Reduce Network Power Consumption by Up To 30%

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1. Introduction

Through the 2015 Paris Agreement [1], governments of the world committed to curbing global temperature rise to well-below 2°C above pre-industrial levels. To achieve this, greenhouse gas emissions (GHG) must halve by 2030 – and drop to net-zero by 2050. Ambitious but crucial, it's a challenge an increasing number of companies across every sector are accepting. Telecommunications is no exception.

On the other hand, in the era of digital transformation, access networks play a pivotal role in delivering high-speed internet services to end-users. However, the growing demand for high-speed internet connectivity typically involves higher-order signal modulation and/or larger bandwidth spectrum. These two approaches to increase the network throughput necessarily entail higher levels of transmitted power, both in wireless and wireline networks.

Hybrid fiber-coaxial (HFC) access networks, combination of fiber and coaxial cable technologies, have long been a cornerstone of broadband infrastructure and still represent a 50% market share in North America [2]. Between 44 and 50% of the power consumption of cable operators is consumed by the outside plant according to the latest research from SCTE Energy 20/20 Program [3]. Traditional network operators implement a drop-in approach to maintain amplifier legacy locations by installing a new amplifier module with higher downstream and/or upstream bandwidth, helping minimize upgrade downtime and cost. As coaxial cables present higher attenuation at higher frequencies, amplifier output levels must be raised. This trend, together with the growing deployment of Wi-Fi access points and 5G small cells powered by the HFC network, leads to believe that the previously mentioned 44-50% ratio of power consumed by cable operators will only increase in the short and mid-term.

A big contributor to GHG emissions is electrical energy consumption.

Within this framework, this paper analyzes the power efficiency that traditionally powered outside plant HFC networks obtain, proposes a revolutionary idea based on smart low frequency alternating current (AC) powering and presents the results acquired during the tests performed at a laboratory.

2. Powering HFC Outside Plant (OSP)

2.1. AC - Ferroresonant transformer based power supplies

Unlike passive networks, HFC architectures require energy to power the active devices (optical nodes, amplifiers, Wi-Fi hotspots, small cells etc.) that build them. This power is typically injected into the network with a ferroresonant transformer-based power supply that converts the power from the grid 120-230VAC_{RMS} to a lower voltage range of 63-89VAC_{RMS} at the same frequency of 50/60Hz.

Unlike linear transformers, ferroresonant transformers are designed to go into magnetic saturation. They consist of an auxiliary secondary winding with a parallel capacitive tank to provide a resonant circuit at the supply voltage frequency. The transformer operation is based on the ferro resonance behavior associated with saturated iron cores. They have a robust and reliable design but dissipate more heat than conventional transformers and produce more audible noise at resonance.

The textbook maximum efficiency for a ferroresonant transformer is 94%, but typical designs run as low as 80%. The two main causes for inefficiency: core loss and copper losses. As the operating temperature increases, so will the losses, since copper has a positive temperature coefficient, its resistance will increase about 0.4% per degree Celsius.

In practice, on top of the ferroresonant transformer-based power supplies' design considerations, network powering efficiency highly depends on the system / load that is being powered. In the case of HFC networks, all the active devices use solid state technology that requires DC power. Therefore, the power received from the network needs to be converted to DC for it to be useful, which is achieved with the built-in device power supplies.

This power conversion process entails losses coming mainly from two factors:

1.- Ferroresonant transformers have been used for many years typically to convert a higher AC voltage to a lower AC one. However, its efficiency highly depends on the percentage of load it's connected to, typically becoming more efficient as load gets closer to 100% - see figure below.

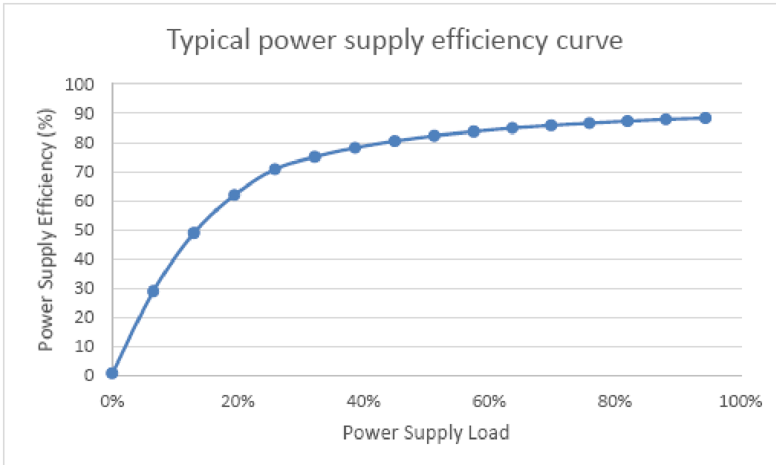

Figure 1 – Typical Ferroresonant Power Supply Efficiency Curve

Given the wide distribution range of loads within HFC networks, actual transformer-based power supplies operating beyond 85% efficiency are extremely rare, 80% efficient or lower are much more common. This means that for every Watt consumed in the HFC network, 1.25 Watts are being actually extracted from the electrical grid.

