This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3123153, IEEE Access

dhanDDate of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2021.Doi Number

Energy Conservation Approach for Continuous Power Quality Improvement: A Case Study

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ABSTRACT This work focuses on a mitigating harmonic filter. It investigates the effect of mitigating harmonic filters in the textile industry with innovative energy conservation strategies for energy bill reduction, which covers a pathway to climate change mitigation. Here, the effect of the harmonic filter is found out by the systematic energy audit methodology (Preliminary, Detailed and Post-Audit phase). From the energy auditing, it has been found that the textile industry needed a passive harmonic filter for harmonic mitigation. Since, third, fifth, and seventh order of harmonic predominantly exists in the system. The high stability at higher current, known tuning frequency, low cost, and low power consumption make the passive filter the best fit for the system. The voltage and current Total Harmonic Distortion Factor (THDF) have been measured using the class 'A' power quality and energy analyzer. The harmonic filter's effect in harmonics mitigation is prominent; 66.45% of the reduction of current harmonics is achieved after installing the passive filter at the Point of Common Coupling (PCC) of the system. Also, the reduction of harmonics ensures energy conservation by reducing additional losses (joule, copper, and eddy current losses). The techno-economic analysis with payback period calculation is carried out and reported. Also, the effect of harmonics like mechanical anomalies (temperature rise) is carefully studied using an infrared thermographic technique in the textile industry's motor loads. The energy conservation and their carbon emission reduction are calculated and reported.

INDEX TERMS Carbon emission reduction, energy audit, energy conservation, harmonic mitigation, passive mitigation techniques, and power quality.

I. INTRODUCTION

According to the Energy Conservation Act of India, the textile industry is conserved as one of the highly energy-intensive industries. India is the third-largest textile exporter in the global arena. In India, the textile industry contributes 2% of the country's Gross Domestic Product (GDP) and 12% of export earnings. According to the India Brand Equity Foundation (IBEF), the Indian textile market's size is expected to touch the US $223 by 2021, growing at a Compound Annual Growth Rate (CAGR) of 10.23% over 2016. The growth rate is equally proportional to energy consumption. Therefore, the energy intensity of the textile industry is rapidly increasing in India. The Power Quality issue (Harmonics) is an undesirable phenomenon that came into existence due to the non-linear electronic components in the power system [1].

The textile industry is fast-growing and completely mechanized by sophisticated machinery to rapidly increase the industry's productivity with high accuracy. This intervention of highly sophisticated machinery has more scope for creating nonlinearities in the system. The Indian textile industries are classified into two, which are organized (spinning and composite mill) and decentralized (handloom, power loom, and fabric processing sector). According to the Beauro of energy efficiency [1], energy auditing is defined as the verification, monitoring, and analysis of energy use, including submission of technical report containing recommendations for improving energy efficiency with cost-benefit analysis and an action plan to reduce energy consumption. Here, the systematic, detailed energy auditing of the textile industry is carried out.

This paper aims to perform the real-time critical case comparison with the de-tuned reactor configuration and without a de-tuned reactor configuration in the high-tension textile industry for its effectiveness study (or) a key initiative for post-audit assessment. The energy auditing process is kick-started with the industry's walk-through audit and came up with a no-cost or low-cost optimization technique for energy cost-cutting. The sophisticated electronic components in the textile automation machinery make the system more complex and prone to nonlinearities, creating harmonic pollution. Table.1 gives the power specifications of the industry, and Figure.1 gives the textile industry's month-wise maximum demand profile; the KVA demand utilization is very low compared with the sanctioned demand. The connected load of the industry is significant with the sanctioned demand. Therefore, sanctioned demand is higher due to the operation pattern, business profile stipulations, and future expansion scope [3].

Table.1. Electrical Specification of Industry under Study

Parameter	Ratings
Sanctioned Demand	250 KVA
Sanctioned Load	259.5 HP + 18 KW
CT Ratio	20 / 5A
PT Ratio	11KV / 110 V

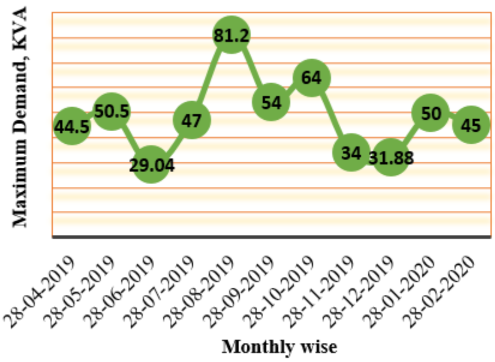

FIGURE 1. Month-wise maximum demand curve of the industry

In the global context, the scope for energy conservation in the textile industry is enormous. The energy conservation potential of the Taiwan textile industry is developed with the roadmap to the Kyoto protocol [2]. In Textile Industry, significant electrical loads like an air compressor, dynamic facilitator, spinning frame, and refrigerator account for 17 %, 57%, 5.4%, and 1%, respectively. The Taiwanese textile industry's energy-saving results are about 46.1 kilometers of oil equivalent and 143.7 kilometers of annual carbon reduction from energy utilization. In Pakistan, the textile industry is considered an energy-intensive industry. A 10-15% benchmarking of energy-saving potential is possible in the textile industry by implementing environmentally sound energy-saving measures.

The optimal sizing, soft starter, and star-delta transition are employed to achieve maximum efficiency with good power quality. The adoption of cleaner production strategies ensures the energy conservation of Brazil's textile industries [3]. The new production line is equipped with environmentally sound and energy-efficient raw material, which paves the way for energy saving of 488,921 kWh/month to reduce the overall energy bill and environmental pollution due to energy utilization. In the Chinese model, the energy conservation measures are taken from the production process line optimization and carbon emission reduction through energy conservation. Energy utilization and carbon emission mitigation have a direct correlation to ensure environmental sustainability.

In the Indian context, the textile industry's energy cost is 15-20% of textile production cost, next to the raw material cost. The industrial process and motor influence on energy conservation are discussed. The authors developed a detailed energy analysis of productive and non-productive machines in the textile industry in Tamil Nadu, India, with a detailed energy saving methodology for the Bale room department, ring spinning, humidification plant, and air compressor. From the results, 56,053 kWh is monthly energy-saving with Rs.2,52,239 per month. The extensive heterogeneity in the process and various technologies involved in the Indian textile industry [4]. Therefore, the industry's clustering is challenging to arrive at a benchmark and compare it with global standards and norms. Innovative energy consumption strategies like installing automatic power factor correction capacitor banks and replacing the inefficient and energy-guzzling motors with the energy-efficient motors in the spinning mill are suggested.

