



Power Supply Energy Auditing Guidebook

1. Introduction

Electrical energy parameters of affordability, availability and sustainability are vital for growth of industrial and commercial services. These parameters are met through actions of different players. Energy auditors can ensure affordability and sustainability of parts of energy supply through conducting energy audits. Auditing power supply is essential to this exercise. An effective energy audit evaluates the entire power supply pathway, from the utility connection, through the distribution system, and finally to the utilization points. This integrated approach ensures that energy losses are identified at every stage, providing a foundation for targeted improvements and informed decision-making.

In this chapter, the guidebook provides a step by step approach the energy auditor can use to identify inefficiencies, compute their magnitude and recommend intervention measures. For auditing of the power system, this chapter handles two sections: components of the power system and the process auditing steps. The equipment powered by the power system – fans, air compressors, pumps and so on – will be discussed in separate volumes. However, plug in loads and motors will be discussed in this volume.

2. Components of a Power Supply System

Components of a power supply system in a facility can be categorized into three sections as illustrated in figure 1.

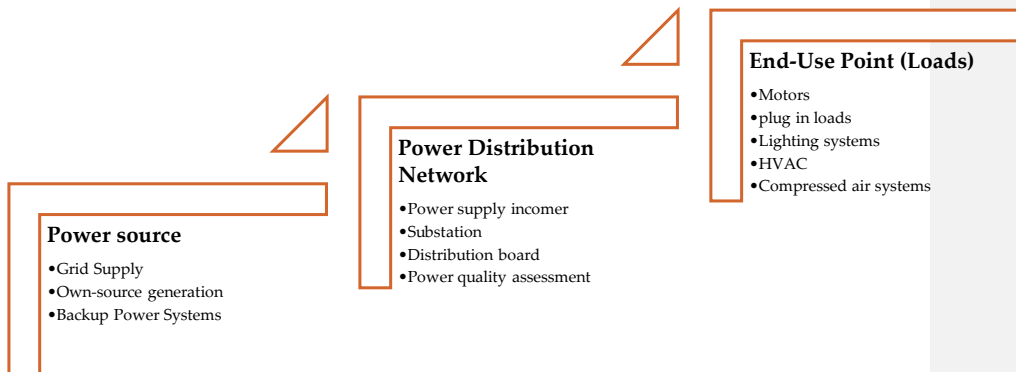


Figure 1 Components of a power supply system

Figure 1 guides the auditor on key components of a power supply system that should be understood prior to initiating a power system energy audit. A whole system audit should consider all the components and their functions.

Power source

A facility could draw electrical power from different sources. These include grid supply, own generation plant and power backup system. It is important for the auditor to establish the actual contribution from each source and their configuration – some are configured to work in hybrid mode where one source is prioritized over the others. For own generation, facilities can get electrical power from onsite mounted solar PV, small hydro, cogeneration, thermal and geothermal power plants.

Sometimes, facility owners with own generation pose the critical question of: “why should I conduct an audit, yet I generate my own power?” It should be noted that the primary energy used for power generation is a shared resource thus mandating every industry player to have a moral duty to use it sparingly. Additionally, saved energy can be used by the facility owner for extra income generation by selling it to



the grid or other consumers. An efficiently run power generation system will have a longer lifespan.

The auditor should also consider the power backup system in the facility. Such systems may consist of either the gensets, Uninterruptible Power Supply (UPS), energy storage systems, or a combination.

Power distribution network

Power distribution network is the infrastructure that supplies power to the points of use within the facility. A single line diagram should be available to aid the auditor to understand the network. In the absence of the single line diagram, the auditor should establish the key subsystems and consumption points in the network.

There are two major power supply system configurations depending on the ownership of the substation that an energy auditor may encounter. In one scenario, the utility owns the substation and the facility is metered on the Low Voltage side of the transformer while in the other scenario, the facility owns the substation and metering is done on the High Voltage side of the transformer. The facility may also have other transformers in different areas to power specific sections. In cases where the substation is owned by the facility, it should then be covered during the audit process.

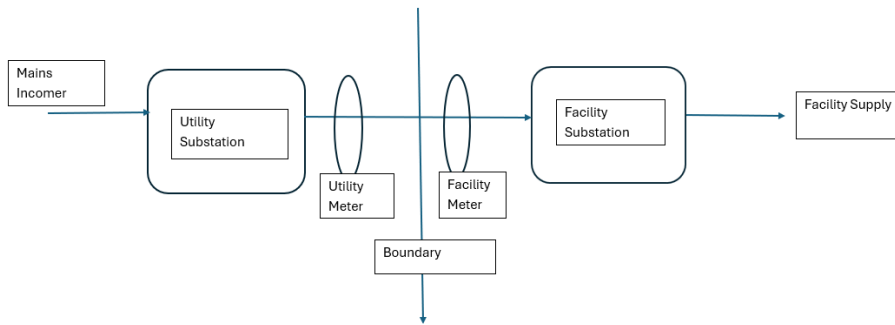


Figure 2: Secondary Substation owned by the Facility.

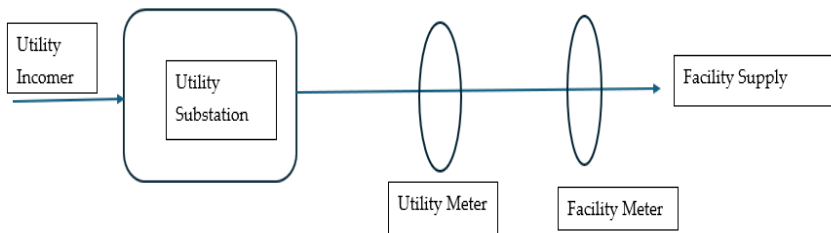


Figure 3: Utility Owned Substation

The power distribution network is discussed as follows.

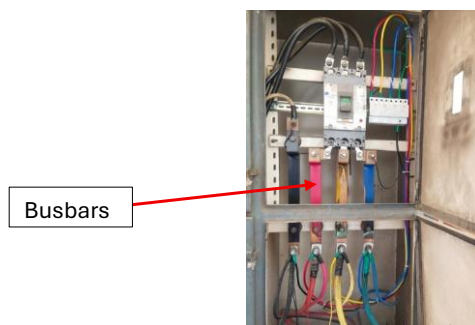
Power supply incomer	This is the interface between the utility and the facility. It includes the switchgear, instrument transformers and protective equipment which are essential for operations of the network.
Substation	A substation consists of a transformer(s) and the associated equipment. The transformation capacity and



supply voltage of the substation varies according to the power requirements of a facility. In some of facilities power is supplied at High or medium voltage. In most jurisdictions, the facility will be required to set up their own substation. The auditor should analyze the performance of such a substation.

Distribution board

This is the main point from which power is distributed to the points of use. It has busbars for connection to other circuits.



Sub Distribution Boards (SDB) receive power from the MDB and distribute to the specific loads or functional areas such as administration blocks, production lines, cold rooms, or workshops. Normally, the MDB and SDB are integrated with internal metering, protective devices, power factor correction equipment, voltage stabilizer and changeover switches.

In properly installed systems, the facilities label the power feeders to the loads. This makes it easy for the energy auditor to identify the areas of interest while



taking measurements. In cases where the labelling is missing, the auditor should enlist the assistance of the facility technician or engineer to guide. Likewise, the auditor should understand the direction of the power flow. This determines the location from where the power measurements should be conducted and the positioning of the current transformers.

Power quality equipment	Power quality determines how well and efficiently the equipment will operate in the facility. In the distribution network, some of the parameters used to determine the power quality include voltage levels, power factor, frequency and harmonics. To obtain the desired power quality, it may be necessary to install corrective equipment. Power quality equipment includes power factor correction equipment, voltage stabilizer and harmonics filter among others.
Cabling and Wiring Infrastructure	Cables and wires deliver power to sections or equipment in the facility. The appropriate sizes of the busbars and cables in the network ensure they meet the current rating of the loads connected.
Earthing System	Earthing is primarily done for safety purposes. However, it also improves power quality by providing a path for the leakage currents. This leakage current leads to undesired additional current on the neutral.



End-Use Points

These are the points or applications at which the electrical power is utilized. The electrical power is converted into the required form such as mechanical, heat and light. This conversion is achieved through use of equipment such as motors, lighting appliances, plug loads, electric heaters, HVAC and compressed air systems.

3. Process Auditing Steps for Power Supply System

The energy audit of power supply systems has three fundamental steps as illustrated in figure 2.