2.- For network design purposes, ideally all the components – both active and passive – should have a purely resistive behavior – and that resistance being as low as possible. The reality is that cable adds an inductive component to its resistance – proportional to its length, and the active devices add a capacitive behavior. These two factors create a phase shift (θ) between the voltage and the current. The ratio between the true power – power in the resistive load – and the apparent power – power considering both resistive and reactive loads – is defined as power factor. A power factor of 1 means the load is purely resistive and apparent power equals true power. Power factors between 0.8 and 0.9 are common in today's networks, depending on the depth of the architecture (N+x) and the length and type of trunk cable used.

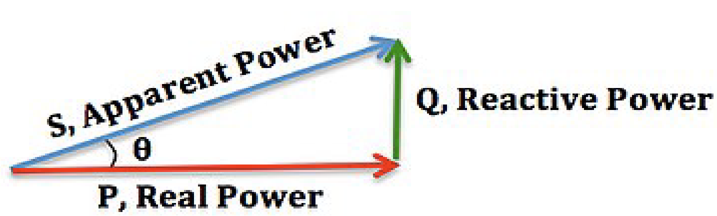

Figure 2 - Real, Reactive and Apparent Power

Both these variables add up to inefficiency in the energy transmission in HFC networks.

2.2. DC - Switching Mode Power Supplies (SMPS)

Switching mode power supplies are electronic power supplies that utilize a high frequency switching regulator to efficiently convert electrical power. These regulators provide electronic isolation by keeping the low voltage equipment separated from the higher mains voltage and regulating the output voltage and current. This keeps voltage constant and prevents short circuits from damaging the power supply and other equipment.

2.2.1. *Pros of DC Powering with SMPS*

The key advantages of SMPS' are:

- Compactness
- High efficiency (up to 99% [5])

SMPS' typically take an AC input, rectify and filter it into DC first, convert it back into a high switching frequency AC, step down the voltage with a transformer and then rectify and filter into a DC output.

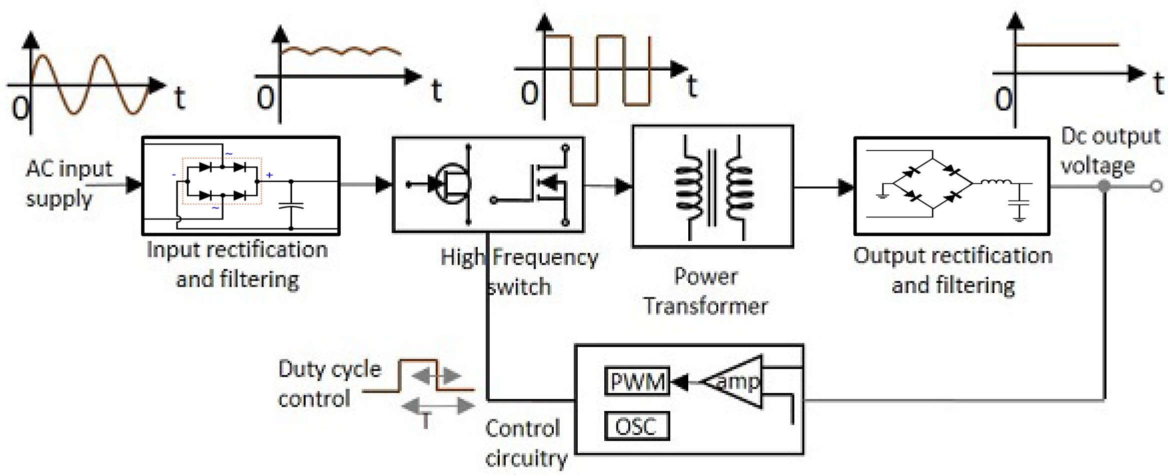

Figure 3 - Functional Diagram of a SMPS

In Figure 3, nothing indicates that the input cannot be replaced with a positive DC voltage. The "Input rectification and filtering" block would just have less stress, as its capacitor would not need to be charging and discharging 50 or 60 times per second.