The energy model is developed for power quality improvement in the textile industry using power factor improvement technologies. A careful energy analysis is carried out, the power factor correction capacitor is suggested, and the effect is verified. The review concludes that the power factor is vital in maintaining the excellent voltage profile, low current profile, and heat generation reduction in the power system and the connected electrical loads. The various forms of the power factor improvement in an SME unit. The underlying design calculations for power capacitors and various power quality issues in a process industry [5].

In the harmonic environment, replacing the super-premium (IE4) line start permanent magnet synchronous motor in the squirrel cage induction motor is highly recommended to have better power quality in the system. The Voltage Total Harmonic Distortion Factor directly relating to the motor temperature rise and copper loss of motor. The Lumped Parameter Thermal Model (LPTM) is an inverse electric motor loss estimation method [6]. Here, the rotor and winding temperature are calculated critically, and a numerical model is developed for the loss analysis. The electromagnetic and mechanical friction losses are tough to compute in the conventional electrical and mechanical assessment methodologies.

The temperature is a crucial parameter in motor performance, and the temperature measurement method needs some alternative ways and means as an inverse approach to better model development. The overall energy audit process of the farmhouse and its electric motor loads, which in turn helps us to study the replacement of old induction type motor loads into energy-efficient motors in the textile industries. Power quality mitigation is a highly recommended technique for energy conservation [7].

The development of an economical and cost-effective T-connected autotransformer for the harmonic environment by combining two single-phase transformers reduces the weight and volume of the transformer [8]. Also, the 72-pulse output gives the more economic pulse doubling results at 60% of full load. From the review, harmonic mitigation is essential for the economic operation of the power system. The development of multiple-order harmonic mitigating filters as a CONTUNE (Continuously Tuning) filter is proposed, and simulated results show the filter's significant results. The theoretical calculation of harmonics without a filter is about 17.2% [9]. The proposed CONTUNE filter is simulated, and it is efficiently performed in multiple orders of harmonic mitigation purposes. The overall power quality and system efficiency have been enhanced by installing Smart Energy Management System (SMES) in the intermittent process industry[10].

The harmonic mitigation is achieved by designing and installing an Electronic Quality Regulator (EQR). The harmonic mitigation is ensured by installing electronic controller-based harmonic filters in the location [11]. The intervention of renewable energy resources ensures sustainability. Solar photovoltaics has a significant scope in catering for the maximum daytime loads [12]. The load management system is essential for the optimal operating of the connected loads. The average life span of 25 years is assured for solar photovoltaics [13] with more significant energy savings.

The review concluded that power quality mitigation is essential in the industrial power system and necessary for efficient and better performance. Implementing a de-tuned reactor ensures better power quality in the harmonic-prone environment of the textile industry. Therefore, better power quality ensures energy conservation. The textile industry's process optimization has significant scope for reducing energy consumption. Also, integrating renewable energy resources ensures sustainability. The rooftop solar photovoltaics have a significant scope on the energy conservation of the textile industry with the more significant energy bill reduction.

II. Existing Power Infrastructure of Industry

The entire process flow diagram of the industry is given in Figure.2. The industry's process kick-started from cotton yarn's raw material fed into the winder's parallel winding plies. The wider section is powered by two numbers of 7.5 HP induction motors. The material is then admitted for the twisting process in a Two For One (TFO) twister powered by three 10 HP induction motor numbers. Also, the 2HP and 5 HP ring doubles are used in the wider section. The significant energy-consuming wrapping process is handled by the sectional wrapper of 30HP and a direct wrapper of 5 HP for beam and weft preparation, a high energy-guzzling process. It is then admitted to five numbers of the parallel (or) series combination of a weaving shuttle loom, which combines three numbers of 3HP and three numbers of 2HP motors. The inspection section is dedicatedly powered by two numbers of 3 HP motor and two numbers of 2 HP loom for quality assurance and inspection purposes. On the whole, 200 HP of installed loads are connected to the power system. In addition, the station loads and auxiliaries are added to the system.

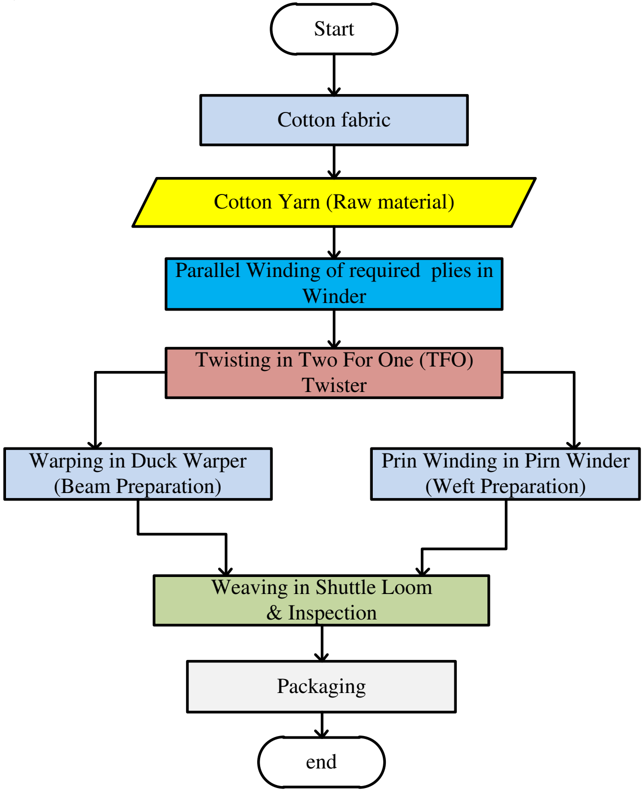

FIGURE 2. **Process Flow Diagram of Industry**

III. Methodology

The energy conservation of the textile industry is kick-started from the preliminary energy audit (or) walk-through audit. To find out the scope for no or low-cost energy-saving measures in the industrial operation—the prerequisites for conducting the detailed energy audit by systematically collecting historical data. The detailed energy audit is started with an objective of energy bill reduction with power quality improvement of industrial operation. Identifying existing electrical infrastructure gives a keynote for a detailed energy audit and to set a reference point. The detailed energy audit results show that voltage and current Total Harmonic Distortion Factor (THDF) is higher than the norms and standards of IEE 519-2014 and IEC61000-30.