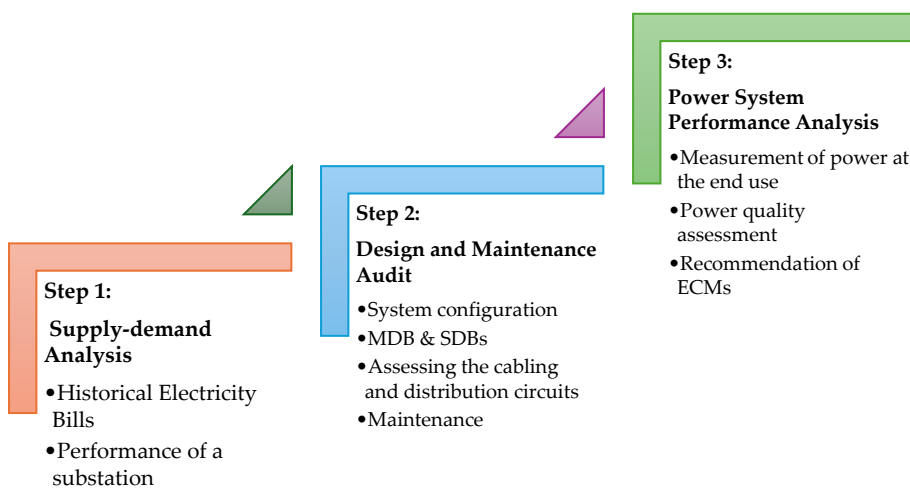


Figure 4 Steps in auditing power supply systems

Step 1: Supply-Demand Analysis

The audit of a power supply system begins at the interface between the facility and the utility provider, progressing through the substation, service entrance infrastructure, main distribution arrangements, and metering installations. The aim is to assess if the facility receives adequate, stable, reliable and quality electrical power. The auditor should examine the tariff structure, contracted demand and historical billing data. Additionally, the auditor should determine facility's power requirements and compare them to the capacity of the substation.



i. Historical bills

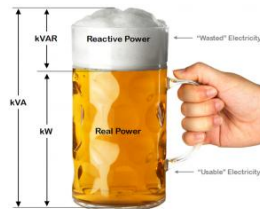
Historical bills can aid the auditor to establish the tariff category and historical consumption of a facility. The bill structure consists of the following components:

Energy charge	Energy charge rate is the cost per kWh for actual energy consumed. To obtain the total energy cost, energy charge rate is multiplied by the units consumed during the billing period.
Maximum demand charge	Power supply has two components: active (kW), reactive (kVar) whose vector sum becomes the apparent power (KVA). Apparent power is used to measure the facility's maximum demand. For grid efficiency and stability, the utility is interested in having low apparent power as possible relative to the active power. As such, this maximum demand is billed separately from the active power. Different tariff structures assign the cost to the maximum demand using different criteria. In Kenya, for example, facilities supplied at high voltage pay lower charge rate compared to those at medium and low voltage supply. There are other countries where the higher the voltage supply level, the higher the demand charges.
Time of use (ToU) rate	This is a time-based pricing structure where the electricity rates vary according to the time of use. In some instances, the rate is higher during a particular time of the day. ToU can be dynamic (based on the electricity market



demand and supply market forces) or static with specific time bands defined in the tariff structure.

Power factor surcharge Power factor is the ratio of active power (kW) to apparent power (kVA). Apparent power is the vector sum of active and reactive power (kVAr). Active power is the useful power that does work, while reactive power is needed to energize magnetic fields. This can be explained using the beer analogy as shown:



In power supply systems, utilities would want to supply as little reactive power as possible. While reactive power is necessary for power transfer, excess reactive power reduces the grid capacity to transfer useful power. It is incumbent upon facilities to manage their appliances in a manner that reduces the reactive power drawn from the grid. To manage this, the utility imposes a minimum value of demand side power factor that a facility should maintain. In some jurisdictions, however, the utility takes the responsibility of managing the power factor.

In Kenya, the minimum power factor set by the utility is 0.9. A violation of this attracts a power factor surcharge. A facility is issued with a warning three times before this



surcharge is implemented. This means that the first three violations do not incur a penalty.

Variable costs	These are costs that a utility imposes on consumers to reflect the changes in the market conditions related to power generation. These costs vary per billing cycle. They include fuel cost, foreign exchange rate (FOREX) adjustment, inflation adjustment cost and congestion fee.
Levies	These are fees, defined by legislation, that utilities collect on behalf of government agencies. In Kenya, these include Water Resources Authority (WRA) levy, Rural Electrification Program (REP) levy, and Energy and Petroleum Regulatory Authority (EPRA) levy.
Taxes	Mandatory charge levied by the government on the electricity bill such as Value Added Tax (VAT)

An analysis of the bills provides a cost breakdown of each of the above components. This will inform interventions that can be made in the power supply system to reduce costs and improve efficiency. These include reducing the maximum demand by load shifting or shedding, improving power factor by installation of power factor correction equipment, and tariff migration. Comparison of energy consumption to production per billing cycle provides the energy utilization index (EUI). The trends in EUI may provide insight into efficiency of the facility.

ii. Performance of the substation

Energy auditing of a substation or transformer installation should focus on evaluating its performance. This evaluation helps to identify energy losses, loading conditions and improvement opportunities. However, this analysis only applies to facilities with utility metering before the transformer (on the high voltage side). This is important



because the transformer performance contributes to the energy bill. The energy auditing of a substation begins with:

a. Visual and physical inspection

A comprehensive energy audit of a substation begins with a detailed visual and physical inspection, which provides the foundational understanding of the equipment's condition before any measurements are taken. At this stage, the auditor should:

- i. Check for oil leaks on the transformer tank and radiators
- ii. Examine the condition of bushings for cracks or contamination
- iii. Look for signs of overheating on connections, cables, or busbars
- iv. Verify the position and condition of the tap changer
- v. Verify the operational status of cooling fans and radiators
- vi. Examine the integrity of grounding and bonding systems.
- vii. Check if the substation environment is clean, dry, and free of obstruction.
- viii. Listen for unusual sounds beyond the normal humming of the transformer

The insights gathered from the visual and physical inspection guide the next step of operational measurements.

b. Operational measurements

The performance of a transformer can be determined by measuring its input and output characteristics and comparing them to the rated values. The rated characteristics are indicated on the nameplate or transformer manual. An example of a transformer nameplate showing its parameters is provided in Figure 3.

EPRA
Energy & Petroleum Regulatory Authority

Type TNOSCT-100/11PNS UNI		
No. 1LPL525913	Year of manufacture 2014	
Rated power 100	kV-A	No. of phases 3
TRANSFORMER to specification EN (IEC) 60076-1		
Rated voltage [V]	Current [A]	Insulation level
HV 11000 ± 2x2.5%	5.25	LI75 AC28
LV 415	139.10	AC3
Tap no.	HV voltage [V]	Connection symbol
1	11550	Dyn11
2	11275	Cooling ONAN
3	11000	Rated frequency 50 Hz
4	10725	Short-circuit imp. 3.88 %
5	10450	Load losses 1750 W
Ambient temp. 40°C		No-load losses 145 W
Temperature rise of:		Total mass 463 kg
Windings 60K		Mass of active part 279 kg
Oil 55K		Mass of oil 100 kg
Type of oil Mineral Nyltro Taurus		Oil to IEC 60296
Windings material HV/LV: Al/Al		Core material: grain-oriented electrical steel
Mass of windings: 53kg		Mass of core: 169kg

Figure 5: A nameplate showing the operating parameters of a transformer

The measurements such as, kVA loading, voltage and current values and temperature are compared with the parameters of the transformer as provided in the nameplate. Measuring equipment such as the power quality analyzer is used to measure the kVA loading, voltage and current. Thermal imaging can be used to identify hotspots, loose connections, or localized insulation weaknesses on the transformer.

These measurements aid in determining whether the transformer is operating at an optimal level. The comparison between the nameplate values and actual measurements help identify issues such as overloading, equipment derating, or inappropriate tap settings that may affect efficiency or reliability.

c. Transformer efficiency analysis

Having carried out measurements and comparison done, the energy audit progresses to a detailed assessment of the transformer's efficiency, losses and loading. To establish the transformer efficiency equation 1 is used.

$$\eta_T = \frac{P_{out}}{P_{in}} \times 100 \quad (1)$$

Alternatively:



$$\eta_T = \frac{P_{out}}{P_{in} + L_T} \times 100 \quad (2)$$

Where

η_T	Transformer Efficiency
P_{in}	Input Power
L_T	Transformer losses
P_{out}	Output Power

L_T is:

$$L_T (kW) = \text{No load loss} + \left(\left(\frac{\text{measured apparent power (kVA)}}{\text{rated apparent power (kVA)}} \right)^2 \times \text{full load loss} \right) \quad (3)$$

No load loss and full load loss are provided in the nameplate of the transformer. The measurements should be conducted to cover an operation cycle.

d. Transformer loading assessment

Transformer loading analysis is done to determine whether a transformer is optimally loaded, overloaded or underloaded. When the transformer is underloaded, its efficiency reduces. Overloading transformers results to poor power quality and reduced lifetime.

The energy auditor should measure load current and voltage per phase, power factor and power demand. These measurements should be carried out for at least for full operation cycle of the facility. Transformer loading is calculated using equation 3:

$$\% \text{ Loading} = \frac{\text{measured kVA}}{\text{transformer kVA rating}} \times 100\% \quad (4)$$

It is recommended that KVA profile be derived for the operation cycle and loading factor calculated on hourly basis. Most transformers perform optimally at 30-70%



loading. It is important to note that overloading a transformer increases its internal temperature. This leads to overheating which results in exponential insulation aging damaging the transformer. Additionally, overloading leads to frequent tripping which results in unreliable power supply. On the other hand, underloaded transformers have poor efficiency. This is as a result of the no-load losses dominating the transformer losses, leading to the facility having poor power factor.

Underloading and overloading efficiency problems can be determined using the transformer loading- efficiency curves. These curves are empirically determined and cover different transformer capacities. Figure 6 presents such a relationship.

