Smart-Grid Based Real-Time Load Management Methodology for Power Deficient Systems

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***Abstract*—We are proposing a load shedding system for future smart cities which can shed load on priority basis. The proposed methodology has the potential to conserve the available energy in an efficient manner and making system immune to intense blackouts and brownouts. The objective is to keep end-user with more reliable and increased power availability and hence keeping higher priority load connected. Load is categorized in flexible manner to provide freedom of priority demarcation. The proposed system consists of two basic controllers: Central Load Manager (CLM) and Local Load Manager (LLM). CLM through sensor receives the real time load demand data, check for its value against threshold power and takes decision accordingly. Control signals are then transmitted to local load manager using TCP/IP technology which acts to shed the load and keeps condition of load (data) in the memory. An extensive simulation environment is developed in SIMULINK-MATLAB and tested under diverse conditions to analyze system's performance and practicality.**

***Index Terms*—smart grid, load management, load shedding, intelligent load shedding (ILS), power system, smart energy city**

I. INTRODUCTION

The planet is progressively marching towards a serious Electrical Energy (EE) crisis, owing to an escalating desire of EE becoming greater than its supply. Demand of electricity is increasing with continuous increase in human population, economic growth, infrastructure development and automation. For in- stance, world's EE production in 1985 was 10,000TWH where as in 2011 it crossed the line of 20,000TWH [1]. In last 25 years consumption of EE got doubled. Moreover, its demand is increasing at much higher rate than rate of increase in generation causing major mismatch in demand and supply.

Shortage of supply, aging infrastructure and inefficient management of available power is causing intense collapse in power availability, which is major hindrance in the economic growth of developing countries. One worst example is Pakistan, a south Asian country where not only domestic users but also industries are suffering from extreme Load Shedding (LS) [2]. Not only developing countries but also developed countries are facing grave energy problems. In the U.S. alone, outages and power quality issues are estimated to cost American business on average more than 100 billion dollar each year [3].

In power system when demand of electrical power tends to get greater than the generation then the traditional solution is LS [4]. However, LS can also be done to disengage faulted portion of system [5] and for improving load factor to keep the operation running smoothly [6].

One solution is to add additional bulk power in the system. However, it requires huge capital investment and long time for completion. Commonly, LS is adopted in developing countries which is an unwanted solution to power shortage issue but it needs to be done in order to avoid disruptions [7]. The need is to smartly utilize available EE and for this purpose power system needs to be smart enough to provide shedding process intelligently. These intelligent energy management systems [8] are being developed under the term Smart Grid and stake holders are betting big on it.

Models of energy management systems for buildings [9], smart homes and industrial facilities [10] have been developed. However, concept of smart energy city (SEC) has yet to be developed, addressing macro-energy management issues faced by emerging power utilities.

SEC would present more realistic approach towards current and future energy issues including shortage of power and its compensation. The essence of SEC is to harness energy from most economical energy sources and to deliver it using most reliable methods with greater control. SEC's energy management systems would provide control not only over transmission end but also on the distribution end to keep demand well under available sources.

To develop energy efficient architectures as basic building blocks of SEC, precise and fast acting sensors, collection of large amount of data through advanced metering infrastructure (AMI) [11], data handling techniques, solid state control systems and self-healing power systems [12] are needed to be deployed in existing cities. SEC has the potential to pay-off the initial investment in replacing existing infrastructure. It can provide more reliability to end-user as well as utility with intelligent energy management systems.

Our goal is to present load management methodology for SEC that can utilize the available EE resources in such a way that end-user get maximum benefit. This

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system will also improve the reliability of the power system due to built-in self-test facility. This paper presents the methodology of Intelligent Load Shedding (ILS) for smart city, inherited with quad-priority categorization of load and bi-directional TCP/IP based communication and control.

The overall paper consists of following sections: The Section II overviews the related work in the area of Smart Grid. The Section III discusses the proposed methodology. Section IV explains the experimental setup. Section V details the implementation results. Section VI concludes the paper.