Therefore, a low-cost, highly reliable passive filter (de-tuned reactor) is designed, proposed, and implemented as a harmonic mitigating technique to maintain the industry's good power quality indices. In addition, the post-audit phase of energy auditing is carried out to obtain the effectiveness of the installed de-tuned reactor with the systemic energy audit approach. Figure.3 illustrates the overall energy auditing phases of the textile industry under study using the Fluke 435-II class 'A' three-phase energy and power quality analyzer with two configurations like with and without a de-tuned reactor. The infrared thermographic technique for mechanical anomalies implemented energy efficiency enhancement strategies on three-phase induction motors and their effect on the harmonic environment. According to the Bureau of Energy Efficiency (BEE), detailed power quality and energy optimization studies were carried out by the Bureau of Energy Efficiency (BEE).

FIGURE 3. **Systematic energy auditing phase using the class 'A' Instrument**

A. PROPOSED HARMONIC MITIGATION FILTER

The proposed harmonic mitigating filtering technique is equipped with the combination of a capacitor and a de-tuned reactor for better power quality enhancement in the system. The de-tuned reactor and capacitors are configured with the series resonant circuit. The real-time power quality analysis has higher validity for designing a harmonic mitigation filter. The harmonic filter design with the power factor enhancing power capacitors enhances overall power quality [14].

The series resonant frequency is the lowest harmonic frequency present in the power system. These de-tuned reactors prevent harmonic resonance issues, capacitor overloading, voltage, and current harmonics suppression at the power system level. The Eq's. (1), (2), and (3) are used for calculating the capacity of the power capacitor. They were leading KVAr supplied by Power Factor compensation equipment for compensation from 0.9 to 0.99.

$$KVAr = \text{kW}*(\tan\varphi_1 - \tan\varphi_2) \tag{1}$$

$$P_{total} = 0.746 * connected\_HP \tag{2}$$

$$KVAr = 200*(\tan(25.84)-\tan(8.1)) \tag{3}$$

For a system voltage of (VS) 415 V, 200 kW, 50 Hz, the KVAr of reactive power supplied by power factor compensation equipment with a standard rating equals 75 KVAr. The resultant capacitor compensation and the de-tuned reactor are employed for better harmonic mitigation in the system. The de-tuned reactor is powered by a 7% relative impedance and at the tuning factor of 3.8. The voltage applied to the capacitor is given by Eq. (4).

$$V_C = \frac{V_S}{(1-P)} \tag{4}$$

Where the system voltage level (V_S) is about 440 V, the voltage applied to the capacitor (V_C) is about 446.24 V, and the 480 V is a recommended rated voltage (V_R) applied to the capacitor range by considering all the safety factors. The reactive power delivered by the capacitor and de-tuned reactor combination is given by Eq. (5). The capacitor and de-tuned reactor combination will deliver 69.75 or 70 KVAr of reactive power at the system voltage level (V_S). The reactive power delivered by the capacitor and de-tuned reactor combination is given in Eq. (6).

$$Q_c = (1-P) * V_s \tag{5}$$

$$Q_N = Q_C * (V_R/V_C)^2 \tag{6}$$

The capacitor and de-tuned reactor combination will deliver 93.45 or 94 KVAr of reactive power at the rated voltage level. The textile industry under study is proposed and implemented with the 75 KVAr capacitor de-tuned reactors for harmonic mitigation in the power system and shown in Figure.4. The harmonic filter is made by combining one number of 20 KVAr, two numbers of 15 KVAr, two numbers of 10 KVAr, and one number of 5 KVAr de-tuned reactors to form the 75 KVAr capacity in the system. The detailed technical specification of each de-tuned reactor is shown in Table.2. This capacitor-enabled de-tuned reactor has the potential for harmonic suppression and power factor improvement in the system.

The operation and control of the installed de-tuned reactor are controlled through the microprocessor-based 6 step output contacts. The targeted power factor correction and harmonic compensation are the fundamental operational procedure. The individual power capacitors and de-tuned reactors are coupled with the protection Miniature Circuit Breaker (MCB) and relay to turn ON and OFF electrically. The human-machine interface (HMI) is used for the sophisticated manual operation and control of the power capacitor and de-tuned reactors. The input current signal is provided through the current transformer for the optimum capacitor and reactor configuration. Also, defective step identification and optimization have been embedded in the microprocessor configuration.

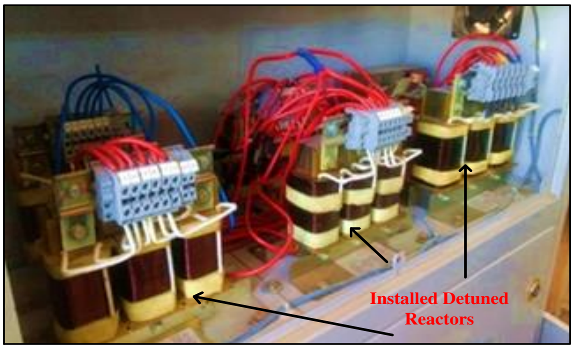

FIGURE 4. **Installed De-tuned Reactors**

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Table.2. Technical Specification of De-tuned Reactors

Parameter	**Ratings**			
KVAr	20 KVAr	15 KVAr	10 KVAr	5 KVAr
Voltage	440 V	440 V	440 V	440 V
Frequency	50 Hz	50 Hz	50 Hz	50 Hz
Tuning Order	3.8	3.8	4.2	3.8
Inductance	2.282 mH	3.016mH	3.703 mH	9.05 mH
Ie rms Max	21.3 A	21.3 A	16.1 A	7.1 A
Insulation level	1.1 kV	1.1 kV	1.1 kV	1.1 kV
Insulation Class	H			
Standard	IS 5553, IEC 60076-6			
Type	Dry, magnetic circuit, impregnated			

IV. Results and Discussion of Harmonic Analysis of Industrial Power System

The harmonic analysis of industry was carried out using the class 'A' three-phase energy and power quality analyzer for precise measurements. Figure.5 gives the time evolution of -voltage THDF of the industry generated by fluke power log 5.2 PC application software. The present V-THDF is under the IEEE 519-2014 and IEC 61000 standards and norms. In Figure.5, the %H₁ AN, %H₁ B, and %H₁ CN represent the % voltage harmonics of R-Phase, Y-Phase, and B-Phase, respectively. The third order, fifth-order, and seventh order of voltage harmonics exist in the industrial power system. The seventh order of harmonics is predominantly present in the system. The V-THDF has a relationship with the voltage unbalance, increased current consumption, and performance deterioration of induction motors; therefore, care must be given for mitigation.

