True and False Energy-Saving Devices

Alexander E. Emanuel, Fellow, IEEE

Abstract—This paper explains the mystifying performance of a nonlinear capacitance used as a passive energy-saving device (ESD). According to the law of energy conservation, such ESD’s cannot improve motor efficiency. Theoretical and experimental studies prove that the bulk of the perceived “energy savings” is caused by the current transformers phase-angle error.

Index Terms—Energy-saving devices, power factor correction.

I. INTRODUCTION

INDUSTRIAL restructuring, international competition, and environmental restrictions that make the construction of new power plants and transmission lines prohibitively expensive, as well as the need to import foreign oil, are significant parameters that continuously shape society’s attitudes toward electric energy. Today, more than ever before, there is a need to conserve electric energy. Such a situation prompts engineering minds to focus on new visions, to invent, to improve on older energy conversion technologies, to optimize designs, and to develop better active materials and insulators that lead to more compact and more efficient equipment. On the other hand, the same opportunities sometimes will prompt the development of products, the energy savings capabilities of which are questionable and cannot be substantiated.

The goal of this paper is to explain the cause for measurement errors that may lead to the wrong conclusion that a passive energy-saving device (ESD) can insure energy savings of 10%–25%.

II. TRUE ESD’S AND TECHNOLOGIES

In all the stages of energy transfer or conversion from electrical to mechanical, to light, to thermal, to chemical, or vice versa, the law of conservation will always be supreme. Mathematically, this law is expressed by the simple equation

\[ W_i = W_o + \Delta W \]

where
- \( W_i \) is input energy;
- \( W_o \) is output energy;
- \( \Delta W \) is energy lost, i.e., converted in useless forms of energy.

The efficiency of an energy converter is

\[ \eta = \frac{W_o}{W_i} = \frac{1}{1 + \delta} \quad \delta > 0. \]

As technologies are progressing, the values of \( \delta \) for different applications will decrease, but will never be nil.

Today, by every 1.0 J of mechanical energy delivered by a medium-size motor, 3–4 J of fuel energy must be used at the power plant. Conversely, for every 1.0 J saved at the electromechanical energy converter’s output, 3–4 J of fuel energy are spared.

Energy savings and conservation can be achieved by many legitimate venues. Here is a reminder of some important technologies and methods known today that will help reduce the end user’s energy bill. Some technologies are just emerging and some are known and have been used for a long time.

1) Methods that Directly Help Reduce the Input kilowatthours
   a) Renewable energy sources—Wind power generation, photovoltaics, geothermal, and biomass are the most developed technologies that allow cogeneration at competitive cost in favorable locations [1].
   b) Energy conversion optimizers—These are power electronics devices that create conditions for optimum transfer of energy to the loads. Three major categories of devices are identified.
      i) Adjustable-speed drives—These are ideally suited to reduce energy consumption for pumps, compressors, blowers, and fans by eliminating the throttling energy loss by means of adjusting the velocity of the motor [2].
      ii) Optimum voltage controllers—Such devices automatically adjust the input voltage to the best value that yields maximum motor efficiency for a given mechanical power [3], [4].
      iii) Electronically ballasted lamps—The efficacy (lm/W) of electric discharge lamps is greatly increased when supplied at a higher frequency.
   c) Use of higher efficiency equipment—New ferromagnetic materials, such as amorphous steel for transformer cores, lower resistivity conductors, reduced airgap designs, permanent-magnet dc and synchronous motors, better bearings, and better insulators (higher dielectric strength and temperature) allow for designs of equipment with better efficiency.

2) Methods That Help the Electric Utilities to Reduce Energy Loss, Release Capacity, and Postpone Capital Expenditure
Fig. 1. Energy-saving device connected at the motor’s bus.

a) *Demand-side management programs*—The utility shifts loads at certain times of the day, reducing the need for energy at particular times.

b) *Energy storage devices*—Conventional batteries, fuel cells, flywheels, and superconductive coils can be used to store energy during the low demand and release it during the peak hours. Such devices help the utilities to reduce the generation reserve margin [5], to operate the power plants with improved efficiency, and to reduce the power loss in the network [6].

c) *Active filters and dynamic compensators*—These provide current harmonic cancellation, help restore voltage balance, improve the power factor, and eliminate voltage dips and surges or momentary interruptions [7], [8].

d) *Passive filters and power factor correction capacitors*—These devices help improve the power factor, hence, reduce the power system’s energy losses. These devices are time-honored and proven methods. They are inexpensive and reliable. Their main drawbacks are lack of continuous adjustment and the possibility of harmonic resonances. Passive filters also may become overloaded by sinking harmonics generated elsewhere.

III. “FALSE” ENERGY SAVERS

“False” energy savers are devices that will not perform as claimed in their promotional literature. This paper describes two devices, one that marked the beginning of the era of false ESD’s and a second that is today’s fad. Both devices are supposed to reduce the energy bill when connected in parallel with a load (see Fig. 1).

A. Surge Arresters

In the mid 1970’s, a thriving industry of false ESD’s was marketing voltage suppressors, claiming that “...in our electrically active environment with 180,000 transients per hour,” voltage suppressors will help save as much as 20% of energy [9]. While surge arresters offer excellent protection against voltage surges, they do not provide energy savings. The promoters of these false ESD’s asserted that high-frequency voltage transients cause supplementary losses, mainly in the cores of motors and transformers. By clamping voltage spikes, these additional losses are said to be much reduced, thus leading to improved overall efficiency of the end user’s facilities. However, one detail was omitted from the misleading commercial literature of that time: the fact that the bulk of the surge energy was transferred from the core to the surge arrester. The fact that the power loss caused by the surges was minute when compared with the load kilowatts was also conveniently unmentioned.

In 1977, the National Council of Better Business Bureaus reported that studies showed there was no merit in the claim that voltage suppressors will reduce electric bills [10]. In the 1980’s, the voltage-arrester-based ESD was practically forgotten, losing its marketability power.

B. Shunt Capacitors

A few years ago, the old ESD with voltage arresters reemerged, but in a more convincing genetic mutation. The main ESD component is a capacitor, with some nonlinear inductances added in series or parallel. In some versions, the capacitor and the inductances may be tuned to act as a harmonic filter. Voltage suppressors, fuses, and lights play secondary roles. The line current waveform is distorted, but its fundamental phasor leads by 90° the voltage, thus giving the appearance of a nonlinear capacitor. In patents, newspapers, and promotional advertisements, the distributors claim that energy savings on the order of 10%–25% have been measured, and these substantial savings are typical for inductive loads, such as heavy motors and fluorescent lights. The fact that medium and large electric motors operate with rated efficiencies of 80%–95%, and savings of 20% may mean efficiencies larger than unity, did not deter either the distributors from selling, nor many commercial and industrial organizations from installing, the new ESD’s. The main reason behind this “faith” in the ESD are actual demonstrations that prove that the ESD performs as claimed. Many reports and letters attest to the outstanding prowess of the capacitor-based ESD in saving huge amounts of energy, even when the observed facilities were operating with a power factor near unity. These results mystify many sincere engineers. Following is a review of some explanations and evaluations.

1) When the ESD is energized, the motor voltage increases with an increment of $\Delta V = 0.1\%–2\%$. The increase in the voltage translates into a reduction of the slip that causes a slight improvement of the rotoric efficiency. If the motor operates at a relatively low slip, $s < 0.08$, then it is reasonable to assume a linear expression for the torque-slip equation. For the motor without ESD,

$$T_N = kV^2s_N$$

and for the motor with ESD,

$$T_W = k(V + \Delta V)^2s_W \approx kV^2\left(1 + \frac{2\Delta V}{V}\right)s_W.$$

