and utility is considered fair if it meets the following criteria. They are based on the real world experience.

- Criterion-1 (Fixed charges for must run appliances) indicates that the price paid by a given consumer to satisfy the must run

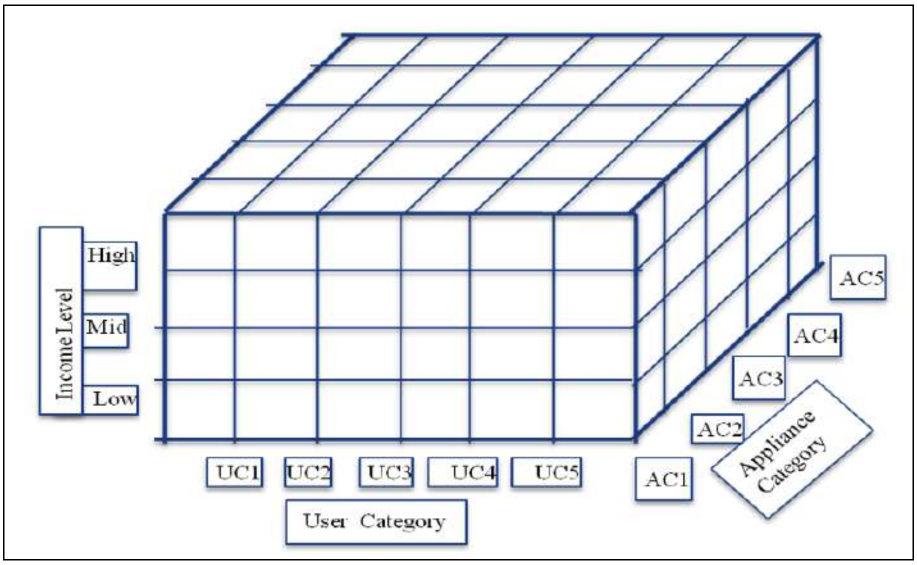

Fig 1: Multi-dimensional differential pricing

Services (base load) should be time-invariant. That is, in case a residential consumer who participates in a EM-program fails to comply with stated terms and conditions of the program, he should be penalized only for the energy consumption that is over and above the amount required to satisfy his base load (e.g. lighting) requirements. Must run services usage must always be charged at a fixed rate.

- Criterion-2 (Multi-dimensional differential pricing) implies that the pricing is based on the type of user, type of appliance used and the ability of consumers to pay. Here are the three dimensions (categories):
- User Category: This refers to the type of consumer, such as, residential, commercial, industrial etc. In general, these will be referred to as User Category1 (UC1), User Category2 (UC2) etc.
- Appliance Category: This refers to the type of appliance, such as, “must run” (lighting for example), “optional” (heater, AC, washing machine for example) etc. In general, these will be referred to as Appliance Category1 (AC1), Appliance Category2 (AC2) etc. Note that the type of appliance can be identified by building intelligence in the infrastructure or by using smart appliances.
- Income Level: This refers to the ability of consumers to pay their electricity bill. For example, the income levels could be low, mid, high etc.

Differential pricing based on multi-dimensional categorization needs to be attractive enough during peak period to ensure wider participation of consumers. Multi-dimensional categorization that may form the basis of energy pricing.

Having defined fairness in terms of fixed charges for “must run” appliances and differential pricing based on multiple dimensions (user category, appliance category and income level), let us explore, if there exists any pricing scheme that satisfies the above- defined fairness criteria. Specifically, flat rate scheme charges fixed rate to users regardless of type of appliance used and the ability of users to pay. However, it takes into account the type of user (residential users and industrial users are charged differently). Hence it satisfies the criterion of fixed charges while not fully satisfying the criterion of multi-dimensional differential pricing. In case of RTP, there is no fixed base price as the consumers are charged dynamic price. Therefore, even “must run” appliance usage is charged at different rates at different time slots based on market price. The consumers who participate in EM programs should be given an incentive by charging them a lower price for meeting their “optional” (AC2) needs compared to those who do not participate in the DR programs. Here b stands for “base” or “must run” or AC1 category; “o” stands for “optional” or AC2 category. One assumption is that the supply is sufficient to meet the “must run” (AC1) needs of all consumers belonging to different categories at all times including the peak hours.

7. Conclusion

A smart grid in itself is no doubt an innovation and successful upgradation over its precursors, i.e the conventional grids. But smart grids with renewable energy prove to be even better in terms of efficiency, design and operation cost, resource utilization, customer integrity etc. The blessing of this renewable energies is that when they are coupled with smart microgrids, there is very less, in fact practically no energy loss. This is due to the fact that if under some load condition, there happens to be excess energy that cannot be exploited at that point of time, they can be easily stored for future use. This not only reduces loss, but also is critical for times when demand is high, but power supply is low. The undeniable advantage of renewable energies as we have observed is their abundance and ease of utilization. Although each source of renewable energy has its own, limitations yet appropriate methodologies can be devised to do away with these constraints. One area that definitely needs more attention is use of a particular renewable energy source in some geographical area where that energy is not abundant, or is nil. This can be actuated by importing and exporting the surplus power in one microgrid to bulk power grids of distant geographical areas. Renewable energies are inexhaustible and can be utilized in smart power grids endlessly. But there still remains one drawback in the existing integration method. It has been proven by research workers over the world that a single renewable energy source utilized at a time in the smart grid does not render full utilization of the resource because a part of it will be lost in the process, regardless of how advanced the grid is. So for further upgradation of the existing smart renewable energy driven grids, two or more energy source needs to be combined to augment the functioning of each individual energy source. This naturally paves way for growth of the next generation smart grid renewable energy technology.

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