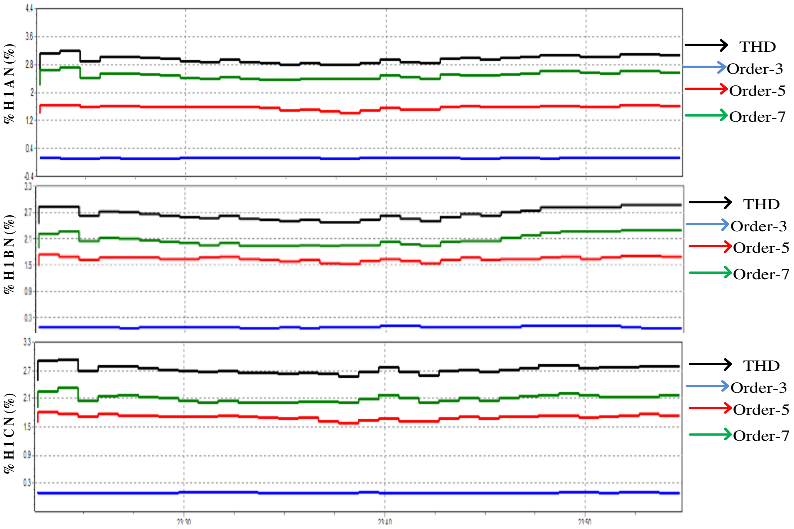

FIGURE 5. Time versus Voltage-Total Harmonic Distortion Factor

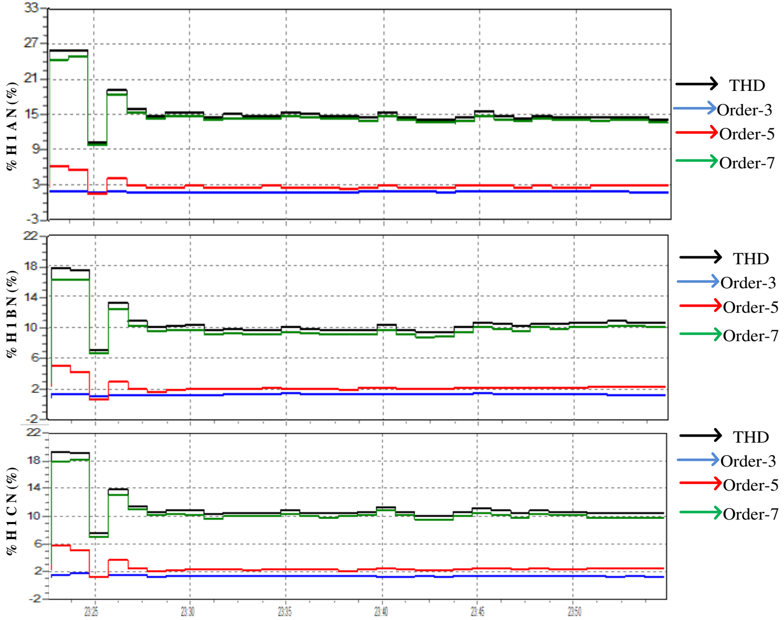

FIGURE 6. Time versus Current-Total Harmonic Distortion Factor

Figure 6 gives the current total Harmonic Distortion Factor (I-THDF) time evolution, analyzed and created by Fluke Power Log 5.2 PC application software. In Figure.6, the %H1 AN, %H1 B, and %H1 CN represent the % current

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harmonics of R-Phase, Y-Phase, and B-Phase, respectively. The third order, fifth-order, and seventh order of current harmonics exist, out of which, seventh order of harmonics is significant in the system. I-THDF has a relation with the performance of electrical and electronic loads in the system. The most likely mechanical anomalies like high-temperature rise and noise, increased energy consumption, performance deterioration, and lifespan deterioration of induction motors; therefore, care must be given for mitigation. From these results of a detailed energy audit, the harmonic mitigating filter design is proposed, and its effectiveness studies after installation of the same as a post-audit phase.

V. Results and Discussion of Post-Audit Analysis of Industrial Power System

A. Effect of filter in power system

Figure.7 and 8 illustrate the graphical representation of time versus voltage profile without- de-tuned reactor and with- de-tuned reactor configuration, respectively. The prominent abnormalities are noticed during the without filter configuration. The voltage profile is increased by 1.6% from the fundamental level (without filter configuration). The enhanced voltage is clear for the effectiveness of de-tuned reactor configuration. Similarly, Figure.9 and Figure.10 illustrate the graphical representation of time versus current profile without- de-tuned reactor and with- de-tuned reactor configuration, respectively. The with-filter configuration current profile shows that the maximum utilization of loads is nearly balanced and with little fluctuations compared to without filter configuration.

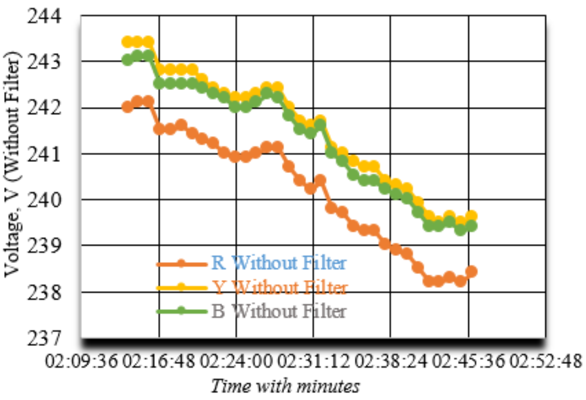

FIGURE 7. Voltage versus time (without filter)

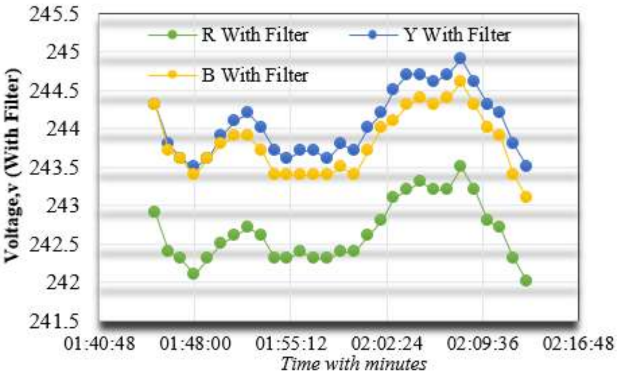

FIGURE 8. Voltage versus time (With filter)

