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Impact Analysis of Energy-Efficient Demand-Side Management in Six-Bus Systems: Replacing Lighting Loads Based on Consumer Preferences

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Abstract— One of the most important strategies for improving power utilization and lowering total energy usage in distribution systems is energy-efficient Demand Side Management (DSM). Within a substation's load profile, this study assesses the effects of swapping out incandescent lights for consumer-preferred, energy efficient substitutes like LEDs and Compact Fluorescent Lamps (CFLs). Despite certain harmonic distortion issues related to non-linear lighting loads like CFLs, DSM techniques in particular, demand response strategies have been demonstrated to lower power costs, improve power factors, but increase Total Harmonic Distortion (THD). The study evaluates system metrics, including power, THD, power factor, and energy consumption, under different load combinations using MATLAB simulations. The findings of analyzing optimal power flow (OPF) on a six-bus network and modeling a balanced three-phase system show decreases in real power demand, operational losses, and system expenses. Additionally, the economic advantages of DSM interventions are highlighted by differences in Locational Marginal Pricing (LMP) among bus nodes. Results indicate that DSM techniques greatly improve system sustainability and efficiency in power distribution networks by implementing targeted load reduction and energy-efficient lighting.

Keywords: *OPF, THD, Power quality, CFL*

1. INTRODUCTION

Energy efficiency has become a crucial area of focus in power management due to the ongoing increase in global energy consumption and the depletion of fossil fuel resources. Demand Side Management (DSM) techniques have been shown to be successful in lowering costs and conserving energy by providing incentives for customers to switch or reduce their power consumption during periods of high demand. In order to lower total power consumption and enhance system performance, DSM requires replacing traditional high-energy lighting with energy-efficient substitutes like light-emitting diodes (LEDs) or compact fluorescent lamps (CFLs) [1]. Energy consumption is decreased, operational expenses are decreased, and a more balanced and dependable power distribution network is achieved by substituting energy-efficient lights for incandescent ones [1]. According to studies, DSM techniques in distribution systems maximize power flow, guarantee voltage stability, and reduce power losses, making them a workable way to save money and energy. However, using non-linear loads, such as CFLs in place of traditional incandescent lights, results in harmonic distortions, which can alter voltage waveforms and impact power quality. Large-scale lighting changes are therefore possible for operational and financial reasons, as research shows that these power quality problems stay within allowable regulatory bounds

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[2]. This study examines the effects of switching out incandescent lighting in a substation with consumer-preferred energy-efficient substitutes, with a particular concentration on how it affects cost-effectiveness, power quality, and load flow. This study adds to the increasing amount of research that highlights the advantages of DSM in power distribution networks from an economic and environmental standpoint [3].

2. PROBLEM STATEMENTS

Compact fluorescent lamps (CFLs) and other non-linear lighting loads like LEDs have improved energy efficiency but increased harmonic distortion, particularly third-order harmonics. Harmonic pollution from these devices occurs because they draw current in a way that distorts the voltage waveform, injecting high-frequency currents that create total harmonic distortion (THD) [4-8]. This distortion can lead to increased losses, reduced equipment lifespan, and interference in electronics and transformers not designed for high harmonic levels. Studies show that CFLs can produce THD levels as high as 120% or 72% without filtering, far exceeding the limits set by power quality standards and the much lower distortion of traditional incandescent lights [9-12]. Demand Side Management (DSM) and Demand Response (DR) are being used more and more to control load demand, promote energy efficiency, and lower harmonics to enhance power quality and load profiles, particularly with non-linear loads like LEDs and CFLs. Energy-efficient lighting is encouraged by utilities and Independent Service Operators (ISOs) to improve grid efficiency, prolong equipment life, and reduce maintenance expenses. Aggregators encourage load shifts to balance grid demand and lessen peak load pressure, which aids in coordinating end-user involvement in DR schemes. To improve power quality and equipment longevity, passive or active filters are employed to reduce Total Harmonic Distortion (THD), especially at substations. DSM and DR allow for real-time modifications to optimize grid costs, while Locational Marginal Pricing (LMP) reflects supply-demand restrictions at network locations [13-17]. To provide stable and affordable power distribution, LMP promotes DR interventions during periods of high demand or congestion.