As mentioned in the previous section, all active devices use solid state technology that requires DC powering. In order to power this solid-state technology, they are built with a device power supply (typically a SMPS) that converts the network supplied AC voltage received via the coaxial cable from a ferroresonant power supply to a lower DC voltage.

Powering HFC outside plant networks using DC supplied by SMPS would offer the following benefits:

1. Higher power supply efficiency, from typical 80% in ferroresonant power supplies to 90-95% with SMPS.

2. Power factor would be 1, since both the voltage and the current would be perfectly in-phase. Apparent power would equal real power; reactive power would be zero.

3. Capacitors in the input rectification and filtering stages of the SMPS of the active devices in the network would be less stressed as they would not need to be recharged and discharged 50 or 60 times per second. This would imply a better meantime between failure (MTBF). It is important to note at this point that the ratio between the current that flows through a capacitor and its voltage is described by the following formula:

$$I_c(t) = C\frac{dV_c(t)}{dt}$$

   Where:
   - I_c is the current that goes through the capacitor,
   - C is the capacitance,
   - V_c is the voltage between the outer conducting plates of the capacitor,
   - t is time

4. Cable losses would reduce significantly. Cable losses are proportional to the current that flows through them times the voltage that is dropped (P = I * V). The voltage dropped in the cable is proportional to the current that flows through it times the resistance of the cable itself (V = I * R). The coaxial cable DC loop resistance is normally specified by the cable manufacturer in ohms per 1000 feet. Thus, the cable losses can be expressed as $P = I^2 * R$.

   The current (I) that flows through the network is needed to provide power to the active devices as well as to charge the capacitors of the first stage of their power supplies. In pure DC powering, since there is no voltage transitions,

$$\frac{dV_c(t)}{dt} = 0 \rightarrow I_c(t) = 0$$

   there is no current needed to recharge those capacitors (once a stable operation has been achieved).

5. Less power drawn by the network has the potential of extending the runtime provided by the existing standby batteries.

All the advantages mentioned above point in the direction of a significant power consumption reduction in the outside plant network by using DC power provided by SMPS.

In order to verify this theorical benefits, a network model was built using three trunk amplifiers and thirteen line extenders connected through hardline coaxial cable, as per the diagram below:

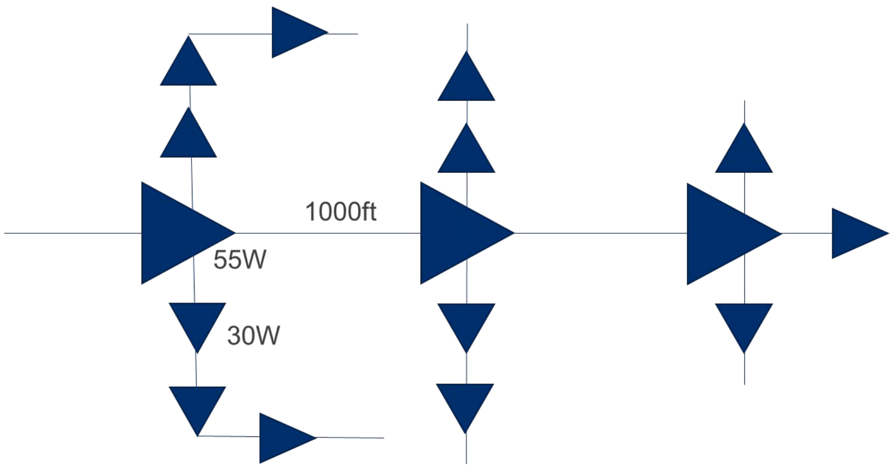

Figure 4 – Network Model for DC Powering Test

Measurements were taken both with a ferroresonant power supply adjusted to $89V_{RMS}$ quasi-square wave and a SMPS with an $89V_{DC}$ output. The total cable power loss dropped from 214W with the ferroresonant power supply to 115W with the SMPS (46% reduction). Overall, the power drawn from the electrical grid dropped from 964W with the ferroresonant power supply to 713W with the SMPS (26% reduction).

2.2.2. Cons of DC Powering with SMPS

This approach is impractical, however, because of the electrolysis and corrosion problems which can result. In the case of DC, the constant and single-direction flow of ions in the presence of water and air forms an oxide layer on the surface of copper and aluminum cables, gradually corroding and deteriorating their surface. This can eventually lead to common path distortion (CPD) noise problems in the network.

In addition to that, normally OSP active devices have an inbuilt surge arrestor in the form of a gas discharge tube (GDT) or a protection thyristor SIDACtor® [6]. These components are intended to protect the active devices from dangerous voltage that might be caused by a nearby lightning bolt.