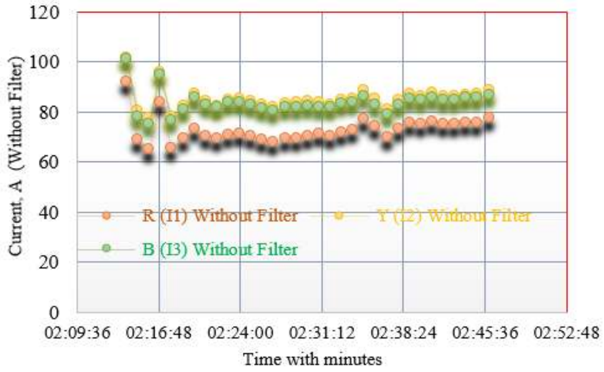

FIGURE 9. Current versus time (without filter)

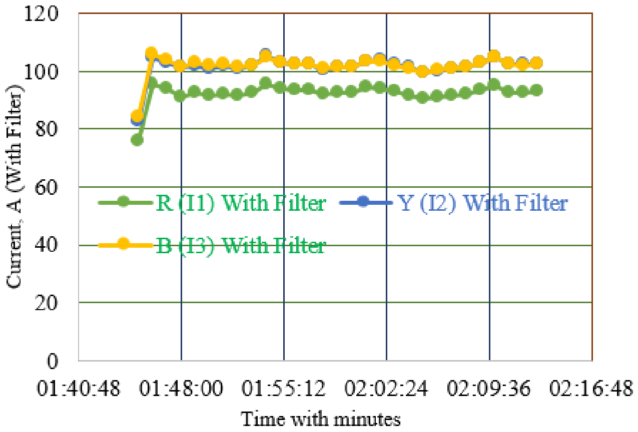

FIGURE 10. Current versus time (with filter)

Figure. 11 and Figure.12 illustrate the graphical representation of time versus V-THDF profile without- de-tuned reactor and with- de-tuned reactor configuration, respectively. As per the IEEE 519-2014 and IEC 61000 standards, at the PCC [15], the maximum allowable V-THDF of 5%. The system configuration without a de-tuned reactor is recorded as 2.77 %. The configuration with a de-tuned reactor is recorded as 2.67 %. The effectiveness of with- de-tuned reactor configuration is clear by the reduction of V-THDF by 3.61%. The lower effectiveness of harmonic voltage suppression is mainly due to inductance value selection. The selection of inductance value is restricted to 90% of the predominant harmonic frequency. The presence of current harmonics is predominant in the system.

Therefore, harmonic voltage mitigation has a lower significance. However, the voltage harmonic level is under the limits of Central Electricity Authority guidelines at the point of common coupling.

Figures 13 and 14 illustrate the graphical representation of time versus I-THDF profile without- de-tuned reactor and with- de-tuned reactor, respectively. The maximum allowable I-THDF of 8% is the IEEE 519-2014 and IEC 61000 standards at the PCC. The system configuration without a de-tuned reactor is recorded as 15.5 %. The configuration with a de-tuned reactor is recorded as 5.2 %. The effectiveness analysis was carried out at the constant loading condition. The effectiveness of with- de-tuned reactor configuration is clear by the reduction of I-THDF by 66.45 %. The passive filter's effectiveness is highly significant from the overall power quality analysis of with and without- de-tuned reactor configuration. It enhances the overall system health and efficiency by suppressing voltage and current harmonics.

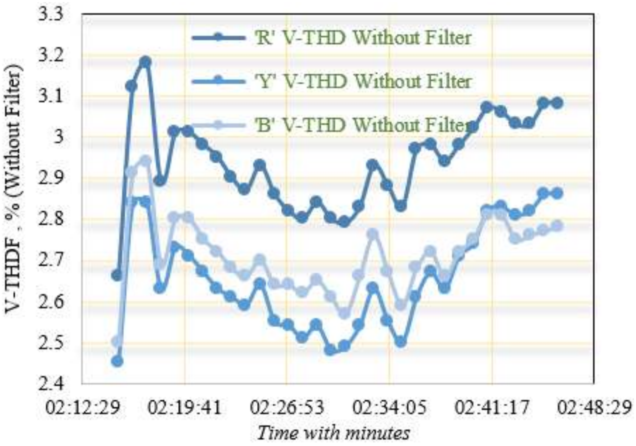

FIGURE 11. V-THDF versus time versus (without filter)

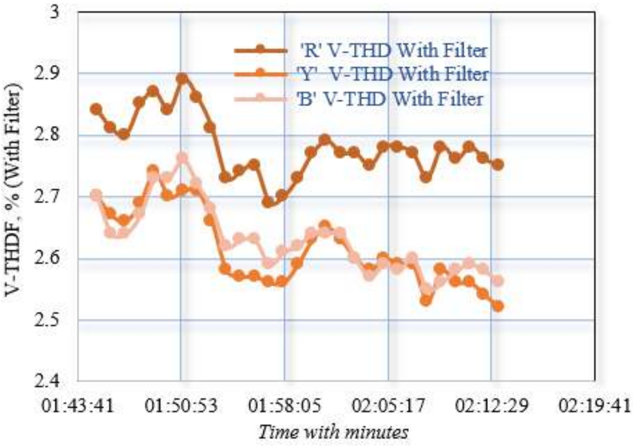

FIGURE 12. V-THDF versus time versus (with filter)

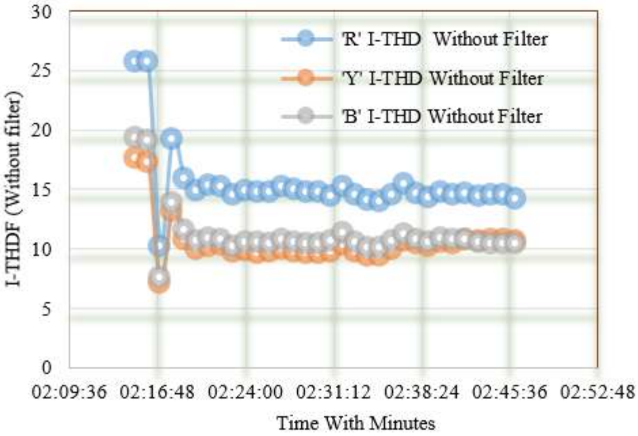

FIGURE 13. I-THDF versus time (without filter)

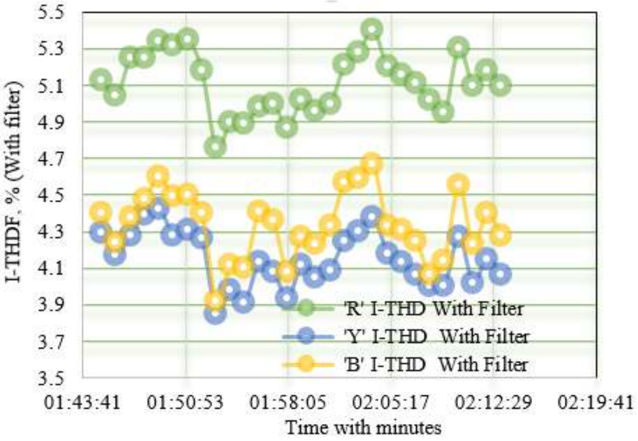

FIGURE 14. I-THDF versus time (with filter)

B. Effect of filter on motor performance

The mechanical anomalies like noise, temperature, and torque ripples are highly developed due to the voltage harmonic distortion. The rise in motor temperature is directly associated with the presence of voltage harmonics in the system. As per the National Electrical Manufacturers Association (NEMA) recommendations, 5% of the voltage-total harmonic distortion factor in the system could reduce the overall motor capacity up to 95% from its full performance percentage [16].

With harmonics, the high frequency in the system will lead to an increase in the overall effective resistance of the motor winding. This increased effective resistance is due to the skin effect, and it leads to an enormous amount of copper loss and motor life span reduction. The voltage unbalances in the system unbalance the motor current by almost 6 to 10 times than the rated current. Therefore, the overall performance and life span of the motor are reduced drastically in the textile industry. The proper balancing of loads [17] ensures the better performance of electric loads.

Figure. 15 Shows the Infrared thermography of the motor winding, which is taken during the industry's operation without a passive filter in the system. The motor winding temperature is higher than the manufacturing specification due to voltage harmonic distortion in the textile industry.

Figure.16 gives the motor winding infrared thermography when the passive filter is switched ON in the industrial power system.

The IEC 60034-26 (Voltage Unbalance Factor) is calculated for the industry from the detailed voltage analysis. The 100 times the ratio of maximum deviation of voltage from the average voltage of the three-phase system to the average voltage defines the percentage voltage unbalance factor. The percentage voltage unbalance factor is about 1 % without filter configuration and less than 0.2% with filter configuration. Therefore, the maximum utilization of motor full load capacity (say 100%) is possible because of a reduced voltage imbalance in the system by installing the passive filter.

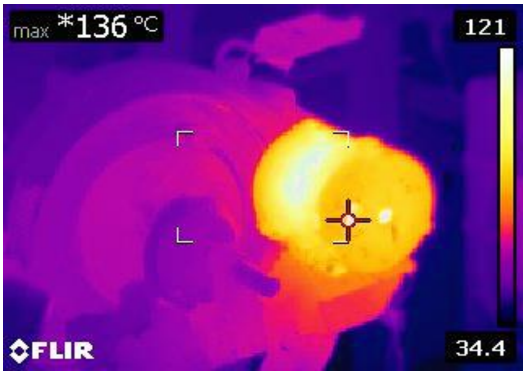

FIGURE 15. **Infrared Thermography of Motor without Filter configuration**

FIGURE 16. **Infrared Thermography of Motor with Filter configuration**

C. Effect of harmonics in lighting system

The existing lighting infrastructure of the industry is entirely powered by 50-55 circuitry watts of the fluorescent lamp. The precise lux measurement is carried out in the various working locations of the industry. As per BEE's lighting recommendations, the 150-lux level should be adequate for Bale breaking, blowing, carding, roving, slubbing, spinning (ordinary counts), winding, heckling, spreading, and cabling purposes. The recommended lux level of 200 is required for Warping, slashing, dressing, dyeing, doubling (fancy), and spinning (fine counts). The 700-lux level is necessary for healing, weaving, and cloth inspection in the Indian textile industry premises.

Based on the measured lux level, sufficient lighting of 350 lux is provided in the winder, wrapper, and shuttle loom sections. The periodic maintenance for dustless operation is suggested for the better lux level output from the existing lighting infrastructure. In addition, the 350 lux is not adequate for the weaving section. Therefore, the retrofitting of fluorescent lamps with the energy-efficient LED lighting system for the recommended lux level with better power quality (voltage and current harmonics).

The non-linear load-LED has a significant power quality impact on the power system. The recent LED driver circuit development is incorporated [27] with the passive filtering circuit for harmonic mitigation. Therefore, the retrofitting of fluorescent lamps with energy-efficient LED lighting significantly reduces harmonics [18] in the system. The IEEE 519-2014 and IEC 61000-3-2 Electromagnetic compatibility (EMC) limit the system's current harmonics by less than 16A per phase. The recent LED drivers are equipped to provide sophisticated power factor improvement with the harmonic mitigation of I-THDF up to 43% [19].

D. Techno-economic analysis on textile industry energy conservation

The power factor and harmonics are the crucial parameters in the power system [20]. The power factor improvement techniques and harmonic mitigation have a significant scope on economic benefits, respectively. As per the Central Electricity Authority (CEA) and Tamil Nadu Electricity Regulatory Commission (TNERC) guidelines [21], the voltage total harmonic distortion factor greater than 5% is not permissible. Also, the current harmonics greater than 8% is not recommended for the HT-Tariff- III consumers. The harmonics dumping level greater than the allowable limit will be penalized by 15% of their current consumption charges of the monthly energy bill. The dispensation of power factor compensation below 0.75 is penalized by 2 percent of the current consumption charges of the monthly energy bill. The one unit (kWh) of electricity under the HT-Tariff- II costs about 8 rupees and a demand charge of 350 per kVA/month. The payback period is the ratio of capital investment cost to the annual cost saving [22] and is shown in (7).

$$simple\_payback = \frac{\text{Capital Cost}}{\text{Annual Savings}} \qquad (7)$$

The detailed energy audit of the textile industry under investigation shows that the voltage and current total harmonic distortion are recorded as 2.27 % and 15.77 %, respectively. The percentage harmonics recorded are more significant than the TNERC guidelines. In addition, the average recorded lagging power factor of 0.9 is recorded at the point of common coupling. The lagging power factor of 0.9 is considered being a poor power factor as per the guidelines of TNERC.