3. METHODS AND PROCEDURES

User-defined load combinations can provide an output load that is applied to a node bus in a six-bus system. Replacing the system load by a percentage reduces output consumption. The lower estimated load is utilized to generate an OPF solution for the system.

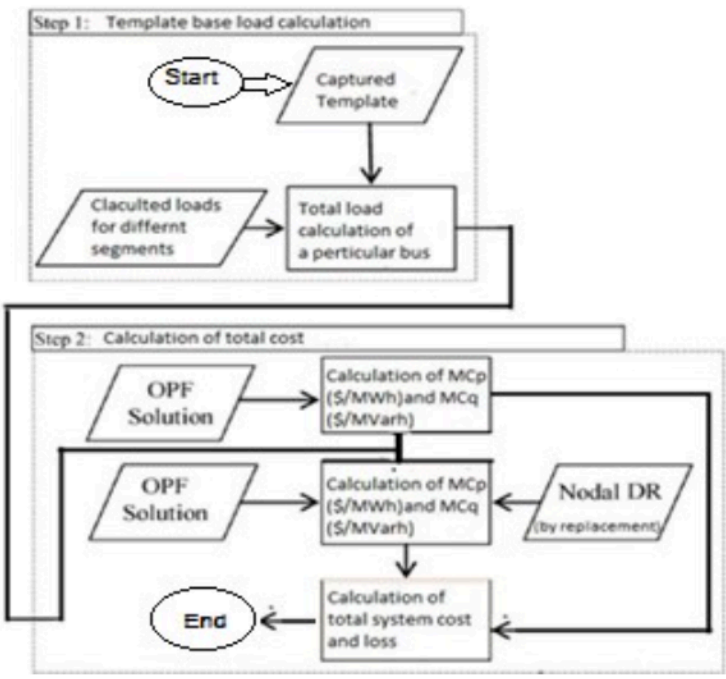

Fig. 1. Process of cost calculation

3.1 Template Base Load Calculation

Data was collected using a computer-controlled setup and saved in a server system before being analyzed [10]. During a capture period, NT samples are obtained as NT-length sequences, as indicated in (1) and (2)

$$v_{acq} = \{v_{acq}(n)\}_{n=1}^{N_T} \quad (1)$$

$$i_{acq} = \{i_{acq}(n)\}_{n=1}^{N_T} \quad (2)$$

Power may be obtained for specific loads, such as CFLs and FLs, with electronic or magnetic ballasts at any time.

$$P_{load} = \frac{1}{N}\sum_{n=1}^{N} v_{tmp}(n) i_{tmp}(n) \quad (3)$$

For any mixed combination, the power can be calculated as

$$P_{mixerload} = \frac{1}{N}\sum_{n=1}^{N} v_{tmp}(n)\,[n_{CFL}(n) * i_{CFL}(n) + n_{EFBL}(n) * i_{EFBL}(n) + n_{MFBL}(n) * i_{MFBL}(n) + \cdots] \quad (4)$$

3.2 The Optimal Power Flow (OPF) Solution Formulation of The Network

The OPF solution is calculated using MATPOWER software. To determine the OPF solution, use the following equation:

$$\min_x F(x) = \sum_{i=1}^{N_0} f_P^i(p_g^i) + f_Q^i(q_g^i) \quad (5)$$

Subject to

$$H(x) = 0 \quad (6)$$

$$G(x) \le 0 \quad (7)$$

$$x_{min} \le x \le x_{max} \quad (8)$$

$$x = \begin{bmatrix} \theta \\ V_{min} \\ P_g \\ Q_g \end{bmatrix} \quad (9)$$

The objective function, F, is the sum of each generator's real power cost function. f_P^i and reactive power cost functions, f_Q^i where i=1… and n_g is the number of generators. The equality constraints, H, refer to the nonlinear real and reactive power balancing equations H_P and H_Q, where i=1 and n_b= the number of buses:

$$H = \begin{cases} H_P(\theta, V_m, P_g) = P^i(\theta, V_m) + P_d^i - P_g^i \\ H_Q(\theta, V_m, P_g) = Q^i(\theta, V_m) + Q_d^i - Q_g^i \end{cases} \quad (10)$$