Assuming that in the range $s_W < s < s_N$ the load torque remains constant, i.e., $T = T_N = T_W$, results in

$$s_W = \frac{s_N}{1 + 2\Delta V/V}.$$
the rotoric efficiency $\eta_R = 1 - s$ increases, hence, the ESD is producing the following improvement:

$$\frac{\eta_{RW} - \eta_{RN}}{\eta_{RN}} = 1 - s_W - (1 - s_N) = \frac{s_N}{1 - s_N} \frac{2\Delta V}{V}.$$  

For example, if $s_N = 0.04$ and $\Delta V/V = 0.02$, the rotoric efficiency will gain a minute 0.17%. Ignoring the impact of $\Delta V$ on the core losses and considering that the stator winding losses decrease 4%, a motor with 85% efficiency will benefit by an overall energy saving of less than 1% at full load.

2) A few reports claim that the ESD helps restore voltage balance. It is well known that the rotor losses drastically increase in the presence of a negative-sequence rotating field, hence, any device that helps to cancel or even reduce the negative-sequence voltage is useful. A simple theoretical investigation of the hypothetical circuit shown in Fig. 2(a) proves that the linear capacitances do not help improve the voltage unbalance [see Fig. 2(b)]. The definition used for voltage unbalance is

$$%\Delta V = \frac{\text{Max. Deviation from Mean Value}}{\text{Mean Value}}.$$  

Actual measurements on a 100-hp motor equipped with a commercial ESD have proven that the ESD does not restore voltage balance (see Fig. 3).

3) Some ESD distributors suggest that the conversion of harmonic current to useful energy is the key to the energy-savings phenomenon. This explanation does not give much thought to the meaning of amperes-to-joules conversion. Even if the intention was to assume that the energy associated with the harmonic power flow can be converted into useful energy, the large energy savings expected are still far from being covered. Field and laboratory measurements proved that even nonlinear loads with large total harmonic distortions of the current ($THD_I$) in excess of 100% have harmonic active power less than 1% of the input power [11]. A typical induction motor has $THD_I < 8\%$ and harmonic active power less than 0.2% of the total power.

4) When the distance between the ESD-equipped motor and the energy meter is large enough, then, through power factor improvement, the joule losses in the line connecting the meter with the motor are reduced. For typical situations, the overall energy saving in the end user’s network will not exceed 2%.

IV. HOW ARE NONEXISTENT ENERGY SAVINGS MEASURED?

Some engineers point the finger at papers that proved that wattmeters or kilowatthourmeters err when the current is distorted [12]. The current distortion caused by the ESD is too small to cause significant wattmeter and kilowatthourmeter errors; moreover, such errors usually do not favor the end user and will not exceed 3%.

A careful investigation of the instrumentation used for ad hoc demonstrations of ESD’s leads to the current transformers (CT’s) being the main culprits for the false results. Inadvertently, the ESD promoters do not use metering-class CT’s, but simple clamp-on CT’s, rated for burdens lower than actually connected. The equivalent circuit and the phasor diagram of a CT is shown in Fig. 4. The primary current $I_p$ has two components, the secondary current $NI_s$ and the excitation current $I_m$. The actual current phasor $I_p$ and the measured current phasor $I_s$ are not in phase. The current $I_p$ lags behind $I_s$.

This small phase-angle error $\epsilon$ is causing a measurement error. A motor operating with a power factor $PF = \cos(\theta)$ and without an ESD has the actual input power

$$P = VI \cos(\theta).$$
but the measured power is

$$P_N = V(NI_N)\cos(\theta_N - \epsilon_N)$$

and it is larger than $P$.

Now, if a capacitance-based ESD is added, the new measured power is

$$P_W = (V + \Delta V)(NI_W)\cos(\theta_W - \epsilon_W)$$

the new phase angle is reduced to

$$\theta_W = \tan^{-1} \frac{I_N \sin \theta_N - I_{\text{ESD}}/N}{I_N \cos \theta_N}$$

and the measured current is

$$I_W = \sqrt{(I_N \cos \theta_N)^2 + (I_N \sin \theta_N - I_{\text{ESD}}/N)^2}$$

where $I_{\text{ESD}}$ is the ESD fundamental current, assumed to lead the voltage by 90°.