According to the Central Electricity Authority (CEA) and Tamil Nadu Electricity Regulatory Commission (TNERC) guidelines, the penalty levitated towards the energy utilization of the textile industry is summarized. The monthly energy consumption of 10,000 kWh is recorded in the history of energy consumption. Based on the current consumption charges of HT-tariff-III, the sum of rupees 25,000 per month penalty will be levitated towards the poor power quality, and the sum of rupees 3,350 fine is levitated towards the lagging power factor. Therefore, rupees 28,350 is levitated towards the poor power quality to the textile industry under investigation.

At the point of common coupling, the voltage total harmonic distortion factor, current total harmonic distortion factor, and power factor of the textile industry are enhanced by installing the harmonic filter. The overall power quality of the textile industry is improved to eliminate the penalty levitated by CEA and TNERC on the HT-tariff III guidelines. The overall capital investment includes the materials cost, labor cost, interest, tax, and depreciation cost of 10% towards the design and installation of harmonic filter is calculated and reported. The following components like de-tuned reactors: heavy-duty power capacitors, multi-function harmonic indicator, control relay, contactors, moulded case circuit breakers, miniature circuit breakers, high temperature withstanding wires, and cable incomer, enclosure with a protection class of IP42 were included in the investment cost of the harmonic filter. The installation and commissioning of a harmonic filter are calculated as rupees 2300 rupees per kVAR. Therefore, from the specifications mentioned above, the investment cost for a harmonic filter is about 1, 70,000.00 Rupees. The installation of a harmonic filter achieves an annual saving of 3 40,200.00 rupees. The simple payback period of 0.5 years or six months is highly economical and technically workable for significantly enhancing overall power quality.

The voltage and current harmonic distortions are prone to generate additional system losses. The additional system losses include copper and eddy current loss in the distribution transformer. Also, current harmonics increases the system joule losses in the conductor and asynchronous machines. The current (I_{rms}) is greater than the fundamental current in the harmonic prone environment. These additional energy losses have been mitigated through the installation of a passive filter. Figure.17 compares the percentage of total harmonic distortions versus joule losses and current (I_{rms}). Based on the installation of a passive filter, energy conservation is achieved through continuous power quality improvement.

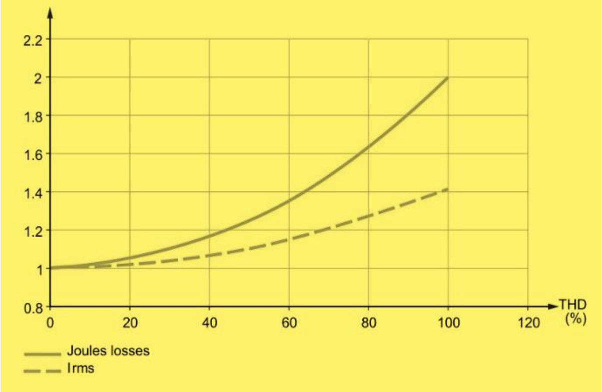

FIGURE 17. Harmonic Distortion versus Additional System losses [23]

In addition, the industry is powered by 160 numbers fluorescent lamps with a low lux level from the detailed lighting analysis. Therefore, good quality 20-watt energy-efficient LED installation could save 51.2 kWh of power-saving per day of 20 operating hours. As per India's Central Electricity Authority (CEA) [24], 1.04 kg-CO2/ kWh is the assumption for India's CO2 emission calculations. The annual energy saving of 18,432 kWh has direct scope for annual carbon emission reduction of 19,170 kg (or) 19.17 tons from the industry. The detailed energy and economic analysis for energy conservation measures help in cost estimation and payback calculation [25] for LED retrofitting of the textile industry. The cost economics for the retrofitting of LED gives the payback period of fewer than 1.2 Years. Therefore, LED retrofitting is highly economical and eco-friendly.

VI. CONCLUSION

The detailed energy auditing of the textile industry is carried out by adopting the systematic energy auditing methodology. The scope for energy conservation through power quality improvement is presented in work successfully. From the textile industry's detailed energy auditing, the Voltage Total Harmonic Distortion Factor (V-THDF) and Current Total Harmonic Distortion Factor (I-THDF) are within IEEE 519-2014's standard limits IEC 60034-26. The installed passive filter achieves the V-THDF reduction of 3.61% and I-THDF reduction of 66.45%. Therefore, the effectiveness of the designed harmonic filter in the harmonic mitigation activity is highly significant.

In the harmonic-prone environment, the harmonic filter achieves an 80% reduction of voltage unbalances. This reduction in voltage unbalances aids in the reduction of motor temperature, noise, and torque ripples. The result of infrared thermography ensures the significant enhancement of three-phase induction motor performance by a 33.82 % reduction in motor temperature. The energy conservation is ensured by reducing joule, copper, and eddy current losses (additional losses). In installing a harmonic filter, the overall cost saving of 3, 40,200 rupees is achieved with a significantly lower payback period of 6 months. The installation of a harmonic filter is highly economical and workable.

In lighting, the retrofitting of fluorescent lamps with the energy-efficient Light Emitting Diode (LED) lamp ensures the significant annual energy saving of 18,432 kWh with a payback period of fewer than 1.2 years. In addition, sustainability is ensured by 19.17 tons of annual carbon emission reduction. In addition, the installation of solar photovoltaic (renewable energy resources) has significant scope for sustainability.

REFERENCES

[1] D. P. Report, "Bureau of Energy Efficiency," 2021. https://beeindia.gov.in/content/publications-0 (accessed Jul. 23, 2021).

[2] G. B. Hong, T. L. Su, J. D. Lee, T. C. Hsu, and H. W. Chen, "Energy conservation potential in Taiwanese textile industry," *Energy Policy*, vol. 38, no. 11, pp. 7048–7053, 2010, doi: 10.1016/j.enpol.2010.07.024.

[3] G. C. de Oliveira Neto, J. M. Ferreira Correia, P. C. Silva, A. G. de Oliveira Sanches, and W. C. Lucato, "Cleaner Production in the textile industry and its relationship to sustainable development goals," *Journal of Cleaner Production*, vol. 228, pp. 1514–1525, 2019, doi: 10.1016/j.jclepro.2019.04.334.

[4] M. S. Bhaskar, P. Verma, A. Kumar, and N. Delhi, "Indian Textile Industries Towards Energy Efficiency Movement," *International Journal of Environmental Science: Development and Monitoring*, vol. 4, no. 2231, pp. 36–39, 2013.

[5] N. Lalith Pankaj Raj and V. Kirubakaran, "Energy Efficiency Enhancement and Climate Change Mitigations of SMEs through Grid Interactive Solar Photovoltaic System," *International Journal of Photoenergy*, 2021, doi: https://doi.org/10.1155/2021/6651717.

[6] A. Zeaiter, E. Videcoq, and M. Fénot, "Determination of electric motor losses and critical temperatures through an inverse approach," *Electrical Engineering*, 2020, doi: 10.1007/s00202-020-01098-0.

[7] D. Thomas, G. D'Hoop, O. Deblecker, K. N. Genikomsakis, and C. S. Ioakimidis, "An integrated tool for optimal energy scheduling and power quality improvement of a microgrid under multiple demand response schemes," *Applied Energy*, vol. 260, no. December 2019, p. 114314, 2020, doi: 10.1016/j.apenergy.2019.114314.

[8] R. Abdollahi, "Power quality enhancement of a T-connected autotransformer based on 72-pulse AC–DC converter with rated power reduction," *Electrical Engineering*, vol. 102, no. 3, pp. 1253–1264, 2020, doi: 10.1007/s00202-020-00948-1.

[9] A. Eren and A. M. Vural, "Arm cortex M4 microprocessors based ± 100 kVAR energy quality regulator for reactive power/neutral current compensation, load balancing and harmonic mitigation," *Engineering Science and Technology, an International Journal*, 2021, doi: https://doi.org/10.1016/j.jestch.2021.05.022.

[10] L. P. R. Nadimuthu and K. Victor, "Optimization of Energy-Intensive Process in Ayurvedic Medicine Manufacturing Unit—a Case Study," *Process Integration and Optimization for Sustainability*, 2021, doi: 10.1007/s41660-021-00194-3.

[11] A. Ali, Arshad, H. Akhtar, M. U. R. Siddiqi, and M. Kamran, "An efficient and novel technique for electronic load controller to compensate the current and voltage harmonics," *Engineering Science and Technology, an International Journal*, vol. 23, no. 5, pp. 1042–1057, 2020, doi: https://doi.org/10.1016/j.jestch.2019.11.009.

[12] L. P. R. Nadimuthu and K. Victor, "Performance analysis and optimization of solar-powered E-rickshaw for environmental sustainability in rural transportation," *Environmental Science and Pollution Research*, pp. 34278–34289, 2021, doi: 10.1007/s11356-021-12894-x.

[13] P. R. G. N. Lalith, G. Prabakaran, A. Murugaiyan, and V. Kirubakaran, "Hybrid Photovoltaic-Thermal Systems: Innovative CHP approach," in *2018 4th International Conference on Electrical Energy Systems (ICEES)*, 2018, pp. 726–730, doi: 10.1109/ICEES.2018.8442352.

[14] C. Sreenath, S. Prabhakaran, V. Rajakumaran, C. Shankar, S. S. S. Velan, and V. Kirubakaran, "Energy auditing of payment tiles making small scale industry: Suggestions and recommendations for energy conservation," in *2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015]*, 2015, pp. 1–4, doi: 10.1109/ICCPCT.2015.7159445.

[15] US Department of Energy Advanced Manufacturing Office, "Eliminate Voltage Unbalance," 2005. [Online]. Available: http://energy.gov/sites/prod/files/2014/04/f15/eliminate_voltage_unbalanced_motor_systemts7.pdf.

[16] K. Kamaleswaran, M. Venkateshwaran, P. Harinath, M. A. Mydeen, and V. Kirubakaran, "Energy conservation potential in the rural industry: A case study on coir industry," *IEEE International Conference on Circuit, Power and Computing Technologies, ICCPCT 2015*, 2015, doi: 10.1109/ICCPCT.2015.7159444.

[17] N. Phannil, C. Jettanasen, and A. Ngaopitakkul, "Harmonics and reduction of energy consumption in lighting systems by using led lamps," *Energies*, vol. 11, no. 11, 2018, doi: 10.3390/en11113169.

[18] S. E. Remi Bolduc, "Impacts of LED lighting on power quality - EE Publishers," *Articles: EE Publishers, Articles: Energize, Articles: Vector*, 2018. https://www.ee.co.za/article/impacts-of-led-lighting-on-power-quality.html.

[19] S. S. S. Velan and V. Kirubakaran, "Implementation of energy conservation and management activities and its economics in GRI boy's hostel - a case study," in *2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)*, 2016, pp. 1–10, doi: 10.1109/PESTSE.2016.7516491.

[20] R. P. B. da Silva, R. Quadros, H. R. Shaker, and L. C. P. da Silva, "Effects of mixed electronic loads on the electrical energy systems considering different loading conditions with focus on power quality and billing issues," *Applied Energy*, vol. 277, no. May, p. 115558, 2020, doi: 10.1016/j.apenergy.2020.115558.

[21] TNERC, "TAMIL NADU ELECTRICITY REGULATORY Determination of Tariff for Generation and Distribution," 2017.

[22] D. A. Selvaraj and K. Victor, "Design and Performance of Solar PV Integrated Domestic Vapor Absorption Refrigeration System," *International Journal of Photoenergy*, vol. 2021, p. 6655113, 2021, doi: 10.1155/2021/6655113.

[23] Electrical Installation Guide Contributors, "Effects of harmonics - Increased losses," *Electrical Installation Guide*, 2019. http://www.electrical-installation.org/enw/index.php?title=Effects_of_harmonics_-_Increased_losses&oldid=26856 (accessed Aug. 21, 2021).

[24] Central Electricity Authority of India, "CO2 Baseline Database for the Indian Power Sector," *Central Electricity Authority*, 2018. https://cea.nic.in/wp-content/uploads/baseline/2020/07/user_guide_ver14.pdf (accessed May 20, 2020).

[25] S. Yoomak and A. Ngaopitakkul, "The study of harmonic reduction in Light Emitting Diode (LED) roadway lighting system," *Proceedings - 2016 17th International Scientific Conference on Electric Power Engineering, EPE 2016*, 2016, doi: 10.1109/EPE.2016.7521726.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3123153, IEEE Access

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