The inequality constraints, G, consist of apparent power flow limits for the from F_f, and to F_t, ends of each line:

$$G = \begin{cases} g_f = |F^f(\theta, V_m)| - F_{max} \\ g_t = |F^t(\theta, V_m)| - F_{max} \end{cases} \quad (11)$$

The optimization vector includes vectors for voltage angles, voltage magnitudes (V_m), and generators' real and reactive power outputs ($P_g$and Q_g)[18-21].

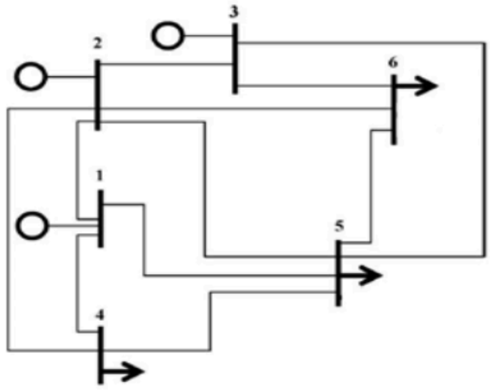

Fig. 2. Diagram of the Six Bus System

4. CASE STUDIES FOR DIFFERENT TYPES OF LOAD COMBINATIONS

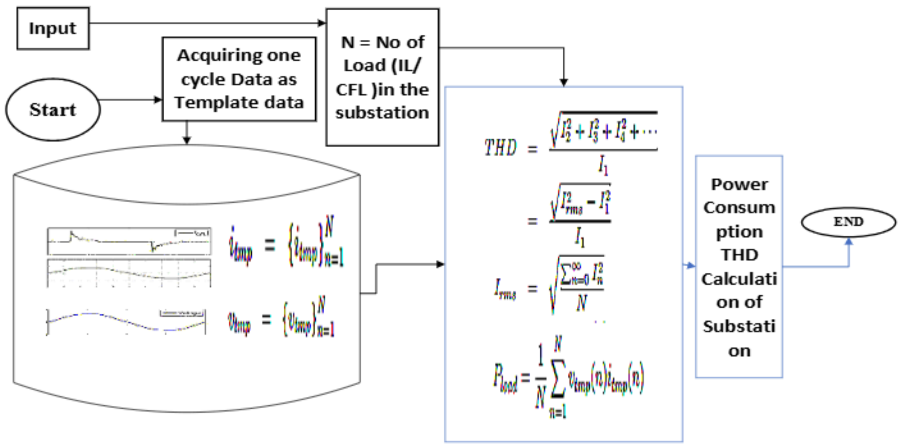

Fig. 3. Mathematical Flow chart

Power, Total Harmonic Distortion (THD), Power Factor (PF), and energy requirements are among the system factors that are assessed for a variety of loads inside a substation in this research. A MATLAB program is used to compute these parameters, and the results are used to optimize the load-serving entities (LSEs) at the nodal level [22].

Table 1: Loads under a 200 MVA transformer

Load Type	Loads under a 200 MVA transformer		
	Unit Power (Watt)	*Quantity* (1000Pcs)	*Total Power* (KWatt)
Fan	60	360	21600
Refrigerator	150	120	18000
AC	1500	30	45000
Washing Machine	500	45	22500
Heater	1000	45	45000
Lamp	60	270	16200
CFL	23	345	7935
TL with MB	40	225	9000
TL with EB	40	165	6600

Assumptions that make on the overall network consideration:

•The system was modelled as a balanced three-phase system, with loads distributed equally across single-phase units.
•Calculations were performed in a single-phase representation for simplicity.