The power “saved” by connecting the ESD is

$$\%PS = 100 \frac{P_N - P_W}{P_N} \approx 100 \left[ 1 - \frac{I_W \cos(\theta_N - \epsilon_N)}{I_N \cos(\theta_W - \epsilon_W)} \right].$$

The geometrical interpretation of this false savings of power is depicted in Fig. 5. The two cosine power curves, one for the load without the ESD and the smaller for the power factor compensated load, intersect the actual power line at two points. Each point gives the true phase angles $\theta_N$ and $\theta_W$. Due to the CT phase-angle errors, the measured power will be larger than the actual power. For the angle $\theta_N$, the measurement error caused by $\epsilon_N$ is $\Delta P_N$. When the ESD is connected, the angle $\theta_W$ decreases to $\theta_W$, and the error $\Delta P_W$ caused by $\epsilon_W$ is smaller than $\Delta_N$. The difference between the two errors yields what is mistaken for savings of power. Theoretical computations of the “perceived” energy savings are presented in Fig. 6. The graphs give $\%PS$ versus $\cos(\theta_N)$, while the CT phase error $\epsilon$ is parameter. It is learned that, for $\epsilon_N = 10^\circ$ and $I_{\text{ESD}}/I_N = 0.5$, errors in excess of 10% are possible. The larger the ratio $I_{\text{ESD}}/I_N$ and the angle $\epsilon_N$, the larger is the measurement error and the “perceived” savings of power.

The phase-angle error $\epsilon$ is a function of the CT’s burden (secondary circuit impedance) and primary current. The larger the burden, the larger $\epsilon$ becomes. One must also be on guard for the eventual existence of residual flux caused by transient dc biasing of the core. A persistent residual flux will contribute to large phase-angle error [13]. For a given burden,

$$\epsilon \approx \epsilon_R \left( \frac{I}{I_R} \right)^\alpha.$$
\[ -0.2 < \alpha < 1.2 \] The lower values of \( \alpha \) correspond to metering-class CT's.

The CT phase-angle error explanation was checked on laboratory measurements conducted on a 7.5-hp motor using commercially available ESD's. A microprocessor-based polyphase power meter was used to measure kilowatts, kilovoltamperes, power factor, voltages, and currents. Clamp-on CT's with the ratio 100:1 and \( 5.9 \) served as current transducers. Published results on a similar measurement for a 100-hp motor were also analyzed. For both motors, the actual measured savings (see Fig. 7) compare well with the computations based on the "e theory." These experimental measurements, implemented under controlled conditions, i.e., a steady mechanical load, show that even with inadequate CT's, the measured "savings" are far less than the ones advertised in the promotional literature.

V. CONCLUSIONS

The capacitance-based ESD is a power factor improvement device. It produces legitimate energy savings and demand reduction, just as an equivalent power factor capacitor will. One should keep in mind that some capacitance-based ESD's do not provide the optimum capacitance for power factor correction, and the cost of the ESD normally exceeds by far the cost of an equivalent of-the-shelf capacitor.

Such a passive device, regardless of the nature of the load, is not capable of producing significant energy savings in the load itself.

As concerns harmonic mitigation properties, unless the ESD is carefully designed to operate as a tuned filter, the ESD will not have a beneficial effect. A low quality factor, \( Q = h\omega L/R \), renders a filter ineffective. In some situations, the ESD nonlinearity may cause some harmonic cancellations and, in others, it may exacerbate the harmonic current injection.

When connected with very short leads, it may provide good voltage surge protection.

When ESD measurements are performed for validation or demonstration purposes, metering-class transducers are a must. The measurements must be conducted with metering-class CT's, recently calibrated and traceable to the National Institute of Standards and Technology (NIST). Prior to testing, it is also imperative to check and document the power or energy meter accuracy under low power factor and distorted waveforms conditions.

REFERENCES