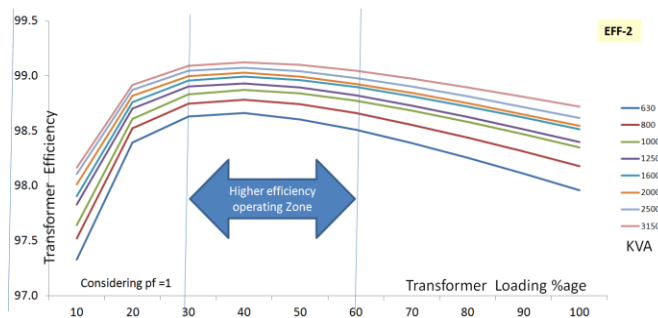


Figure 6: Transformers efficiency curves

An auditor can use the curves and the identified transformer loading to determine the losses. Take for example a 630 kVA transformer loaded at 10% as illustrated in figure 6, this translates to an efficiency of 97.3%. If the transformer was optimally loaded (30-60% loading), the efficiency would have been 98.5%. This is 1.2% energy savings. Similar computations can be done for transformer loading.

Worth noting is that parallel operation of transformers reduces the overall impedance to power flow by a factor equivalent to the number of transformers in operation. It should also be noted that some facilities may have widely varying transformer load profiles due to differences in consumption across different equipment and time. A case



in point would be a facility with two related factories operating in batch processes, where factory A's output is used as an input in factory B. Facilities such as Tobacco processing plant and dairy factories operate under such arrangements. If such arrangements are supplied by only one transformer, they can lead to cases of substantial underloading when one factory is un-operational. In such circumstances, the auditor may guide the facility to have separate transformers for the different load centres.

Example 1

- a. A plant has two identical **500 kVA** transformers, each with a no-load loss of **0.80kW** and full load copper loss of **6.0 kW**. The plant average load is **430 kVA** and has never exceeded **455 kVA** in the past. An energy auditor while conducting the energy audit found that only single transformer is kept in operation and second transformer is switched off. Establish whether one transformer should be running or the transformers should run in parallel.

b. DATA

c. Monthly Power Data

Month	KVA	kW	PF
1	454.50	431.78	0.95
2	450.80	419.24	0.93
3	430.70	387.63	0.9
4	431.00	379.28	0.88
5	425.40	361.59	0.85
6	427.20	375.94	0.88
7	438.30	363.79	0.83
8	445.00	364.90	0.82
9	429.20	347.65	0.81
10	420.60	386.95	0.92
11	428.10	389.57	0.91
12	421.20	370.66	0.88
13	418.60	343.25	0.82
14	431.40	396.89	0.92
15	451.00	428.45	0.95
16	451.00	383.35	0.85
17	420.10	369.69	0.88

18	417.20	346.28	0.83
19	434.40	356.21	0.82
20	418.10	342.84	0.82
21	433.70	390.33	0.9
22	426.50	405.18	0.95
23	416.20	407.88	0.98
24	401.10	381.05	0.95
Ave	430.05	380.43	0.88

d.

e. Measured daily

Time - hr	KVA	KW	PF
1.00	456.80	433.96	0.95
2.00	454.80	422.96	0.93
3.00	435.70	392.13	0.90
4.00	428.10	376.73	0.88
5.00	425.60	361.76	0.85
6.00	425.30	374.26	0.88
7.00	441.30	370.40	0.84
8.00	442.00	363.53	0.82
9.00	453.20	372.75	0.82
10.00	421.60	387.87	0.92
11.00	418.10	380.47	0.91
12.00	431.20	379.46	0.88
13.00	418.60	343.25	0.82
14.00	431.40	396.89	0.92
15.00	451.00	428.45	0.95
16.00	411.00	349.35	0.85
17.00	421.30	370.74	0.88
18.00	41.50	34.83	0.84
19.00	454.40	373.73	0.82
20.00	448.10	407.77	0.91
21.00	433.70	390.33	0.90
22.00	426.50	405.18	0.95
23.00	437.20	428.46	0.98
24.00	421.10	400.05	0.95
Average	417.90	372.72	0.89

Answer.

a. Work out the total losses when **single** and **both** transformers are in operation. The Analysis will be like this;

i. Transformer Losses (when 2 transformers are in operation)

No load loss = 0.80 kW / transformer

Full Load loss = 6.0 kW / transformer

Full Load loss at operating load = $(215/500)^2 \times 6.0 = 1.1094$ kW/ transformer

Operating loss per transformer = $0.80 + 1.1094 = 1.9094$ kW / transformer

Operating loss for both the transformers = $1.9094 \times 2 = 3.8188$ kW

ii. Transformer Losses (when 1 transformer is in operation)



No load loss = 0.80 kW

Full Load loss = 6.0 kW

Full loss at operating load = $(430/500)^2 \times 6.0 = 4.4376$ kW

Operating loss per transformer = $0.80 + 4.4376 = 5.2376$ kW

Increase in transformer losses (when 1 transformer is in operation) = $5.2376 - 3.8188 = 1.4188$ kW

The plant should operate two transformers in parallel operation, as there is a power saving potential of 1.4188 kW

Step 2: Design and Maintenance Audit

Once the incoming power supply system has been assessed and its performance clearly understood, the energy audit progresses into evaluating the internal power distribution system. This stage examines how electrical energy is routed from the main distribution board (MDB) through feeders, sub-distribution boards (SDBs), protective devices, and cabling networks to the final loads. The auditor should determine the efficiency, reliability, safety, and suitability of the distribution infrastructure, and identify opportunities for minimizing technical losses and improving operational performance.

i. Main Distribution Board (MDB)

The auditor should evaluate connections at the MDB to assess the condition of the cables, busbars and breakers. Some anomalies that can be picked out at the MDB include loose connections, degraded busbars, noise, scorched and charred cables, and historical breaker trips. These provide an indication of inefficiencies downstream. Attention should be given to panel cleanliness, ventilation, and the presence of VFDs or soft starters.

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During an energy audit, power at the main incomer is logged at the MDB. The logged data is analyzed to identify current and voltage imbalances, global power factor, load profile and harmonics.

In some instances, the facility can be overbilled due to inaccuracy of the utility meter. The auditor should ascertain the accuracy of the utility meter. This can be done by comparing the readings from the utility meter against the readings from the energy logger used during the audit.

ii. Sub-distribution boards (SDBs) and protective devices

From the MDB, the auditor moves outward through the SDBs. SDBs supply power to specific loads, departments or functional areas, for example: administration blocks, production lines, cold rooms, or workshops. Each SDB is inspected for rating compliance, proper labeling, breaker condition, phase balancing, and conductor sizing.

iii. Energy metering and sub-metering

Energy metering and submetering exist in a facility for monitoring, accountability and decision making. Where a facility does not have submeters, the auditor may recommend installation. This will aid in setting sectional energy performance targets and tracking them. This way, each section in the facility becomes accountable for energy efficiency interventions.

iv. Assessment of the cabling and distribution circuits

Cable sizes determine the voltage drops and the resistive losses. The auditor should thus assess the conductors to determine if their size is suitable for the current flowing through them. Undersized cables lead to increased energy losses. Unnecessarily long cables can lead to avoidable voltage drops. In tea factories, for example, significant voltage drops are frequently found in long cable runs to remote withering trough motors, resulting in higher current drawn and increased energy consumption. The



auditor should calculate voltage drop (using actual measured values), compare it to allowable limits (typically below 5%), and identify parts of the network where conductor upgrading or re-routing would be beneficial.

The auditor can use a thermal imaging camera as one of the ways to detect undersized conductors, overloaded circuits and loose terminations which manifest as hotspots in the images. Other methods include visual examination of insulation for any sign of burn out.



v. Power quality assessment

Power quality can have an effect on the energy performance of electrical equipment. Apart from analysing the power parameters at the MDB, the auditor should assess the power quality within the internal distribution network. The auditor should take measurements at the SDBs to determine the power quality characteristics such as voltage dips, swells, flickers and fluctuations, harmonics, transient spikes, and frequency variations.

In manufacturing plants with induction motors for example, auditors may observe voltage dips during motor starting, necessitating recommendations for soft starters, VSDs, or staggered starting sequences. Similarly, facilities with solar PV systems integrated through inverters may exhibit harmonic distortion or power factor variations, depending on inverter technology and loading conditions.

The auditor should record and interpret these parameters using power quality analyzers. These parameters should then be linked to equipment performance or premature failures observed during the equipment inventory.

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Step 3: Power System Performance Analysis

Power quality assessment

Electric power quality is the degree to which the voltage, frequency, and waveform of a power supply system conform to established specifications. To establish the power quality at the point of use, measurements are taken at the equipment terminals. This is done to determine the voltage levels, phase-to-phase and phase-to-neutral imbalance, voltage drops, current distribution, harmonics, power factor, frequency stability, and starting currents. These measurements help detect undesired conditions such as voltage fluctuations, load imbalance, Total Harmonic Distortion (THD), and poor power factor.

The auditor should evaluate the load characteristics and operating profile, including:

Electricity baseload	The auditor should compare the readings of energy consumption during the baseload period and the computed energy inventory of the baseload equipment in the facility. Baseload equipment in a facility could comprise appliances such as security lighting, servers and phantom loads. If the measured baseload is over 15% (as per ASHRAE standards) higher than the computed energy consumption from the baseload equipment, the auditor should investigate the discrepancy, determine its root cause, and provide appropriate recommendations.
Part-load operation	The part-load depends on the operations and equipment efficiency. This will be dealt with in specific volumes of this guidebook.