The power parameters can be used to create load-serving entities (LSEs) at the nodal level, incorporating demand response (DR) strategies. DR often involves reducing energy consumption, such as replacing incandescent lamps with energy-efficient options like CFLs. Studies show this leads to notable energy savings, reduced peak demand, lower power losses, and improved system stability.

Possibilities for Demand-Side Management The substitution of energy-efficient substitutes like CFLs for traditional illumination (incandescent lights) is one of the study's major contributions to DSM. Numerous studies have shown that these kinds of changes can result in a significant drop in energy usage, which lowers overall demand and the lowest peak power needs. As reflected in the above table, the percentage reduction in incandescent load due to CFL replacements results in a reduction of both real power demand and overall THD (Total Harmonic Distortion), leading to an improvement in the power factor. Such reductions help improve the efficiency of the overall system and contribute to significant energy savings.

4.1 Optimal Power Flow (OPF) Solution for a Six Bus System

In the Second Step, consideration had been taken for a six bus system shown in the figure (Fig. 2). The details of the system setup are listed in Table III. This phase is essential for calculating the overall cost and loss of the system, depending on the load configurations. Through the use of MATPOWER, the system is assessed under a range of load scenarios, including the effects of load reductions brought on by DSM (switching from incandescent to CFL bulbs). Results of the OPF Analysis: The OPF solution highlights the savings obtained by substituting conventional lamps by displaying the system's overall cost and loss under various demand response scenarios. The predicted loss and cost per hour, along with the load flow statistics, demonstrate how DSM improves system efficiency. The system converges rapidly, and DSM's reduction of the fifth bus's load lowers operating expenses and improves system dependability. All the other parameters were taken from the reference [23].

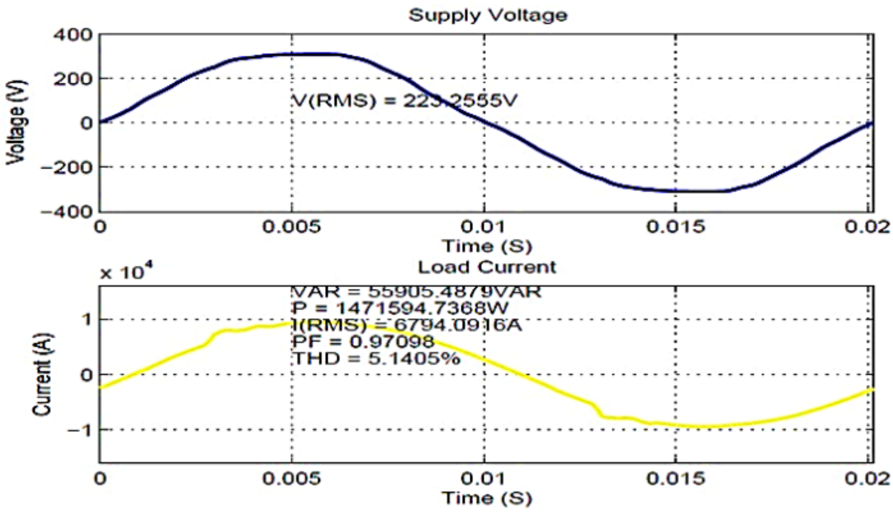

Fig. 4. Current voltage waveforms for LSE for a Node Bus

4.2 Units Load Reduction at the Nodal Level

Every 25% replacement of CFLs for incandescent lamps results in a decrease in load at the nodal level. A progressive reduction in the overall system power and an increase in the power factor may result from this demand response. The consequences of the load reduction are shown in Energy consumption and system costs, which are greatly decreased when traditional incandescent lamps are swapped out with more energy-efficient models, like

CFLs, in the substation's load profile. By putting DSM techniques into practice, especially at the consumer level, utilities can improve the system's overall power quality, minimize operating losses, and lessen demand. The Current voltage waveforms for LSE for a Node Bus are shown in Figure 4.

5. OUTCOMES AND EVALUATION

The results of this study are consistent with other studies on DSM and energy efficiency, suggesting that these tactics can be very important for maximizing energy use and promoting sustainable energy systems. The system output data also illustrates how DSM affects the overall real and reactive power as well as the operational cost of the system. In Table II, all variations in the real and reactive power, along with the costing per hour, are included. Also, the LMP analogy for different calculations is shown in the graph (Fig. 5).

Table 2: Load Replacement by Percentage for Demand Response

Load Reduction	Parameter for Demand Response				
	Real Power (MWatt)	*Reactive Power* (MVAR)	*Total Total* (MAmp)	*THD* (pc)	*PF* (pc)
No Reduction	147.16	5.59	6.79	5.14	0.971
25 pc Reduction	144.77	5.59	6.69	6.25	0.97
50 pc Reduction	142.39	5.59	6.58	7.39	0.969
75 pc Reduction	137.48	5.59	6.28	9.92	0.98
100 pc Reduction	137.43	5.59	6.26	9.98	0.98

The table summary shows that the total cost per hour is lower for Demand Response (DR) at any node, even when energy-efficient alternatives are used to replace lighting demands (as shown in Table II). Though it stays within the bounds specified by the IEEE 519 standard, this modification can cause a slight decline in the network's power quality. The Locational Marginal Pricing (LMP) at each node changes considerably across different bus points, according to the graphical study. Nodes two and three maintain a constant LMP value, whereas other buses, like bus five, experience a decline in LMP value as load is reduced. It's interesting to see that when the load drops, the LMP at the generator on one bus somewhat increases. In conclusion, the overall system cost will be reduced as DSM activities replace incandescent lights with energy-efficient lighting; however, the LMP at various network locations will not show consistent reductions.

The calculated data illustrates the hourly variation of Locational Marginal Prices (LMP) and their impact on economic metrics such as the difference with retail tariffs and objective value throughout the day. During early hours (1:00–6:00), the LMP remains relatively stable with low price differences compared to the retail tariff, resulting in modest objective values between $32,000 and $33,000. However, as demand increases from 7:00 onwards, LMP values escalate, especially during peak hours (12:00–17:00), where prices and objective values rise significantly, reflecting increased energy consumption costs. Notably, from 18:00 to 22:00, the LMP range widens drastically, with maximum LMP values spiking to above $300/MVA-hr, resulting in negative differences with the retail tariff, indicating a possible surplus generation scenario. This leads to exceptionally high objective values, peaking at $82,105 during the 19:00 hour. These trends reflect typical demand-supply dynamics and the importance of strategic DSM measures to optimize energy usage, particularly during high-price intervals.

The graph in Figure 6 shows the effects of varying levels of power reduction on key electrical parameters for an industrial system. As the percentage reduction in real power increases from 0% to 100%, real power output decreases steadily from 147.16 MW to 137.43 MW. Interestingly, reactive power remains constant at 5.59 Mvar across all reduction levels, indicating that reactive power demand is independent of the real power reduction in this scenario.

The total current also decreases progressively from 6.79 A at 0% reduction to 6.26 A at 100% reduction, aligning with the reduced real power consumption. However, Total Harmonic Distortion (THD) increases significantly from 5.14% to 9.98%, suggesting that power quality may deteriorate as reductions in real power are applied. The power factor (Pf) starts at 0.971 and slightly improves to 0.98 at higher reduction levels, likely due to the consistent reactive power and decreased real power. These observations emphasize the trade-offs between energy savings, power quality, and system efficiency in Demand-Side Management (DSM) strategies

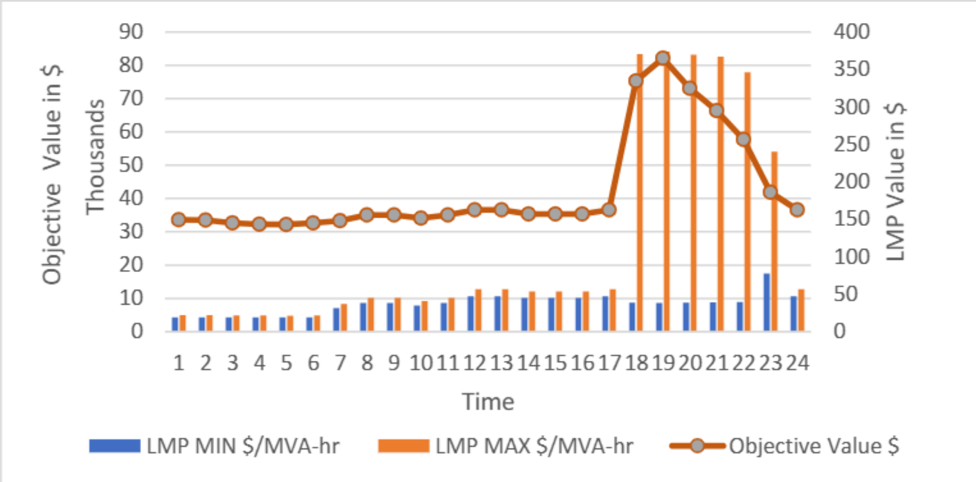

Fig. 5. LMP (max/ min) Vs objective values for a Node Bus

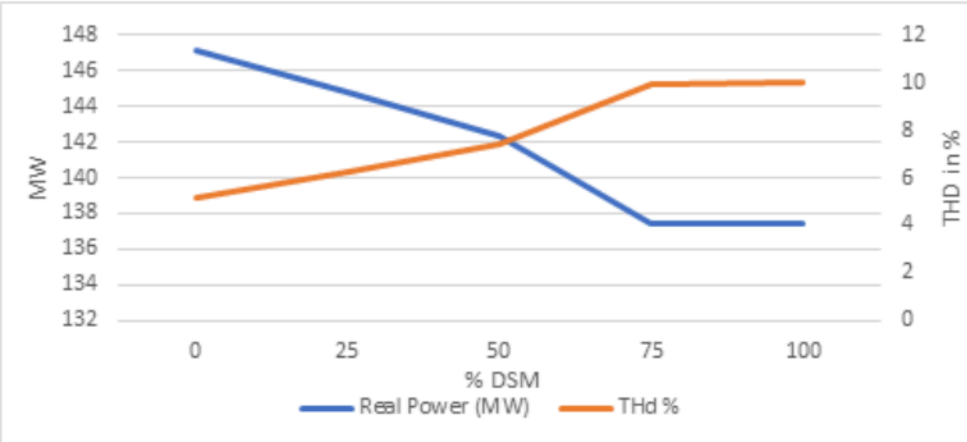

Fig. 6. Quality Vs objective values for a Node Bus

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6. CONCLUSION

The paper suggests a novel method for modelling loads using waveform templates. Real-time waveforms that have been acquired undergo manipulation to create the templates. The power quality parameters of a distribution system with various load combinations are ascertained using these templates. It is discovered that the individual current waveform of CFL contains THD of greater than 12%. The THD of an electronic ballast is close to 20%. The CFL and electronic ballast each have extremely significant individual harmonic distortions. The overall power scale shrinks to about 20% of the lamp load when a CFL is used in place of a lamp. Nevertheless, the leading power factor drops from unity to 0.57. However, the power quality does not change much when an electronic ballast is used in place of a tube light with a magnetic ballast. Even so, it raises the power factor from a lagging 0.57 to nearly unity. The THD is not greatly impacted when switching the ballast for tube light loads from an electronic ballast to a normal magnetic ballast.

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