During an electrical storm, transient voltages are induced onto the OSP network by lightning currents which enter the conductive shield of suspended cable or through buried cables via ground currents.

Both components are present at every terminal of the active device between the OSP network and ground. Under normal circumstances they are in a high-impedance state, but when they suffer a surge, they will change to a low-impedance state releasing the surge energy to the ground, reducing the residual voltage of the circuit and thereby protecting the active device or the human body from any damage.

These surge arrestors will reset – meaning will go back to a high-impedance state - on an AC port at the zero-crossing every half-cycle for an AC signal. This will re-establish the energy supply to the active device and maintain the network operational once the AC power has stabilized. However, for DC power lines, these arrestors will not reset (will stay in low-impedance mode) and no energy will be delivered to the active devices, effectively disabling the network.

3. Smart Low Frequency AC (SLFAC) Powering HFC

The major improvements obtained in the reduction of the power consumption of the HFC OSP using a highly efficient SMPS motivated Technetix to further investigate into the obstacles that prevent the usage of this technology and discover through innovation solutions to overcome them.

3.1. Corrosion vs Power Frequency

An investigation was run based on the application of an AC signal with various frequencies lower than 60 Hz, down to a DC signal (0 Hz). The aim was to create a worst-case scenario and therewith set up a benchmark for future corrosion experiments with other materials (and/or material combinations), environments and measurement methodologies.

For that purpose, a standard electrochemical setup was chosen with copper as the material under investigation and seawater as electrolyte. A three-electrode electrochemical cell was built – see Figure below:

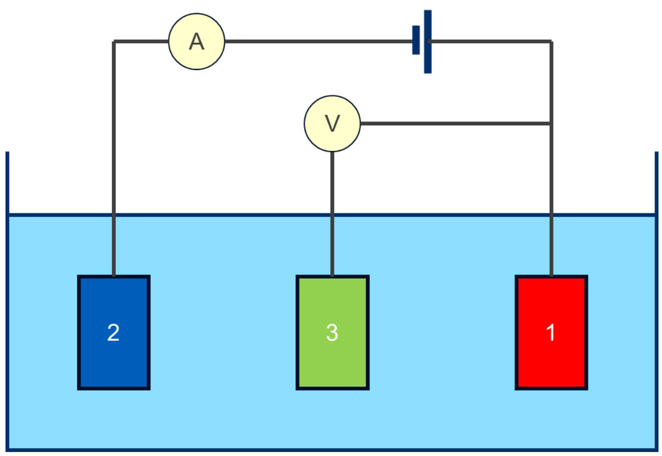

Figure 5 – Three-Electrode Electrochemical Cell

Where 1 is the working electrode, 2 is the counter electrode and 3 is the reference electrode.

This electrochemical cell was subjected to a series of measurements over a period of more than ten hours per frequency (from 0Hz to 60Hz). Then the working electrodes were weighed before and after the test, in an attempt to measure the corrosion rate from weight loss. This operation was conducted in triplicate to verify reproducibility of the results.

The following chart shows the average polarization resistance (log scale) values plotted against frequency.

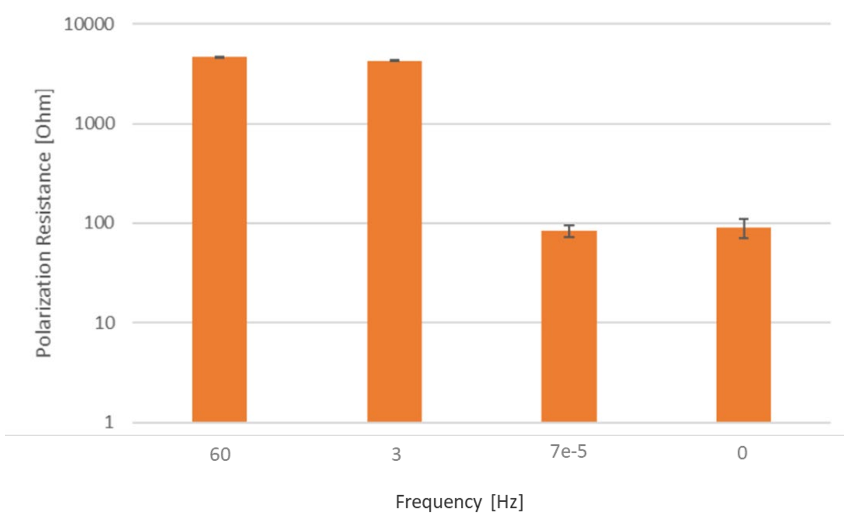

Figure 6 – