"Power Quality Comparative Analysis of Luminaries for Optimum Solution for Consumer and Utility".

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Abstract - *Lighting comprises of nearly 20% of world's electricity consumption. The demand for high efficient electrical equipment has grown exponentially in the last decades. Modern luminaries like CFL, LED has power electronic circuits inside, so that this non-linear load results in harmonic distortion. The incandescent lamp (IL) is a resistive load, its power factor is unity and its current is harmonic free, but it consumes higher power. In case of CFL the power consumption is low but it produces the harmonic. In same way, LED having very low power consumption as compare to IL, CFL but its power factor is low, also it draws harmonic current. As this harmonic current passes through the impedance it causes voltage distortion and hence degrading of overall power quality occurs. In this paper we are focusing on different luminaries that are used in residential area such as IL, CFL and LED. We have measured the power quality related parameters using KRYKARD ALM 30 power quality analyzer for separate load of luminaries and then for combinations of load. Then according to observations of parameters like power consumption, Efficiency, THD, lamp cost, lifetime, cost of electricity per annum etc., we had recommended the combinations of luminaries number that should be used for a specific area (ex. 1 BHK area) with the consideration of power quality remains in IEEE standard tolerance limit. So that it will be beneficial for utility side as well as residential consumers***.**

Key Words: **THD, harmonic, power consumption, power factor, KRYKARD ALM 30 analyser.**

1. INTRODUCTION

One of the major electrical loads on a utility grid is industrial, street and residential lightings [1]. The older incandescent lamps and magnetic choke of fluorescent tube consumes more energy. These older technology luminaries have higher losses so that its efficiency is low. Due to all this the demand increases. So the for fulfilling the demand, power generations have to be increase. In power generation there are considerable fossil fuels burning which turns into adverse impact on environment [3].

In recent years to enhance the energy efficiency and as a measure of energy conservation, the use of compact fluorescent lamps (CFL) and Light Emitting Diodes (LED) increased rapidly. Compared to the incandescent lamp (IL) the modern illumination equipment represents non-linear loads that pollute the electric power distribution system by injecting current harmonics and deteriorating the grid voltage [2].

These harmonic sources adversely affect other loads connected on same bus and degrade a system bus. It also affects the grid in terms of high reactive power demand (poor power factor), distortion in currents and hence affects the overall power quality.

2. OBJECTIVES

- To design a demonstration model (three kit) for different luminaries like LED, CFL, Incandescent lamp each of having nine quantities on the plywood board.
- Then using the Power Quality analyzer measure the Power Quality parameters such as power factor, frequency, voltage variation, current THD and voltage THD etc.
- To take combination of measurement using Power Quality Analyser and analyse the result with the graph, waveforms, curves etc.
- Comparative analysis of each load & then mixed load for same lumens output.
- T0o do linear programming simulation in MATLAB software to obtain the solution of mathematical model.
- To find techno-economic solution with respect to consumer and utility stakeholder.

3. TERMS AND DEFINITIONS

3.1. Power Quality

There can be completely different definitions for power quality, depending on stakeholder. For example,

- In concern to utility Power quality define as reliability and show statistics demonstrating that its system is 99.98 percent reliable [4].
- Manufacturer of load equipment define power quality as those characteristics of the power supply that enable the equipment to work properly. These characteristics can be different for different applications [4].
- Ultimately power quality is a consumer-driven issue [4].
- As per IEEE 1100 power quality is "the concept of powering and grounding sensitive electronic equipment in a manner suitable for equipment" [4].

3.2. Harmonic Distortion

As per **IEEE 519-1992** harmonic is a "sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency."

- Harmonics are mainly generated from non-linear loads. Transformers, electric motors, generators, arc furnaces, arc welders, DC converters, inverters, Television power supplies, switched mode power supplies, high pressure discharge lamps, compact fluorescent lamps, light emitting diodes, laptop and mobile phone chargers and other similar electronics and power electronics equipment are the major sources of harmonic generation [4].
- In the nonlinear load current is not proportional to the applied voltage
- The sinusoidal voltage applied to a nonlinear resistor in which the voltage and current vary according to the curve shown in figure 1. Though the applied voltage to the resistor is perfectly sinusoidal, the resulting current is distorted in nature. Increasing the voltage by a few percent may cause the current to double and resulted in different wave shape. So that it's a major source of most harmonic distortion in a power system.

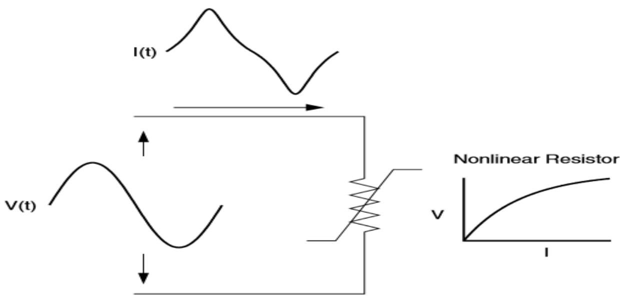


Figure 1: Current distortion due to nonlinear resistor [4]

- Voltage distortion is the result of distorted currents passing through the linear, series impedance of the power delivery system. Though the source bus is pure sinusoidal, the nonlinear load draws a distorted current. Figure 2 illustrate that harmonic currents flowing through the system impedance result in harmonic voltages at the load. The amount of voltage distortion depends on the impedance and the current [4].

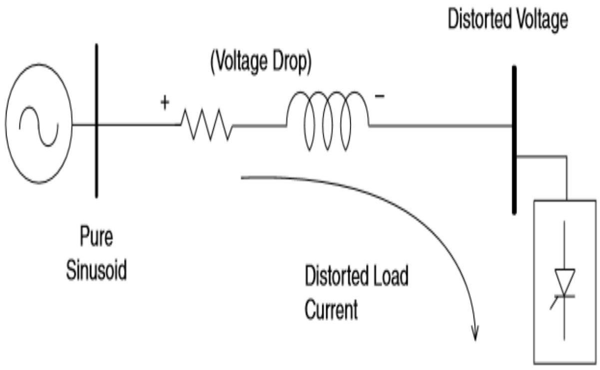


Figure 2. Harmonic current flowing through the impedance [4]

3.3. Harmonic Indices

IEEE Std.1992-519 recommends keeping voltage THD ≤ 5% and current THD ≤ 32% in utility power distribution line of <69 kV.

I. Total harmonic distortion (THD)

The Total harmonic distortion is the ratio of the root-mean square (RMS) value of the harmonic content of an alternating quantity to the RMS value of the fundamental component. THD is most commonly used to indicate the harmonic content in a distorted voltage and current waveform. This index can be calculated for either current or voltage [4]. It is abbreviated as THDi and THDv .The Voltage THD may be expressed as [7],

$$THD = \frac{\sqrt{\sum_{h>1}^{hmax} V_h^2}}{V_f}$$

Where V1=Vf.

RMS values of overall distorted waveform are as,

$$RMS = \sqrt{\sum_{h1}^{h_{max}} \mathrm{Mh}^2}$$
$$= M1\left(\sqrt{1+THD^2}\right)$$

Where Mh is the rms value of harmonic component 'h' of the quantity M.

- Similarly line RMS current can be written as [7];

$$I_{RMS} = \sqrt{I_f^2 + I_h^2}$$

- THD is a very useful quantity for many applications. It can provide a good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load [7].

II. Total demand distortion (TDD)

- When THD is referred to the fundamental of the peak demand load current rather than the fundamental of the present sample, is called total demand distortion (TDD) [4].

$$TDD = \frac{\sqrt{\sum_{h=2}^{hmax} I_h^2}}{I_L}$$

IL is the peak, or maximum, demand load current at the fundamental frequency component [7].

$TDD = I_F \times I_L \times TDD$

IF is the fundamental current at fundamental frequency.

3.4 Power Factor

Power factor is a ratio of useful power to real work (active power) to the power supplied by a utility (apparent power) [4], i.e.

$$Power\ Factor = \frac{P}{S}$$

In the non-sinusoidal case the power factor cannot be defined as the cosine of the phase angle. The power factor that takes into account the contribution from all active power, including both fundamental and harmonic frequencies, is known as the true power factor.

The true power factor is simply the ratio of total active power for all frequencies to the apparent power delivered by the utility.

Utilities often try to maintain system PF from 0.85 to 0.95. The PF reflects the efficiency of an electrical power distribution system. All the energy saving lamps requires additional power factor correction capacitor circuits [6].

3.5. High THD and Low PF scenario

Incandescent lamp being a pure resistive load so it does not suffer with low power factor issue and thus always presents a unity PF. Also IL does not require special electronic driver for starting purposes therefore no harmonic problem occurs during operation. LED and CFL lamps need special driver circuitry for their safe operation thus generates harmonic distortion [7].

PF and Current THD are two different phenomena arising out of entirely different situation. One of the impacts of current THD is to increase magnitude of RMS current that increases the I2R losses. However, a small load with 200% THD cannot affect overall system but a large load with even 100% THD can seriously impact the system.

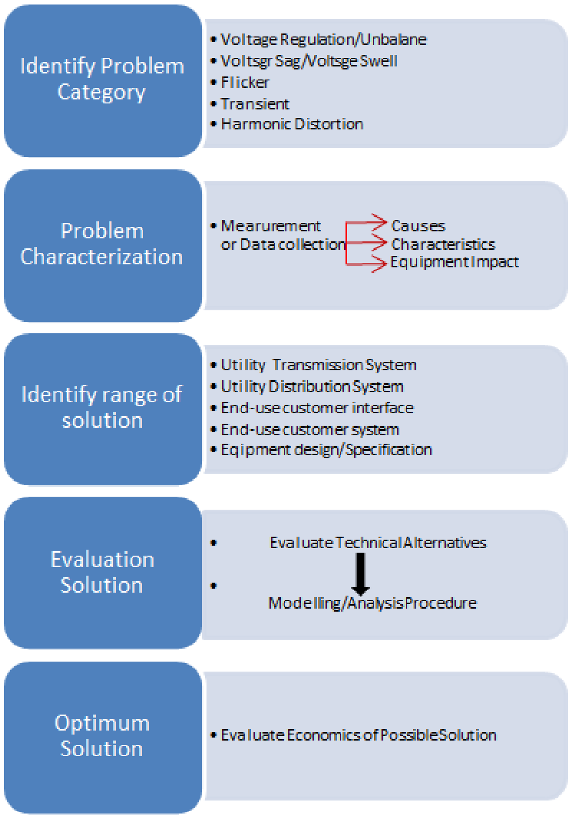
Similarly, a smaller load with 0.4 PF cannot affect the system but a large load with 0.6 PF can adversely affect the system. Reducing harmonic or improving power factor reinforces each other but PF cannot be unity in the presence of harmonics. As the PF reflects overall losses, therefore, harmonics contribute to power loss, Harmonic affects displacement factor so that total kVA demand increases [7]. Total PF is equal to the product of distortion and displacement factor.

4. METHODOLOGY

4.1 Power Quality Evaluation Procedure

Power quality problems consisted wide range of different phenomena. Each of these phenomena may have a variety of different causes and different solutions that can be used to improve the power quality and equipment performance [4]. Table 1. Shows general steps that are often required in a power quality investigation, along with the major considerations that must be addressed at each step [4].

Table 1: Power Quality Evaluation Procedure [4



4.2 Demonstration Steps

In this experiment, 60W IL, 15W CFL and 7W LED are used. These lamps are commonly used for indoor lighting. Using the KRYKARD ALM 30 Analyser the performance data for IL, CFL and LED are observed. In the experiment nine (9) luminaries of each were taken as a sample. These samples have different power ratings (**But same lumens output**) and it's from different manufacturers.

A. Different scenarios are considered with full and partial replacement of incandescent lamps. A comprehensive comparison between incandescent, CFL and LED are made in terms of power quality measurements.

B. There are several ways to compare between different types of lamps but we had done on the basis of their lumen output i.e. by considering the lumens output of luminaries same (1 CFL of 14 watt equivalent to 1 LED of 7 watt equivalent to 60 watt Incandescent lamp).