Peak demand In steady operations, the peak demand should almost be always constant. During measurements if an auditor observes an outlier peak demand, they should investigate. In some instances, the auditor may need to investigate the peak by observing how the facility staggers its loads.

For load characteristics electricity load factor is calculated using equation XX.

$$\text{Load Factor (\%)} = \frac{\text{Energy Consumption in the Billing Period (kWh)}}{\text{Maximum Demand (kW)} \times \text{Time in Billing Period (hr)}} \times 100 \quad (5)$$

The load factor is the utilization rate or efficiency of electrical energy usage. A high load factor indicates that the load is using the electric system more efficiently, whereas consumers that underutilize the electric distribution will have a low load factor. It is a useful method of determining if a facility is utilizing its electrical equipment consistently (higher LF) or using the equipment for a shorter duration (lower LF), thereby paying a demand penalty. An average load factor of 50% is preferable for demand charge per kVA as applied under commercial industrial (CI) tariff

After evaluating the load characteristics and operating profile, the auditor should analyze the following: power factor; THD; and voltage and load imbalance.

Power factor

Power factor is an indication of how efficient electrical energy is converted into useful work. In mathematical terms, Power Factor (PF) is represented by equation

$$PF = \frac{\text{real power (kW)}}{\text{apparent power (kVA)}} \quad (6)$$

The relation between apparent power, real power and reactive power can be illustrated using figure 6.

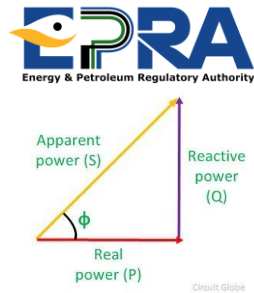


Figure 6 Relationship between apparent, real and reactive power

As illustrated in figure 6, power factor is calculated using equation xx:

$$PF = \cos \phi \quad (7)$$

Ideal power factor should be 1. This can be attained for purely resistive loads. However, most loads in a facility are inductive in nature and as a result the power factor is less than one. During an energy audit, PF is directly measured using a power quality analyzer. The obtained value informs the auditor if power factor correction is necessary.

During an energy audit, the auditor should analyze the electricity bills to get the average monthly power factor. They should also take measurements on the main incomer to verify the power factor. The auditor can then design a power factor correction bank with the aim of improving the power factor to meet the utility threshold. It is, however, desired that the power factor be as close to unity as possible. When designing a power factor correction bank, care should be taken to avoid overcompensation which results in a leading power factor. Overcompensation attracts surcharge.

The other ways of improving power factor in a facility include:

- i. Optimizing the loading of induction motors through minimization of idling, installation of Variable Frequency Drives on induction motors with varying load demand and ensuring motors are operated close to their rated capacity (75% loading).



- ii. Operation of electrical equipment at the rated voltages. This can be achieved by installation of voltage regulators in case of voltage fluctuations in the system.
- iii. Regularly inspect and maintain power factor correction unit(s)
- iv. Retrofitting inductive light sources such as fluorescent lamps with LED lamps.

Examples 1 and 2 illustrate power factor correction in different facilities.



Example 1

During an energy audit of a bakery, the following baseline data was collected:

Month	kVA Demand	kW Demand	Power Factor (P.F)
Jan-25	160	120	0.7500
Feb-25	182	140	0.7692
Mar-25	170	128	0.7529
Apr-25	190	150	0.7895
May-25	165	135	0.8182
Jun-25	178	110	0.6180
Jul-25	155	145	0.9355
Aug-25	200	130	0.6500
Sep-25	168	125	0.7440
Oct-25	180	138	0.7667
Nov-25	172	142	0.8256
Dec-25	168	133	0.7917
Average	174	133	0.7644

During the energy audit, 24-hour measurements on the main power supply incomer were taken as shown in Table 2.

Phase	Power Factor		
	Min	Average	Max
PF1	0.72	0.803	0.999
PF2	0.756	0.794	0.981
PF3	0.76	0.789	0.999
PFT	0.768	0.786	0.84

It can be established that the average power factor at the facility over the baseline period was 0.7644 and the Apparent power demand of 174 kVA and real power demand of 133 kW. To improve the power factor of the facility to unity, the auditor should design a power factor correction bank in steps. This can be done by establishing the total reactive power needed using equation:



$$\text{Reactive Power } (Q_{\text{needed}} = P \cdot \tan(\cos^{-1}(PF_{\text{current}}))$$

$$Q_{\text{needed}} = 133 \cdot \tan(\cos^{-1}(0.7644)) \\ = 112.18 \text{ kVAr}$$

The energy auditor should have studied the load variation in the facility to recommended capacitor bank with a given number and sized steps.

For example, in this case, it can be

Bank Size (kVAr)	Number
25	3
10	3
5	1
2.5	1

The steps will ensure automatic switching when the load varies and eliminates scenarios of under compensation or overcompensation.

The savings by power factor correction can be calculated for both reduced kVA demand and power factor surcharges. For this case scenario in Kenya, the facility had average monthly High-rate charge of Ksh 625,000, low-rate charge of Ksh 415,000 and the kVA charge of Ksh 191,400. The average monthly power factor surcharges are calculated by:

$$P.F \text{ surcharges} = 0.02 \times K \times \text{sum of charges} \quad (8)$$

Where:

$$K = \frac{(0.9 - \text{Average } P.F)}{(0.9 \times 0.01)}$$

Sum of the charges = KVA Charge + Low-rate charge + High-rate Charge

$$K = \frac{(0.9 - 0.7644)}{(0.9 \times 0.01)} = 15$$

$$P.F \text{ Surcharges} = 0.02 \times 15 \times 1,231,400$$

$$\text{Average Monthly } P.F \text{ Surcharges} = \text{Ksh } 369,420$$

Compared to the energy charge cost, this translates to

Example 2:

Consider the following data collected from a sugar processing plant.

Months	Production (Tonnes)	Demand kVA	Demand kW	Power Factor, PF	High-Rate kWh	Low-Rate kWh	Total kWh
Jan-23	31,685	240	142	0.59	24,849	17,379	42,228
Feb-23	58,404	180	122	0.68	26,913	16,005	42,918
Mar-23	31,605	180	111	0.62	25,110	17,781	42,891
Apr-23	58,878	180	114	0.63	24,687	18,618	43,305
May-23	36,709	180	105	0.58	21,726	17,430	39,156
Jun-23	39,925	180	109	0.61	23,967	17,688	41,655
Jul-23	61,136	210	134	0.64	28,266	18,855	47,121
Aug-23	58,554	180	124	0.69	35,562	17,667	53,229
Sep-23	50,382	180	120	0.67	30,059	18,186	48,245
Oct-23	34,832	180	111	0.62	24,153	18,993	43,146
Nov-23	32,737	180	105	0.58	22,080	16,119	38,199
Dec-23	23,473	150	87	0.58	20,169	18,513	38,682
Jan-24	39,557	180	106	0.59	22,098	18,102	40,200
Feb-24	44,533	180	111	0.62	24,822	16,508	41,330
Mar-24	44,727	180	105	0.58	21,954	17,928	39,882
Apr-24	38,036	150	84	0.56	20,148	15,588	35,736
May-24	50,150	150	84	0.56	21,198	16,083	37,281
Jun-24	39,979	150	85	0.57	20,058	16,347	36,405
Jul-24	49,697	180	104	0.58	22,725	16,320	39,045
Aug-24	43,167	180	106	0.59	23,658	16,956	40,614
AVERAGE	43,408	179	108	0.61	24,210	17,353	41,563

The facility aims to improve the power factor to at least 0.94. Design the size of Power factor correction bank.

Real power, $P = 108 \text{ kW}$

Initial power factor, $PF_1 = 0.61$

Target power factor, $PF_2 = 0.94$

$$Q_1 = 108. \tan(\cos^{-1}(0.61)) \quad (9)$$

$$= 140.29 \text{ kVAr}$$

$$Q_2 = 108. \tan(\cos^{-1}(0.94)) \quad (10)$$

$$= 39.198 \text{ kVAr}$$

Required reactive power for compensation:

$$Q_c = Q_1 - Q_2 \quad (11)$$

$$Q_c = \approx 101.092 \text{ kVAr}$$



Appropriate steps can be selected for the power factor correction bank. The average monthly savings can be calculated as illustrated in Example 1.

Load Balance

Load balance in facility is majorly dependent on distribution boards design and type of loads in facilities. Facility having most of the loads as three phases is unlikely to have challenges with load balancing. Similarly, well designed distribution board ensuring single phase load balancing in facility is likely to have equal loading on the three phases.

The phase currents difference informs whether a system is balanced or not. A balanced system should have a current share of 33.33% per phase, with an allowable deviation of $\pm 3\%$ among the phases. During an energy audit, phase currents are measured and percentage contribution calculated per phase.

$$C_{\%} = \frac{I_{R,Y,B}}{I_T} \times 100\% \quad (12)$$

Where;

$C_{\%}$	Current Percentage Contribution of each phase
$I_{R,Y,B}$	Phase current
I_T	Total phase current

A variation from the ideal is calculated by subtracting ideal phase current from the calculated phase contribution.

Table XX shows the results of computed percentage current contribution for a facility over an operation cycle.



Table 1: Illustration of Percentage Contribution from each phase

Phase	Measured average Phase Current (A)	Percentage Contribution	Variation from the Ideal ratio (33.33%)
R	186.6	20.72	-12.61
Y	283.3	31.46	-1.87
B	430.7	47.82	14.49
N	21.9		

From table XX, it is observed that imbalance variation is more than $\pm 3\%$ for the red and the blue phases. It is therefore necessary to calculate the resulting power losses due to the imbalance. The length of the neutral conductors was approximated to be 3KM with an area of 50mm². These losses are calculated using equation XX.

$$P_N = I_N^2 R_N \quad (14)$$

$$P_N = 21.9^2 \times 0.026 = 12.6W$$

$$\text{Annual energy loss} = 12.6 \times 8760$$

$$= 110 \text{ kWh}$$

High current imbalance causes high neutral currents, leading to energy losses, overheating, reduced motor efficiency and lifespan.

Alternatively.

Assume the facility operates for 7000 hours annually.

Energy Savings

$$[\Delta E = (\sum I(\text{imbalanced})^2 - \sum I(\text{balanced})^2) \times R \times \frac{t}{1000} \quad (15)$$

Where:



ΔE	Energy loss
R	Cable resistance
t	Operating hours
I	Current

For this case:

$$R = \frac{240}{900.6} = 0.266$$

$$\begin{aligned} \Delta E &= (186.6^2 + 283.3^2 + 430.7^2) - (300.2^2 + 300.2^2 + 300^2) \times 0.266 \times \frac{7000}{1000} \\ &= 56271 \text{ kWh} \end{aligned}$$

Voltage Optimization

Electrical equipment is designed to operate optimally at voltages slightly less than utility distribution voltage (220V-230V for single phase and 380V-400V for three phases). Distribution voltage in some countries is mostly 240V and 415V for single phase and three phase respectively. Voltage is distributed at these slightly higher levels to cater for losses and voltage drops on the distribution network. Reducing the voltage supplied to equipment to its optimum levels saves energy consumed, reduces maintenance costs, and ensures the equipment runs for the designed lifespan. The voltage profile of the facility can vary depending on location of loads and their duty cycles.

Voltage optimization can be achieved with tap-changing transformers, fixed step-down transformers and active voltage stabilization solutions. Depending on site characteristics, step-down transformers are typically installed to reduce the voltage by a fixed percentage ranging from 4% to 8%. Voltage optimizers adjust the incoming voltage to ensure that the output voltage is fixed at desired voltage settings.

Figure XX shows an example of appliance nameplate with rated voltage.

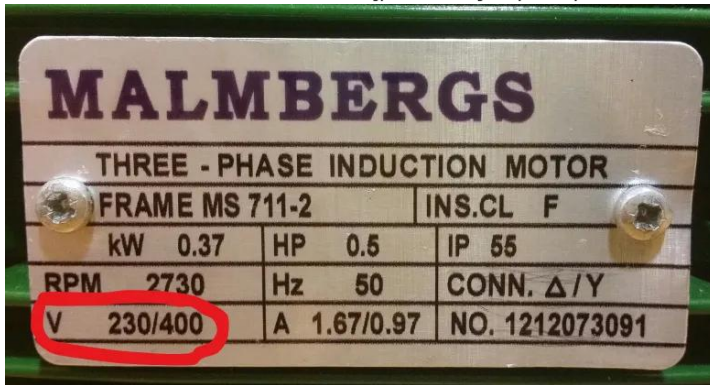
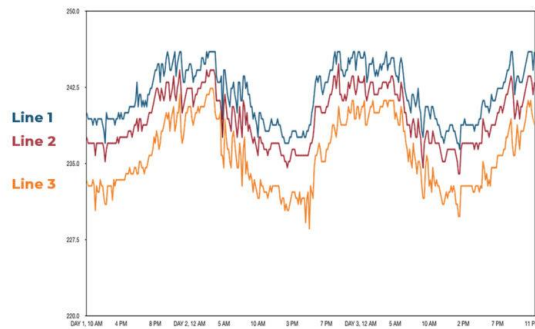


Figure 7: Nameplate of a motor showing rated voltage

As illustrated in figure 7, the rated voltage of the motor is 400V. Operating the motor at higher voltages leads to energy losses.

During an energy audit, the auditor should check supply voltage and compare with optimum operating voltages (equipment rated voltages) of most of the appliances in the facility. In case the voltages vary from the rated, the energy auditor should recommend measures to optimize voltage. These measures include tap changing on the transformer or installation of voltage stabilizer. Tap changing is informed by constant high/low voltages supply to the facility. For example, a tea factory supplied at constant 360V will be required to do tap changing on their transformer to increase the voltage to 400V. Voltage stabilizers on the other hand aid when there are frequent voltage fluctuations. For instance, the voltage keeps varying between 360V and 440 within an operation cycle.

Example of voltage fluctuation is shown in Figure XX



The impact of voltage fluctuations on motor performance can be illustrated in figure XX shown.

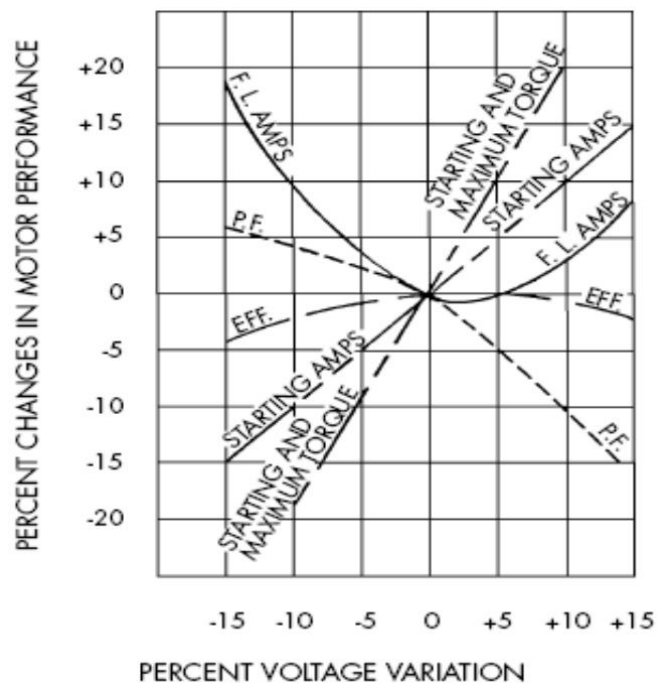


Figure 8: Voltage Variation Effect on Motor Performance

The figure XX can be used to establish motor efficiency and performance at various levels of voltage fluctuations. When operating at less than 95% of design voltage,



motors lose more than 2 percent of their efficiency. Running a motor above its design voltage also reduces power factor and efficiency.

The savings realized by installation of Voltage stabilizers can be calculated by;

$$E_{savings} = \left(1 - \frac{v_1^2}{v_0^2}\right) \times E_0 \quad (16)$$

Where:

V_1	Voltage after stabilization
V_0	Voltage before stabilization
E_0	Energy Consumption in the facility.
$E_{savings}$	Energy Savings

Example XX.

Figure 9 shows measurements at the main incomer of a milk processing plant. The appliances at the facility are rated 230V. Figure 10 and 11 shows average monthly energy billing information for section A and section B of the plant.

Logging Information			
Study type:	Energy study	Topology:	3-ph Wye
Start date:	04/08/2025 10:56:21 AM	End date:	04/08/2025 11:56:21 AM
Duration:	1h 0m 0s		
Averaging interval:	1min	Number of averaging intervals:	61
Voltage [V]			
	AN	BN	CN
Max	258.2 V 04/08/2025 11:56:21 AM	258.2 V 04/08/2025 11:56:21 AM	256.8 V 04/08/2025 11:56:21 AM
linear Avg	254.8 V	254.8 V	253.0 V
Min	251.4 V 04/08/2025 11:26:00 AM	251.4 V 04/08/2025 11:26:00 AM	249.8 V 04/08/2025 11:26:00 AM
Current [A]			
	A	B	C
Max	142.6 A 04/08/2025 11:41:00 AM	123.0 A 04/08/2025 11:41:00 AM	121.1 A 04/08/2025 11:00:00 AM
linear Avg	73.5 A	54.9 A	68.6 A
Min	54.6 A 04/08/2025 11:32:00 AM	29.2 A 04/08/2025 11:03:00 AM	45.3 A 04/08/2025 11:30:00 AM

Figure 9: Measurements in a milk processing plant

The following were average parameters of the facility



Parameters	Value
a) Baseline Period	March 2024- February 2025
b) Energy Consumption	
i. Electricity	
· kWh	45,385
· kVA	155.00
· kW	150
· CEC (Kshs/kWh)	27.46238845
· Cost (Kshs)	1,248,322
· PF	0.967154536

Figure 10: Section A billing data

Parameters	Value
a) Baseline Period	March 2024- February 2025
b) Energy Consumption	
i. Electricity	
· kWh	34,644
· kVA	223.33
· kW	214
· CEC (Kshs/kWh)	31.45931294
· Cost (Kshs)	1,087,685
· PF	0.958977136

Figure 11: Section B billing data

Using equation XX, energy savings from voltage optimization can be calculated by installation of a voltage stabilizer setting the new voltage at 230V:

$$E_{savings} = \left(1 - \frac{230^2}{254^2}\right) \times 80,028$$

$$= 14,409 \text{ kWh}$$

To establish the viability of this measure, the auditor should consider the prevailing cost of electricity and the voltage stabilizer.