II. Related Work

This section summarizes the existing power management techniques. The overall work is categorized into two sub-sections: (i) conventional techniques and (ii) modern techniques.

A. Conventional Techniques

Pre-Scheduled LS techniques to meet demand and supply imbalance is used in many developing countries. Expected error in load forecasting, manual control, excessive LS and complete feeder disconnection make this method nonviable for power systems. Automated under frequency LS methods are based on the frequency drop or rate of frequency deviation [13], [14]. This technique is relatively simple to execute but time delays make its response considerably slow. Time delays are kept in effective range to avoid nuisance trips causing unnecessary LS. Additionally it may result in tripping of distributed generation source [15].

Another advanced PLC based technique being automated and technologically equipped provides many advantages over pre-scheduled and frequency based technique. It provides fast response to irregularities or increasing power consumption. However, it has its own short comings including excessive load shedding during transient disturbances, absence of dual way communication ability and predefined non flexible power limitations [16].

B. Modern Techniques

Modern techniques are relying on utilization of smart grid technology. Its conceptual model presented by National Institute of Standards and Technology provides a high-level framework. It has sub-divided the overall domain into seven fields: Bulk Generation, Transmission, Distribution, Customers, Operations, Markets and Service Providers [17]. It shows all the communications and energy/electricity flows connecting each domain and how they are interrelated [18].

We are more concerned in distribution domain, where electricity is given to the end-user. The distribution network connects the AMI and all intelligent field devices, managing and controlling them through a two-way communications network. It may also connect to energy storage facilities [19] and alternative distributed energy sources [20].

Recent research in this field is mostly focused on intelligent load management systems including demand response techniques [21], [22] for reshaping demand profile. However, there is very little research done on load categorization/priority based ILS systems. It’s an efficient technique which can effectively integrate in future smart cities.

TCP/IP based intelligent load management system is presented in [23], where load is divided into two main categories: High Priority (HP) and Low Priority (LP). Server-client strategy is utilized in which server acting as primary controller monitors and takes decisions whereas clients at receiving ends acting as slaves impose that decision to respective load. Drawbacks include limited categorization of loads and decision making criteria in which defined limits of power are used to shed the load which accounts for load to remain constant or else it will conduct either excessive or malicious shedding.

Moreover ILS in case of faults [24] or islanding [25] is done on the priority basis keeping the supply intact to critical loads and to isolate the faulted portion in power system. But domain of this scheme is limited to occurrence of faults or formation of an island where load exceeds the power generation capacity. It ignores all the other situations of power demand and supply imbalance.

Sector confined architectures have also been presented like Intelligent Load management systems for Industrial facilities, Residential colonies [26] and buildings [27] that are managed locally however power delivery is not a local subject so these systems won’t be affective. As Power transmission and distribution are managed centrally therefore central management units are required for an affective operation.

Since there is not sufficient work done to address the needs of future power hungry cities. The need is to address practical solutions that are not focused to a single compound or a specific user. We have to simultaneously address domestic as well-as commercial end-users. Consequently we are proposing a novel and more generic approach in the next section.

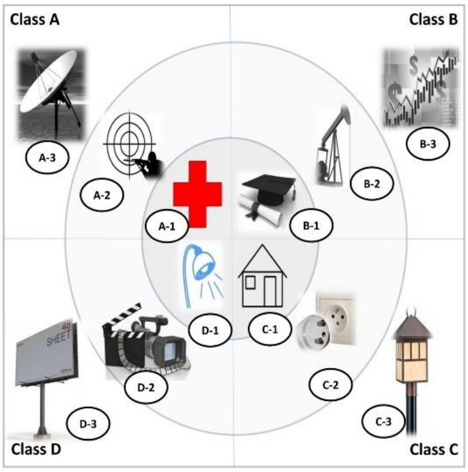
III. Methodology

Due to inherent drawbacks of existing/conventional method, an ILS system is necessary to shed minimum amount of load and to maintain system’s stability. One possible approach is to shed load according to priority with an online monitoring system that is able to coherently acquire real-time system data. This system is helpful in designing future smart energy cities.

The key idea is to prioritize the load and shed it accordingly. A sample load division of a particular city/area is shown in Fig. 1, where load is divided into four classes according to the importance. Furthermore, each class is divided into sub-categories. It is a generic approach and design shown in figure 1 is a possible representation and many other subsets can be made according to other constraints.

The overall load is categorized into following four classes:

(a) Class A
(b) Class B
(c) Class C
(d) Class D



#	Utilization
A-1	Hospital
A-2	Defense
A-3	Communication
B-1	Education
B-2	Industry
B-3	Commerce
C-1	Indoor load
C-2	Sockets
C-3	Garden lights
D-1	Street-lights
D-2	Entertainment
D-3	Hoarding

Figure 1. Load categorization

The load will shed according to the given importance. According to Fig. 1 the most important in any one of class is nearest to centre point and importance of load decreases if moving away from the centre point. If demand is increasing and reaches to a set threshold level then load will start to trip from class D towards A.

Class A: It is the most critical and important load class, and hence should not be disconnected. For example, hospitals, defence installations, telephony. To ensure the availability of power supply, the reserve capacity is always at standby. The baseline generation is set w.r.t. class A (1.5×*Class A*). For instance, if class A is 1000MW then reserve capacity must be equal to the 1500MW. Consequently, if generation does not meet the demand of load or demand curve reach the baseline then system should disconnect loads according to set priority, alarm must be declaring the emergency situation.

Class B: It is an important load class however its disconnection doesn't result in catastrophic failure. For example, educational, industrial and financial sectors. In general, we can adjust the industrial and financial section need by adjusting the per unit price w.r.t. peak hours. Hence decreasing the peak loads.

Class C: It consists of domestic load, which is further categorized into three sub-classes: garden lights, sockets and indoor load. Garden lights will trip on increase the load then sockets and finally indoor load will be disconnected.

Class D: It consists of un-important and non-critical type of load. They are only turned on when excess of bulk generation is available. It consists of street lights, entertainment centres and hoardings. Hoardings being the least important part of class D stands first while shedding the load followed by entertainment and street lights. Class D is least important category of load which is disconnected first in case of increased load or decreased generation.

A. *Working*

The basic model of the proposed ILS is shown in the Fig. 2. Two supply lines (including main and standby supplies) are connected to overcome catastrophic failures.

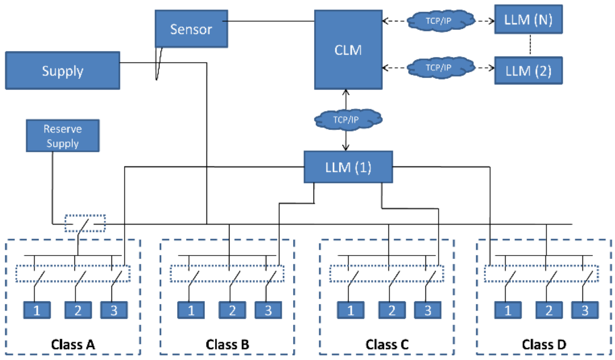


Figure 2. Block diagram of the overall system

All high-level control decisions are taken by CLM unit based on inputs from sensors. CLM will communicate with LLM over bi-directional TCP/IP links. CLM transmit respective data to concerned LLM (e.g. tripping certain load).

We have implemented two models: step-wise (SW) and micro-step-wise (MSW) load shedding.

1) SW sheds the whole class when bulk generation becomes lower than consumption.
2) MSW divides the each class into sub-classes (see Fig. 1) and shed on micro-priority.

MSW give more control and maximum facilitation to the end-user. However its CLM and LLM management is more complex. For example: in MSW when load is increasing then first CLM will communicate with LLM to disconnect D-3 then D-2 and at-last D-3, if needed. Further shedding of class C will be done in same fashion (C-3, C-2, C-1).

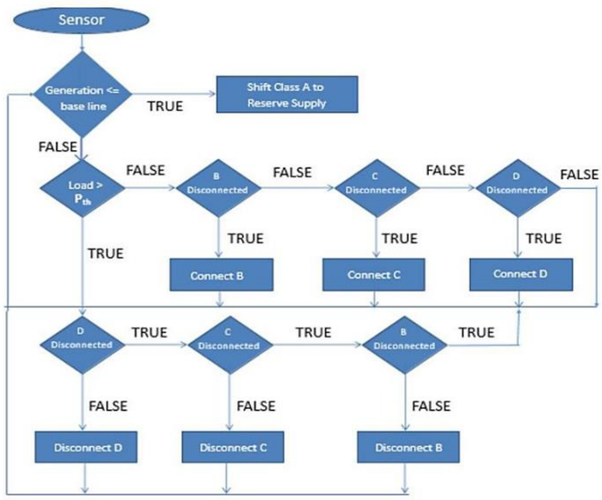


Figure 3. Flow sheet diagram representing working of central load management

Motivational example: The flow of CLM represented in Fig. 3 is explained by taking load curve shown in Fig. 4. Load curve is constructed in order to clarify basic decision making methodology and sequence of system.

Classes are defined by assigning equal amount of load moreover each class is further divided in equal steps showing sub categorization presented in Fig. 1. Example shows gradual increase of load in respective order till class D's load D-3, point of maximum load. In the next half of load curve, shedding sequence is shown by considering gradual decrease in generation which moves point of threshold power (P_{th}) downwards. Sensing this decrease system keeps on shedding load in defined sequence, priority wise till class B's load B-1. Below this point lies baseline of system showing critical load as class A. This load should remain connected with power supply so further decrease is generation is compensated by reserve supply provided for class A load. Fig. 4 also depicts clear difference of categorization between SW and MSW shedding sequence.

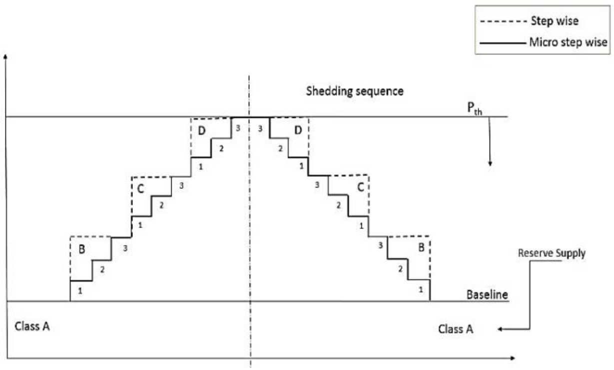


Figure 4. Sample demand curve

IV. Experimental Setup

An extensive system is simulated to quantify the performance of proposed model under diverse conditions. In order to implement an ILS system it is necessary to mention major features and data needed. Our simulation environment must have following salient features:

1) Real-Time monitoring of demand and generation to be able to act dynamically with an ability to record the value of disconnected load in order keep checking for a window to reconnect it.

2) Make fast and precise decisions on LS priorities, based on real-time loading status for minimum amount of shedding in order to completely utilize generated power and provide satisfactory electrical availability to consumers.

3) Able to support two way data communication in order to keep the updated record of load ends status.

4) ILS system would have a dynamic knowledge base with real time values of power generation capacity, threshold of allowable power consumption and category of load.

Simulation environment is developed in MATLAB/SIMULINK (see Fig. 5) to observe the effectiveness of the proposed methodology. Decision making is at CLM and execution, data handling is done by LLM. Class B load is kept constant all-time according to its nature. Class A with reserve supply is understood to continue working under all conditions. P_{th} is kept to be 40 MW as only resistive load is considered for analysis of active power taking power factor as 1. However in case of reactive power (or inductive load), the experimental setup still remain valid by calculating P_{th} dynamically:

$$P\_max = S \cos\theta$$

$$P\_th = P\_max - \chi P\_max$$

where,
P_max = maximum deliverable active power P_th = threshold of active power
χ = suitable tolerance in percentage

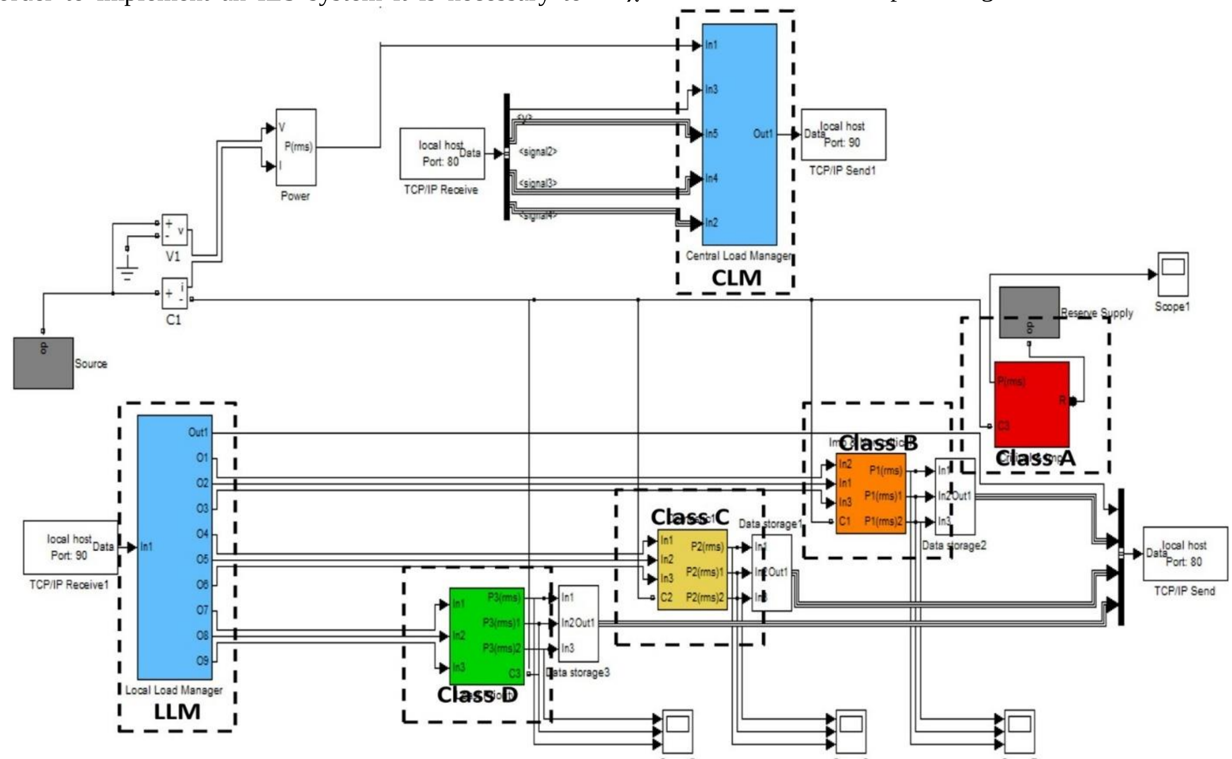


Figure 5. Implemented model in SIMULINK

Controllers are managing load according to set priority.

CLM monitors the bulk input and communicates with the LLM over TCP/IP channel. Channel provides wide spread networking spanning over whole electrical network. Two way communications between LLM and CLM, keep central manager updated with all necessary information. Electrical loads are lumped as subsystems on priority basis being controlled by LLM using smart switches.

The respective load priorities are defined within command matrix, shown in Fig. 6. CLM is fed with the initial matrix structure depending on the load categories and number of LLMs connected in the network. It is programmed to monitor the available power's threshold while keeping the track of power consumption in real time. It processes the matrix according to implemented algorithm and transmits the output matrix using TCP/IP based communication network. LLM instructs the load controllers to connect/disconnect the load and saves the value of power being consumed by load before disconnection in data storage block. After processing, LLM generates updated matrix containing load controllers (ON/OFF conditions) and transmit it along with the value stored in data storage block to CLM for further processing. This cycle continues until load is brought into allowable range under the threshold.

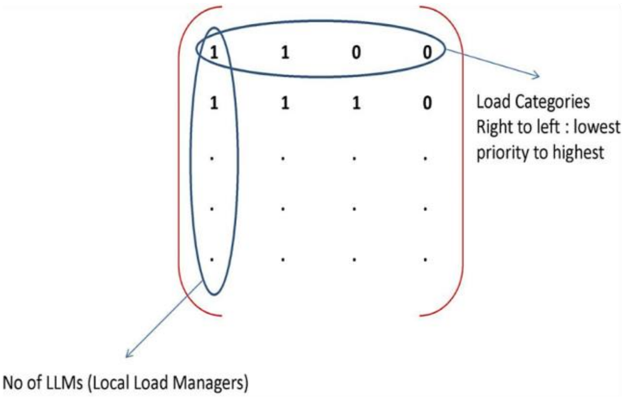


Figure 6. Command Matrix

When load decreases in the OFF peak regions, forcefully disconnected load needs to be reconnected. While CLM keeps on checking for the power window below threshold equal to the data storage block. It reconnects the disconnected load accordingly and algorithm follows the specified sequence again for disconnection.

A. Benchmarks

Simulation is done on the typical data of a small utility for typical seasonal variation throughout the year. Power demand variation is divided into three broader categories.

1) Spring/Fall depicting moderate power demand and average peak value (shown in Fig. 7);
2) Summer with high power demand and intense peak (shown in Fig. 8);
3) Winter with mild power demand and comparatively better load factor (shown in Fig. 9).

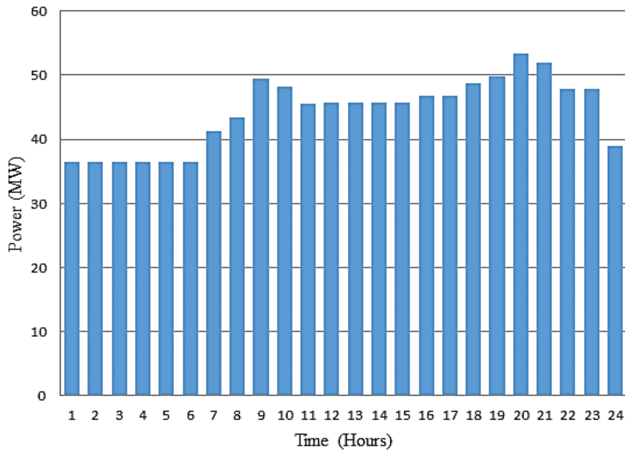


Figure 7. Demand graph - 1 (Spring/Fall)

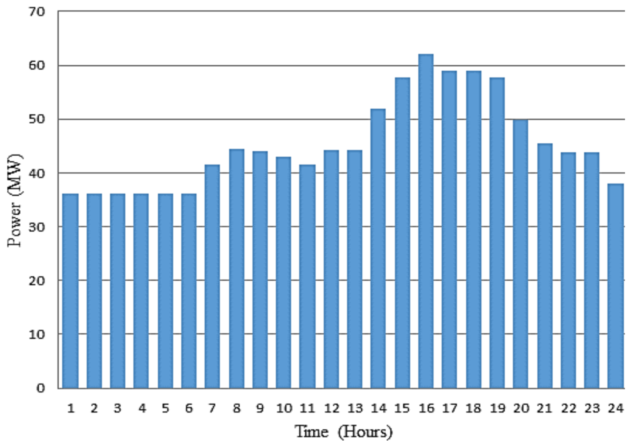


Figure 8. Demand graph - 2 (summer)

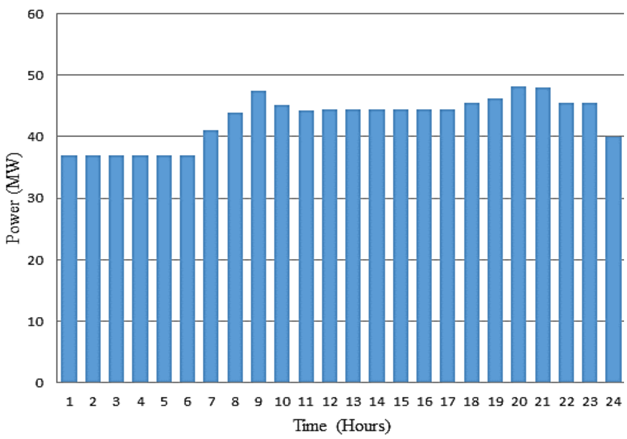


Figure 9. Demand graph - 3 (winter)

V. RESULTS

Both techniques discussed are tested on the data shown in IV-A. The results are compared to show the advantages and usability of each.

Fig. 10 shows load curve for Spring/Fall and load curves obtained after the implementation of ILS. From (1-2) demand resides well under threshold value with no shedding required. Load tends to increase the P_{th} value from (2) onwards where actively monitoring ILS system starts shedding load with ascending priority. For comparison, Traditional LS depicts unreliable flat behaviour by shedding whole chunk without considering any difference in load type causing unreasonable LS further more SW shedding shows excessive load shedding of about 15MW form (3-5). Whereas improved MSW shedding depicts no excessive dis-burdening (3-4) and of about 7MW even in peak conditions (4-5).

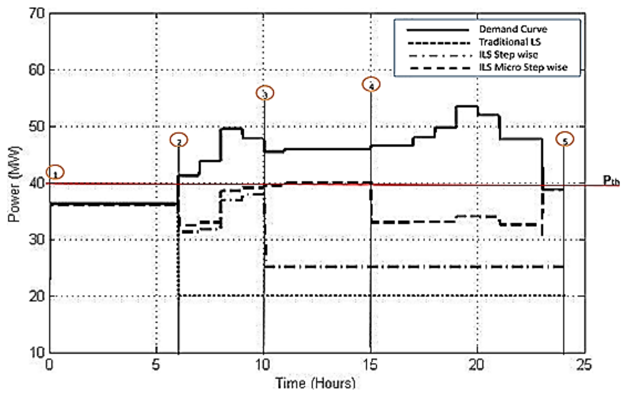


Figure 10. Load curves (spring-fall)

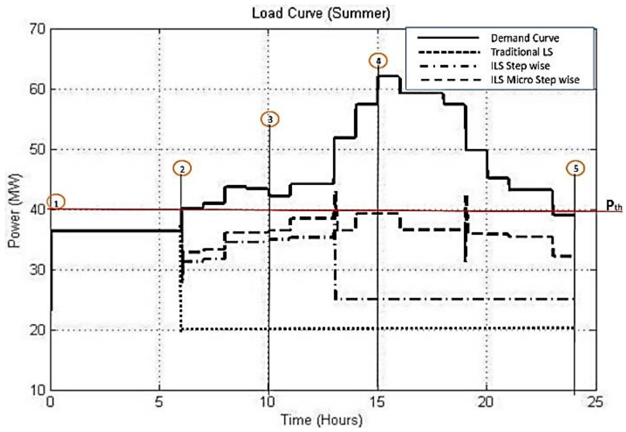


Figure 11. Load curves (summer)

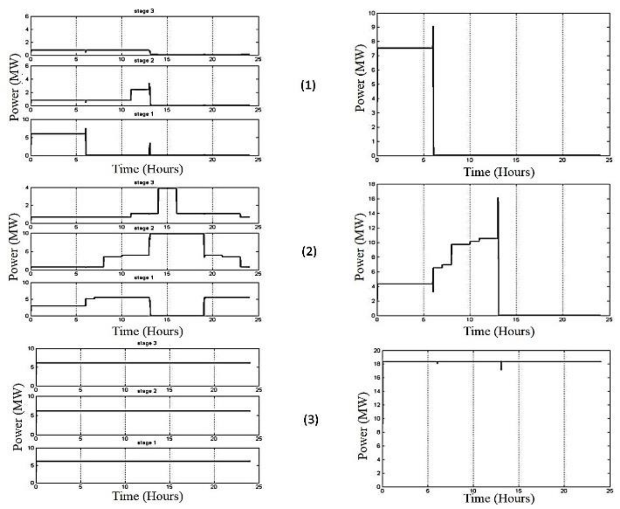


Figure 12. 1-class D load, 2-class C load, 3-class B load, comparison of SW and MSW shedding

Fig. 11 shows load curve for summer with high demand.

Under these intense conditions keeping the electric supply available for high priority load becomes challenging for energy management systems. However results show that proposed model accomplishes this task in predicted manner. Fig. 12 depicts comparison of ILS by SW and MSW shedding for class D, class C and class B loads respectively. From (2-3) MSW model trips class D load partially whereas SW method trips it completely causing excessive load shedding. Further (3-4) demand reaches maximum and even at peak (4) MSW method only sheds partially till class C load, providing full compensation to exceeding demand. Results show that even in extreme conditions demand supply imbalance is compensated by partial or complete load shedding of class D, C loads keeping Class B, A loads seamlessly intact. Additionally issue of excessive load shedding in traditional LS and SW method is addressed well by MSW method.

Fig. 13 shows load curve for winter with comparatively better load factor. Simulation model exhibits ability to smartly handle power demand of various intensities.

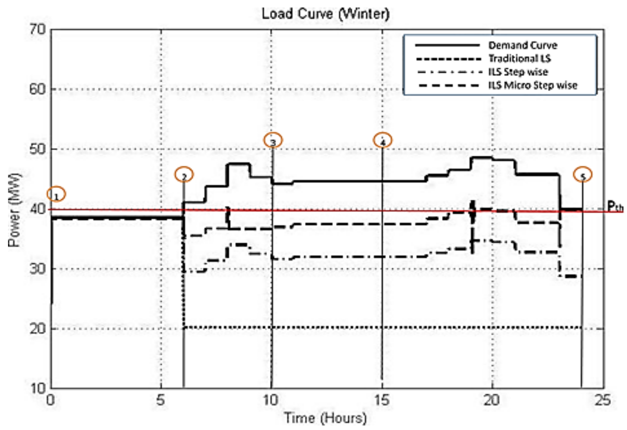


Figure 13. Load curves (winter)

VI. Conclusion

This paper is focused on smart utilization of available energy resources for emerging smart cities. We elaborated the importance of forced power management to facilitate the end user, even without adding extra bulk generation. Goal was to keep the load under specified power threshold while keeping high priority load connected.

We have elaborated two methodologies: SW and MSW load shedding for prioritized loads. MSW give more control and maximum facilitation to the end-user. However its CLM and LLM management is more complex.

The MSW shedding can be beneficial for infrastructures having great mismatch between demand and supply. It can effectively be used in future intelligent energy cities as a part of smart grids. Moreover, it can improve load factor, which will benefit power system in economic sector greatly. The obtained results are encouraging and show the effectiveness of the proposed methodology.

Scope is not limited for smart cities, even present infrastructure if modified can effectively pay-off the principal investment.

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