C. Power quality parameter (Power factor, THDi and THDv etc.) measured with KRYKARD ALM 30 Analyser.

D. These measurements were taken in two format, firstly done for individual loads and then for mixed load with prime consideration of lumens output and area.

E. Then the results analysis done on the basis of obtained data, graph, waveform, curves and comparison with IEEE standard.

F. Then mathematical model was developed for obtaining optimization results. The linear optimization solution obtained by MATLAB software simulation technique.

4.3 Experiment Setup

In the experiment KRYKARD ALM 30 analyzer used. The CT probe of analyzer placed across load current carrying conductor. Whereas the PT probe connected the socket provided on the model. In the experiment the voltage and current harmonic up to the 25th harmonic, THDv, THDi, W, VAR, VA, PF, RMS current & voltage etc. of each configuration measured. Then the analytically found the annual consumption, total investment, annual expenditure and payback period etc. for each configuration. From the observed readings and analytical data the results are obtained as shown in table 4.

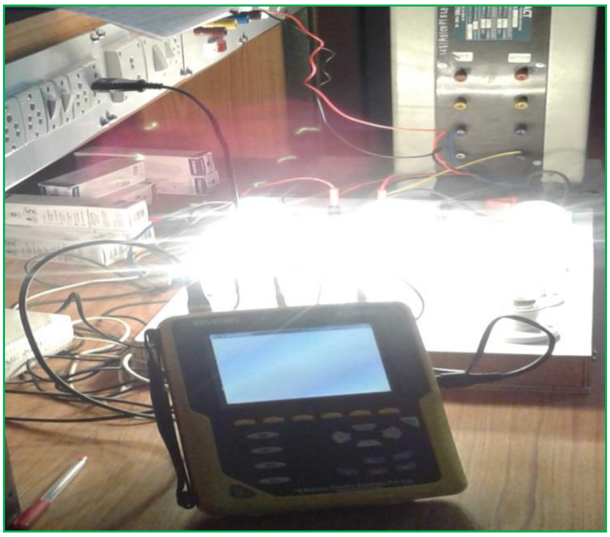


Figure 3: Experiment Setup

4.4 Simulation

The various graph plotted from the experiment readings and analytical calculations. Then the mathematical model developed with the reference of some practical readings. Then its simulation did in MATLAB software using LINPROG technique. From this simulation we got a result which is nearly equal to the practical method.

The reference values used for simulation are mentioned in table 2.

Table 2

	IL	CFL	LED
PF	1	0.916	0.969
THDi	3.6	38.7	16.7
THDv	3.4	3.9	4.5
Power consumed in Watt	544	75.6	124.2

- The key decision to be made is to determine no, of lamps of each type to be used so.
- Let x1, x2, x3 represents no. of IL, CFL and LED lamps to be used.

$$x1, x2, x3 \geq 0$$

- The objective is to minimize kWh consumption. The objective function are as,

Minimize

$$Z = \frac{544}{9}x1 + \frac{124.2}{9}x2 + \frac{75.6}{9}x3$$

- The optimization constraints are as,

1. Total number of lamps is 9.
2. THDv should be less than 5%.
3. THDi should be less than 32%.

- The equations are as follows;

a) $x1 + x2 + x3 = 9$

b) $THD_i = 3.6\,x1 + 38.7\,x2 + 16.7\,x3 \leq 32$

c) $THD_v = 3.4x1 + 3.9\,x2 + 4.5\,x3 \leq 5$

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5/26/174:10 PMMATLAB Command Window1 of 2

>> f=[-60.11 -13.77 -8.44]
f =
  -60.1100  -13.7700  -8.4400
>> A=[0.4 4.3 1.855; 0.377 0.43 0.5; 1 1 1]
A =
    0.4000    4.3000    1.8550
    0.3770    0.4300    0.5000
    1.0000    1.0000    1.0000
>> b=[32 5 9]
b =
    32    5    9
>> Aeq=[]
Aeq =
     []
>> beq=[]
beq =
     []
>> lb=[9 0 0]
lb =
     9    0    0
>> ub=[32 5 9]
ub =
    32    5    9
>> [X,Z]=linprog(f,A,b,Aeq,beq,lb,ub) Optimization terminated.
X =
    9.0000
    0.0000
    0.0000