Power Quality (Total Harmonic Distortion - THD)



Facilities with nonlinear loads like VFDs, UPS, welding machines, LED lighting and Servers tend to have high total harmonic distortion. During an energy audit, the analysis of power quality should inform the energy auditor, the harmonics orders at the facility. The commonly present odd harmonics orders at facilities are 3rd, 5th, 7th, 11th, 13th and 15th. The 5th and 7th harmonics cause lagging and leading reactive power respectively.

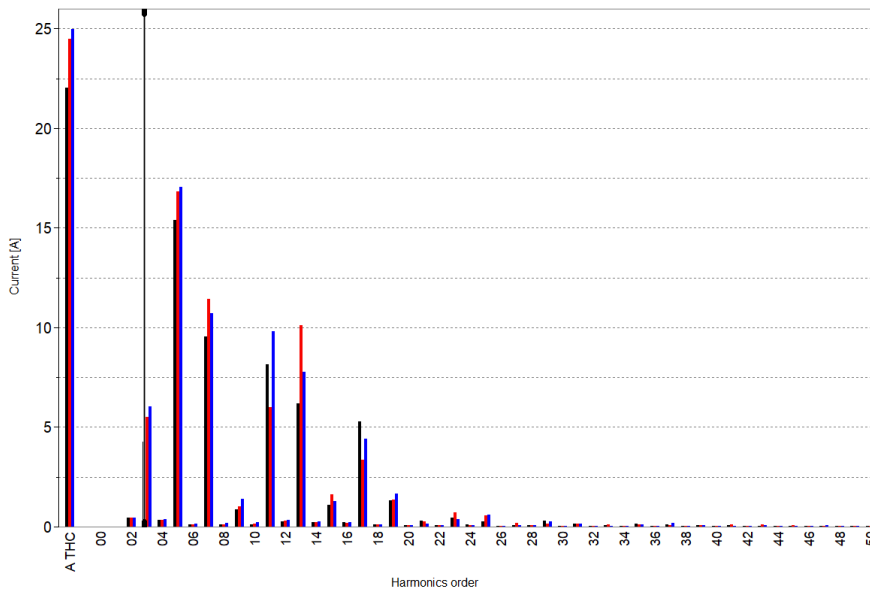
The 5th, 11th, 17th are called negative sequence harmonics. They cause a torque in the opposite direction to normal motor rotation resulting in a reduction in motor performance.

The 7th, 13th, 19th are called positive sequence harmonics. They cause a pulsating torque that falls in and out of phase with normal motor rotation increasing heating and losses.

Triplen or zero sequence harmonics (3rd, 9th, 15th) accumulate on the neutral conductor leading to high neutral currents. High neutral currents lead to overheating from the resistive losses, reduced efficiency and poor performance of equipment. Moreover, high current on the neutral conductor of earthed systems causing distortion of the voltage magnitudes of the phases.

Figure XX shows different harmonics orders in a facility:

Invalid values are not shown.



A power quality analyzer should be used to inform:

Measurement	Why it matters
Neutral current THD	Evaluate impact of triplen harmonics
Power factor Vs Displacement PF	Determine if poor PF is harmonics driven
Load profile vs harmonic variation	Understand when harmonics peak

The severity of the harmonics will inform the mitigation measures. Filters and harmonics traps can be recommended.

During an energy audit, a power quality analyzer (for example Fluke 1736) is used to measure

- TDH_I
- Individual harmonic currents ($I_3, I_5, I_7 \dots$)



- Load current
- Transformer rating and impedance

Therefore, Neutral conductors – triplen harmonic accumulation (3rd, 9th, 15th...)

In 3-phase 4-wire systems:

$$I_N = \sqrt{(I_3)^2 + (I_9)^2 + (I_{15})^2 + \dots} \quad (17)$$

Neutral copper loss:

$$P_N = I_N^2 R_N \quad (18)$$

An audit was carried out in the EPRA server room and current measured as shown:

- Fundamental current $I_1 = 60A$
 $TDH_I = 30\% (0.3)$
- Cable resistance $R = 0.02\Omega$

Fundamental loss

$$P_1 = 60^2 \times 0.02 = 72W$$

Total loss with harmonics

$$P_{total} = 72(1 + 0.3^2) = 78.48W$$

Extra loss due to harmonics

$$P_{harm} = 6.48W$$

Over a year:

$$6.48 \times 8760 = 56.76 \text{ kWh/year}$$

Harmonics measured as a summation on the system

Total RMS Current



The total RMS current (I_{RMS}) includes both the fundamental and harmonic components and can be expressed using the Total Harmonic Distortion (THD):

$$I_{RMS} = I_1 \sqrt{1 + THD^2} \quad (19)$$

Where, I_1 is the RMS value of the fundamental (50 Hz) current (where THD=0). This relationship provides a foundation for estimating harmonic-induced power losses.

Power Losses

For three-phase systems, power losses can be calculated using the following formulas:

- Fundamental Power Loss at 50 Hz for three phase line (P_1):

$$P_1 = 1.5 * R_{Line} * I_{1, true rms}^2 \quad (20)$$

- Total RMS Power Loss, including Harmonics (P_{RMS}):

$$P_{rms}^1 = 1.5 * R_{Line} * I_{Line, rms}^2 \quad (21)$$

- Relationship Between Power losses at the Fundamental (50 Hz) and Total RMS values:

$$\frac{P_{rms}}{P_1} = (1 + THD_i^2) \quad (22)$$

Harmonic currents generated by nonlinear loads lead to several adverse effects on power distribution system components, including

- Excessive heat generation in equipment and cables, leading to accelerated aging and potential failures of motors, transformers and/or cables.
- Decrease in system capacity and efficiency, resulting in higher operational costs and reduced power delivery efficiency.
- Malfunction of protection and measurement devices, compromising system reliability and safety.
- Lowering of power factor
- Motor vibrations
- Voltage regulator malfunctioning
- LED lights flickering

Mitigating Harmonics

¹ Applicable for both Delta and Wye configurations.



The auditor should conduct measurements at the facility and compare the THD with IEEE 519 2022 as shown in table XX

Bus voltage V at PCC	Individual harmonic (%) $h \leq 50$	Total harmonic distortion THD (%)
$V \leq 1.0 \text{ kV}$	5.0	8.0
$1 \text{ kV} < V \leq 69 \text{ kV}$	3.0	5.0
$69 \text{ kV} < V \leq 161 \text{ kV}$	1.5	2.5
$161 \text{ kV} < V$	1.0	1.5 ^a

In cases where the THD are above recommended limits, the auditor can recommend:

- Remove unnecessary non-linear loads
- Change point of connection of identified electrical equipment
- Where possible, use 3ph drives instead of 1ph drives
- Install additional inductance
- Change the size of DC smoothing capacitor
- Use harmonic filters
- Use a drive with an active input converter
- Use 12 pulse drives

Example

During an energy audit of a commercial building, the following data was collected.



Table 2: The collected data during energy audit

Date & Time	Power kW	kVA	PF	Irms1	Irms2	Irms3	L1 Voltage [V]	L2 Voltage [V]	L3 Voltage [V]	Aver Irms (A)	THD [%]
12/01/2026 8:15	92.67	96.71	0.96	112.04	86.91	114.31	240.35	241.64	241.01	104.42	64.18
12/01/2026 7:15	80.63	83.87	0.96	100.56	81.76	95.94	241.39	242.91	242.46	92.75	54.86
12/01/2026 6:15	68.18	70.65	0.96	91.49	60.58	78.41	241.95	243.85	243.05	76.83	59.39
12/01/2026 5:15	47.95	49.94	0.96	69.76	39.28	56.64	242.10	244.24	243.15	55.23	54.06
12/01/2026 4:15	47.75	50.10	0.95	68.50	35.94	56.05	240.51	242.64	241.26	53.50	67.47
12/01/2026 3:15	41.46	43.79	0.95	58.40	33.15	53.22	242.89	244.74	243.40	48.26	54.33
12/01/2026 2:15	43.03	45.20	0.95	61.32	34.87	55.30	242.43	244.27	242.95	50.50	50.71
12/01/2026 1:15	40.42	42.67	0.95	59.39	32.04	53.23	241.35	243.21	242.02	48.22	48.56
12/01/2026 0:15	42.83	45.25	0.95	59.88	32.30	54.64	242.26	244.15	243.02	48.94	60.93
11/01/2026 23:15	48.58	51.50	0.94	65.94	34.77	57.63	242.01	243.92	242.80	52.78	79.57
11/01/2026 22:15	49.23	52.00	0.95	64.40	35.32	59.54	241.40	243.15	242.16	53.09	81.98
11/01/2026 21:15	58.71	61.82	0.95	75.86	39.57	63.95	242.12	244.06	243.00	59.79	101.38
11/01/2026 20:15	52.68	55.44	0.95	68.01	38.86	62.64	239.44	241.35	240.41	56.50	85.39
11/01/2026 19:15	53.00	55.68	0.95	73.88	37.42	61.48	241.91	244.10	242.89	57.59	76.25
11/01/2026 18:15	51.67	54.35	0.95	67.82	37.38	62.72	240.90	243.03	241.82	55.97	79.28
11/01/2026 17:15	49.27	51.86	0.95	65.95	36.77	61.12	241.27	243.30	242.04	54.61	71.03
11/01/2026 16:15	48.21	50.49	0.95	63.16	38.02	61.95	240.52	242.70	241.30	54.38	64.54
11/01/2026 15:15	47.75	50.09	0.95	64.12	36.81	60.10	241.81	243.76	242.46	53.68	64.58
11/01/2026 14:15	49.76	52.26	0.95	65.53	37.40	62.55	241.19	243.10	241.81	55.16	70.47
11/01/2026 13:15	46.75	49.02	0.95	59.86	40.15	60.41	241.17	243.01	241.78	53.48	59.68
11/01/2026 12:15	46.80	49.04	0.95	61.82	39.98	58.73	243.81	245.70	244.43	53.51	56.15
11/01/2026 11:15	46.96	49.09	0.96	57.51	41.82	58.85	243.73	245.64	244.53	52.73	61.09
11/01/2026 10:15	47.23	49.46	0.95	62.80	40.01	58.29	242.98	245.06	243.77	53.70	58.61
11/01/2026 9:15	47.72	49.95	0.96	58.09	43.29	59.30	242.49	244.39	243.22	53.56	63.31
11/01/2026 8:15	45.57	47.47	0.96	61.32	40.91	57.85	242.44	244.21	243.12	53.36	48.75
11/01/2026 7:15	44.23	46.17	0.96	55.23	40.24	56.02	242.99	244.63	243.67	50.50	56.40
11/01/2026 6:15	44.85	46.85	0.96	60.06	39.88	55.90	241.88	243.54	242.56	51.95	53.61
11/01/2026 5:15	44.19	46.29	0.95	60.58	38.88	55.35	240.57	242.09	241.25	51.60	53.67
11/01/2026 4:15	45.67	47.91	0.95	60.30	38.37	55.91	241.97	243.52	242.67	51.53	63.15
11/01/2026 3:15	43.77	45.95	0.95	60.78	37.43	56.48	240.23	241.75	240.81	51.56	52.19
11/01/2026 2:15	40.20	42.18	0.95	55.90	35.92	53.51	241.29	242.88	241.95	48.44	43.97
11/01/2026 1:15	40.92	42.98	0.95	61.01	35.85	52.00	242.62	244.28	243.34	49.62	40.90
11/01/2026 0:15	46.30	48.56	0.95	60.44	40.04	57.19	241.68	243.23	242.50	52.56	61.49
10/01/2026 23:15	49.36	51.80	0.95	67.31	41.49	57.59	243.50	245.03	244.27	55.46	62.63
10/01/2026 22:15	47.36	49.56	0.96	63.53	42.03	58.86	241.79	243.34	242.65	54.81	54.55
10/01/2026 21:15	50.32	52.95	0.95	69.91	41.68	61.71	242.72	244.34	243.56	57.77	57.62
10/01/2026 20:15	48.36	50.85	0.95	65.31	39.16	63.47	241.86	243.63	242.71	55.98	55.82
10/01/2026 19:15	51.83	54.25	0.96	69.68	42.16	66.09	243.09	244.99	244.04	59.31	56.38
10/01/2026 18:15	52.80	55.51	0.95	69.75	47.60	69.06	240.68	242.34	241.45	62.14	52.19
10/01/2026 17:15	51.24	53.90	0.95	63.85	47.24	68.84	242.16	243.77	242.88	59.98	52.20
10/01/2026 16:15	55.19	58.08	0.95	70.14	52.17	71.44	242.30	243.97	242.96	64.58	52.23
10/01/2026 15:15	51.03	53.85	0.95	64.42	49.09	72.01	239.40	241.24	240.34	61.84	45.98
10/01/2026 14:15	60.55	63.82	0.95	79.39	56.78	81.20	238.78	240.66	239.65	72.46	50.18
10/01/2026 13:15	67.73	71.47	0.95	86.31	63.07	90.69	241.20	243.08	242.01	80.02	51.31
10/01/2026 12:15	69.56	73.32	0.95	89.45	66.88	91.51	242.24	244.02	242.98	82.62	48.25
10/01/2026 11:15	71.83	75.68	0.95	89.90	68.07	96.97	238.82	240.45	239.64	84.98	53.56
10/01/2026 10:15	76.28	80.40	0.95	94.88	78.42	94.00	240.43	241.69	241.39	89.10	55.62
10/01/2026 9:15	75.05	78.70	0.95	92.00	75.63	97.92	240.43	241.79	241.28	88.51	51.19

Equation 18 and 19 were used to calculate current at fundamental order, the line resistance and power losses due to THD and the results were presented in Table 3



Table 3: Analyzed data during energy audit.

Date and Time	THD	THD Rfactor	Require I amps	Irms-Ireq	Average Voltage V	R	Power Savings (THD =0)
12/01/2026 8:15	0.64	0.78	81.49	22.93	241.00	2.96	1.55
12/01/2026 7:15	0.55	0.80	74.53	18.22	242.25	3.25	1.08
12/01/2026 6:15	0.59	0.79	60.86	15.97	242.95	3.99	1.02
12/01/2026 5:15	0.54	0.81	44.49	10.73	243.16	5.46	0.63
12/01/2026 4:15	0.67	0.77	41.34	12.16	241.47	5.84	0.86
12/01/2026 3:15	0.54	0.80	38.84	9.41	243.68	6.27	0.56
12/01/2026 2:15	0.51	0.81	41.13	9.36	243.21	5.91	0.52
12/01/2026 1:15	0.49	0.82	39.56	8.66	242.19	6.12	0.46
12/01/2026 0:15	0.61	0.79	38.58	10.36	243.14	6.30	0.68
11/01/2026 23:15	0.80	0.75	39.38	13.39	242.91	6.17	1.11
11/01/2026 22:15	0.82	0.74	39.35	13.73	242.24	6.16	1.16
11/01/2026 21:15	1.01	0.70	42.14	17.66	243.06	5.77	1.80
11/01/2026 20:15	0.85	0.73	41.50	15.01	240.40	5.79	1.30
11/01/2026 19:15	0.76	0.75	43.38	14.21	242.97	5.60	1.13
11/01/2026 18:15	0.79	0.75	41.81	14.17	241.92	5.79	1.16
11/01/2026 17:15	0.71	0.76	41.76	12.85	242.20	5.80	0.96
11/01/2026 16:15	0.65	0.78	42.39	11.99	241.51	5.70	0.82
11/01/2026 15:15	0.65	0.78	41.84	11.84	242.68	5.80	0.81
11/01/2026 14:15	0.70	0.77	42.25	12.91	242.03	5.73	0.96
11/01/2026 13:15	0.60	0.79	42.32	11.16	241.99	5.72	0.71
11/01/2026 12:15	0.56	0.80	42.82	10.69	244.65	5.71	0.65
11/01/2026 11:15	0.61	0.79	41.54	11.18	244.63	5.89	0.74
11/01/2026 10:15	0.59	0.79	42.64	11.06	243.94	5.72	0.70
11/01/2026 9:15	0.63	0.78	41.91	11.65	243.36	5.81	0.79
11/01/2026 8:15	0.49	0.82	43.75	9.61	243.26	5.56	0.51
11/01/2026 7:15	0.56	0.80	40.38	10.12	243.76	6.04	0.62
11/01/2026 6:15	0.54	0.81	41.91	10.03	242.66	5.79	0.58
11/01/2026 5:15	0.54	0.81	41.63	9.98	241.30	5.80	0.58
11/01/2026 4:15	0.63	0.78	40.34	11.19	242.72	6.02	0.75
11/01/2026 3:15	0.52	0.81	41.80	9.77	240.93	5.76	0.55
11/01/2026 2:15	0.44	0.83	40.37	8.07	242.04	6.00	0.39
11/01/2026 1:15	0.41	0.84	41.80	7.82	243.41	5.82	0.36
11/01/2026 0:15	0.61	0.79	41.36	11.20	242.47	5.86	0.74
10/01/2026 23:15	0.63	0.78	43.49	11.97	244.27	5.62	0.80
10/01/2026 22:15	0.55	0.80	44.09	10.72	242.59	5.50	0.63
10/01/2026 21:15	0.58	0.80	46.01	11.75	243.54	5.29	0.73
10/01/2026 20:15	0.56	0.80	44.85	11.13	242.74	5.41	0.67
10/01/2026 19:15	0.56	0.80	47.43	11.88	244.04	5.15	0.73
10/01/2026 18:15	0.52	0.81	50.37	11.77	241.49	4.79	0.66
10/01/2026 17:15	0.52	0.81	48.62	11.36	242.93	5.00	0.64
10/01/2026 16:15	0.52	0.81	52.34	12.24	243.08	4.64	0.70
10/01/2026 15:15	0.46	0.83	51.18	10.66	240.32	4.70	0.53
10/01/2026 14:15	0.50	0.82	59.13	13.33	239.70	4.05	0.72
10/01/2026 13:15	0.51	0.81	65.06	14.97	242.10	3.72	0.83
10/01/2026 12:15	0.48	0.82	67.85	14.76	243.08	3.58	0.78
10/01/2026 11:15	0.54	0.81	68.57	16.40	239.64	3.49	0.94
10/01/2026 10:15	0.56	0.80	71.42	17.68	241.17	3.38	1.05
10/01/2026 9:15	0.51	0.81	71.99	16.53	241.17	3.35	0.92
							38.58

The savings realized by eliminating the THD for 48 hours is 38.58 kWh.

The savings realized for a year can be calculated as:

$$\begin{aligned}
 &= 38.58 \times \frac{365}{2} \\
 &= 7,040 \text{ kWh}
 \end{aligned}$$



The auditor can use the savings to compare with the cost of implementing Harmonics filters in the facility. These financial savings are in addition to the latent benefits discussed in a previous section of this chapter.

Motors

Motors are used as prime movers for most industrial applications, by converting electrical energy to mechanical energy. They perform their work through application of mechanical power to the system. This could be for example driving a fan, a pump impellor or a gear drive. To establish the performance of a motor during an energy audit, the following parameters should be established:

Motor Power rating (kW)	This indicates the mechanical output power of the motor. This should not be confused with electrical power input.
Motor efficiency	Ratio of conversion of electrical power to mechanical power
Rated voltage	This is designed voltage of the motor
Rated current	The current the motor draws at full load
Motor speed (Full load and no-load speed)	This is the motor speed at full load and no load measured in revolution per minute.

To establish the energy performance of the motor, the auditor should measure the following.

Electrical power	This variable is obtained by measuring the electrical power input to the motor.
Power factor	This is the ratio of real power to apparent power drawn by the motor
Input Voltage	This is the input voltage of the motor
Input Current	The current the motor draws during operation



Vibration	Vibrations of motors are undesirable during operation. They are measured using vibrometer.
Motor Temperature	This is the surface temperature of the motor casing and the bearing area.
Motor speed (Full load and no-load speed)	This is the motor operation speed measured by using a tachometer.

The rated and measured parameters can be used to determine the energy performance of a motor. For optimal energy performance, the mechanical power applied by the motor on the driven component should be as close as possible to the rated power. This relationship is determined using the loading factor, computed using equation 23.

$$L.F = \frac{P_m \times \eta}{P_r} \quad (23)$$

Where

$L.F$	Loading Factor
P_m	Measured power
P_r	Rated power
η	Motor efficiency

The loading factor can be used to determine the operating efficiency of the motor using the motor efficiency curve presented in Figure 12.

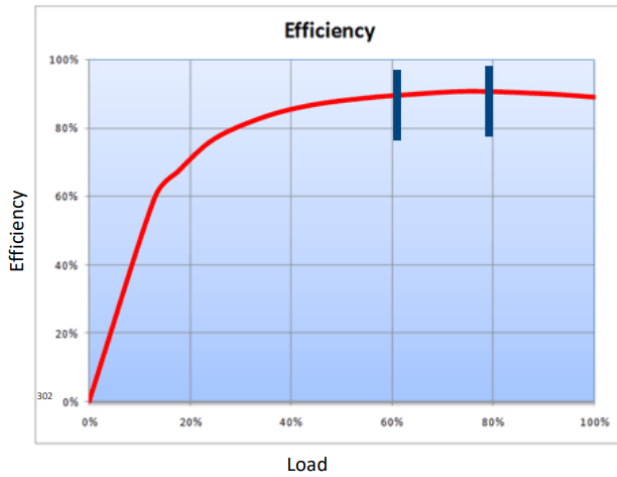


Figure 12: Efficiency Vs Loading of a motor

Similarly, the loading factor impacts the operating power factor of the motor as shown in Figure 13.

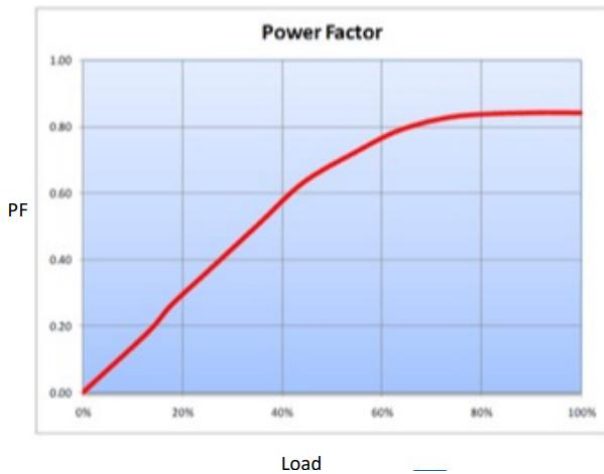


Figure 13: Power factor Vs Loading of a motor

Once the auditor establishes the loading factor of a motor, they should use the loading efficiency curve to determine the prevailing efficiency and suggest improvements in



system operations. If the motor is underloaded (typically below 75% for motors below 20 kW and 50% for motors above 20 kW) the auditor should consider relevant interventions as follows

- i. In cases where there is suboptimal loading of the driven component, for example loading a conveyor belt halfway, then the auditor should recommend for process control. This could mean adding more material during the process.
- ii. Where the process is fully optimal, this may mean the motor is oversized for the required duty and should be retrofitted with a smaller sized motor.

The auditor should also check for overloaded motors. This can be done through carrying out measurements. This is to confirm whether the motor is drawing more power than rated. This is an indication of an overloaded motor. Some other indicators of an overloaded motor include frequent tripping of the circuit breakers, intense heat on the motor casing, burnt smell and increased noise/vibrations.

Motor overloading can be caused by overloaded equipment, misaligned shaft, high and low voltage supply, overly rewound motors, voltage imbalance, phase loss in a three-phase system and excessive Total harmonics distortions on input. The auditor should identify the cause(s) and suggest the correct intervention.

Cause of overload	Remedy
Overloaded equipment	This can be analyzed in two ways: Where the throughput requirements have increased over the operation time thus rendering the originally designed motor to be inadequate, the auditor should call for retrofit, where a bigger motor can handle the increased load.



The second scenario is where there is poor loading practice on the equipment in which case the auditor should recommend improvement in process control.

Misaligned shaft	The auditor should recommend alignment of the shaft.
High and low voltage	The auditor should recommend either tap changing of the transformer or voltage stabilizer to ensure the equipment is supplied with the rated voltage.
Overly rewound motor	The auditor should recommend motor retrofit and advise the facility to have a policy that ensures a motor is not rewound more than two times.
Voltage imbalance	The auditor should recommend for voltage stabilization and achieve voltage balance supply to the motor
Phase loss	The auditor should recommend the facility to have all phases supply when running three phase motors
Total Harmonic distortions	The auditor should recommend for harmonics filters.

The energy auditor can recommend motor retrofits using motors of higher efficiency classes. These classes have better efficiency with improved technology to not only save energy but also have extended lifespan, are more tolerant to phase imbalances and harmonics.

The auditor should also observe other operating conditions of the motors such as frequency of starts and stops; environmental conditions - high ambient temperatures, partially clogged motor vents and dumpy surroundings. as they affect their performance. In some instances, these unfriendly environmental conditions are unavoidable. Take for example a motor operating in a dusty environment like the



dedusting section of a factory. In this case, the auditor should recommend the facility to install a dust tolerant motor. Similar reasoning should be applied to acidic, humid and high temperature conditions.

Variable Frequency Drives

In some industrial operations, motors operate at varying loads. This means that sometimes, they may be required to supply higher or lower mechanical power, depending on the need. In such circumstances, it would be prudent to control the speed of the motor using a variable frequency drive.

A Variable Frequency Drives (VFD) enable motors to run efficiently by matching their speed to the actual load requirements, rather than running continuously at full speed. In addition, the motors have smooth start/stop operations, reducing inrush current and starting mechanical stress on motors. They also improve process control by fine-tuning speed adjustment.

The energy auditor should conduct measurements to show the variations in motor loading before recommending VFD.

The design of a Variable speed drive is done based on motor full-load current or power. Rating of a VFD can be calculated by:

$$I = \frac{P}{\sqrt{3} \times V \times P.F \times \eta} \quad (24)$$

Where

- P Mechanical power of the motor
- I Full load current of the motor
- V Rated voltage
- P.F Power factor indicated on the motor



η Efficiency of the motor

The current value will inform the auditor of the possible standard size of the VFD in the market to be selected. The selected size should be of higher value than calculated current value.

By reducing the speed of motor, VFD leads to power savings. The savings are calculated by:

$$P_{savings} = P_{drawn} \left(1 - \left(\frac{N_{VFD}}{N_{Fullspeed}} \right)^3 \right) \quad (25)$$

Where

$P_{savings}$ Power savings

P_{drawn} Electrical power measured

N_{VFD} VFD speed

$N_{Fullspeed}$ Motor full speed

In most cases, the $\left(\frac{N_{VFD}}{N_{Fullspeed}} \right)$ ratio is expressed as a percentage for example, 10% reduction in speed thus the ratio is 0.9

Example

A reinjection pump with motor rated 22 kW operated on direct on line (DOL) with efficiency of 91% and PF of 0.9. During the energy audit the team realized the reinjection pump was averagely 70% loaded. The pump runs under varying conditions to maintain the pressure and flowrate back the product output where necessary. The pump runs for 1800 hours a year. Consider, by designing the size of the variable frequency drive to accommodate underloading and variation in the



loading. What are the annual energy savings if the speed was to reduce at average of 10%?

From the information given:

$$\text{Electrical power rated: } = \frac{22}{0.91} = 24.17 \text{ kW}$$

The size of the VFD:

$$I = \frac{24.17}{\sqrt{3} \times 400 \times 0.9} = 38.8 \text{ A}$$

The recommended VFD should be the next available size greater than 38.8A.

The power savings:

$$P_{\text{savings}} = (1 - (0.9)^3) \times 24.17 = 6.55 \text{ kW}$$

The motor runs for 1800 hours a year. Therefore, the annual energy savings are

$$= 6.55 \times 1800$$

$$= 11790 \text{ kWh}$$