Z =

  -540.9900

>> Z=Z*-1

Z =

  540.9900
```

Figure 4: MATLAB simulation screenshot

- The results obtained from simulation are mentioned in the table 3.

5. RESULT

- Power Consumption obtained from practical experiments and simulation are as follows;

Table3: Experimental reading vs. simulation result

Combination	From Power Quality Analyser	From Simulation
9 IL	544.1	540.99
9 LED	75.96	76
4 IL + 5 CFL	309.5	309.29
4IL + 5 LED	281.9	282.54
4 CFL + 5 LED	99.9	97.28
2IL + 3CFL + 4 LED	196.4	195.29
3IL + 2 CFL+ 4 LED	243.3	241.63
3IL + 3CFL + 3 LED	244.8	246.96
1IL + 4CFL + 4LED	154.8	148.95

- In this experiment we had taken nine luminaries considering the requirements of a BHK flat. For each type of luminary the price and the lifespan are various so that the initial investment changes as per luminaries category.

- While doing the analytical calculations the following assumptions are made as follows;

  a) Daily working hours are 11 hours.
  b) Electricity charge is 7 Rs/Unit.
  c) For calculation of payback period the baseline power consumption taken as 60 watt of IL. Whereas the lifetime of LED i.e. 15000 hours.

- The reading obtained in the experiments are plotted on the graph (chart 1) and observed for various luminaries configuration against standard reference values. So that it became easy to compare the readings with standard value.
- The THDv value is in permissible limit as specified in IEEE 519-1992.
- The THDi value is in permissible limit except for nine CFL configurations.
- Daily energy consumption is less for nine LED configurations. Also the payback period is less for same configuration.
- All this readings are verified by MATLAB software simulation.

Combination	W	P.F	THDi (%)	THDv (%)	Total initial Investment (Rs.)	Daily Energy Consumption in kW	Total Expenditure/ Annum in Rs.	(Initial cost + Running Cost)/annum in Rs.	Daily Saving (Rs.)	Payback period in years
9 IL	544.1	1	3.6	3.4	1890	5.9851	15291.9305	0	Nil	Nil
9 CFL	124.2	0.916	38.7	3.9	2970	1.3662	3490.641	4285.611	2.9393	3.99462457
9 LED	75.6	0.969	16.7	4.5	1260	0.8316	2124.738	2461.998	3.2795	2.056776948
4 IL + 5 CFL	309.5	0.997	8.2	4	2490	3.4045	8698.4975	9364.9875	1.6422	15.62385824
4IL + 5 LED	281.9	0.999	5.8	3.9	1540	3.1009	7922.7995	8335.006167	1.8354	7.344064235
4 CFL + 5 LED	99.9	0.966	18.8	3.9	2020	1.0989	2807.6895	3348.376167	3.1094	2.950290517
2IL + 3CFL + 4 LED	196.4	0.995	9.3	3.8	1970	2.1604	5519.822	6047.125333	2.4339	6.806962762
3IL + 2 CFL+ 4 LED	243.3	0.998	5.6	2.7	1850	2.6763	6837.9465	7333.129833	2.1056	9.541587513
3IL + 3CFL + 3 LED	244.8	0.997	7.7	4.1	2040	2.6928	6880.104	7426.144	2.0951	9.711040046
1IL + 4CFL + 4LED	154.8	0.987	13.5	4.2	2090	1.7028	4350.654	4910.077333	2.7251	4.936430467

Table no 4: Experimental readings and analytical results

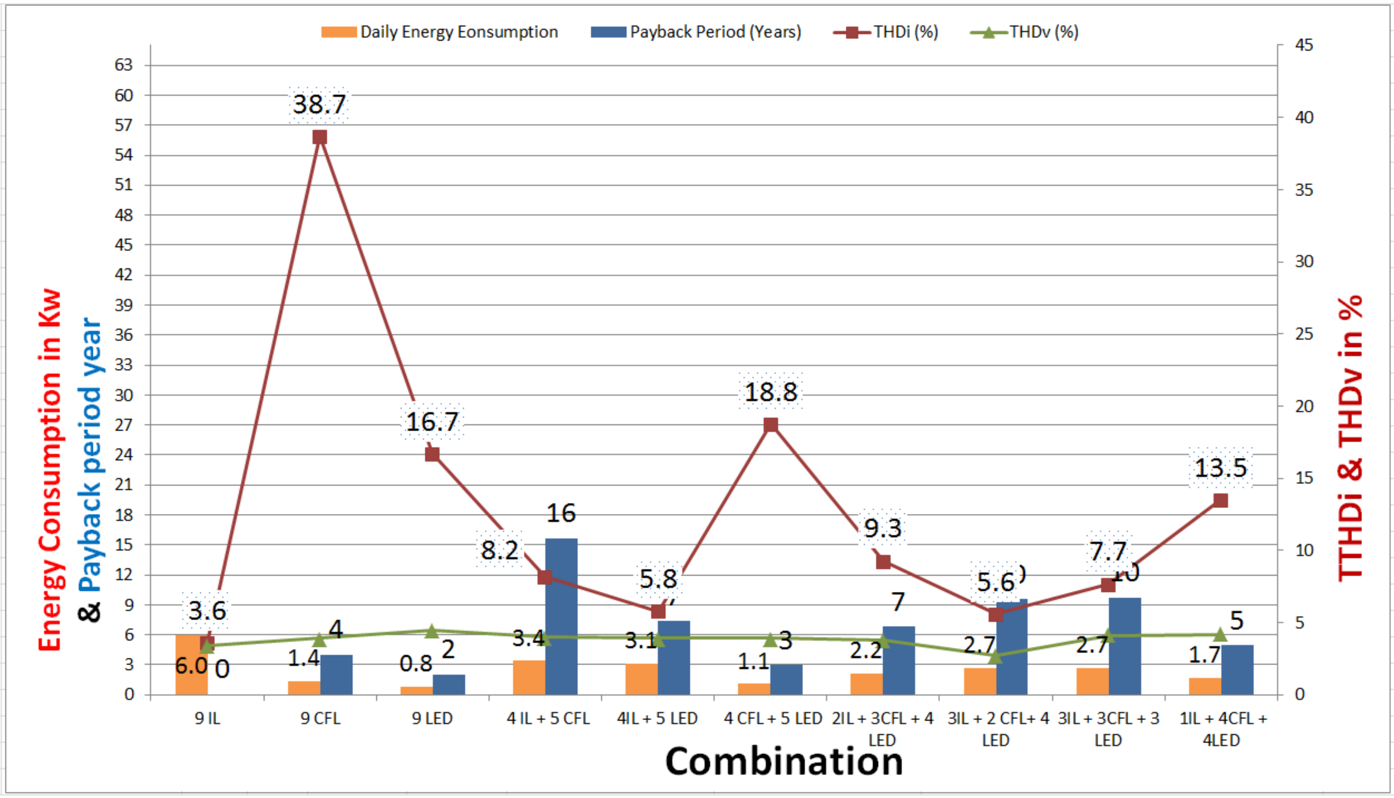

Chart 1: Graph of THDi, THDv, Energy consumption and payback period for all configurations

6. CONCLUSION

- The replacement of Incandescent lamp with modern energy saving devices is useful for consumer as well as for the utility. LED could be a good choice as the LED configuration has low power consumption and higher efficiency. The payback period for nine LED configurations is less.
- For all the luminaries configuration power factor are in the range of between 0.9 to 1. So that any configuration can be chosen w.r.t. power factor.
- The luminaries configuration 1 IL + 4 CFL+ 4 LED are suitable w.r.t. energy consumption, payback period, power factor and both current & voltage THD.
- So that the techno-economic performance comparison of various luminaries forced to use LED widely; with corrective technique implementation to reduce THDi.

7. REFERENCES

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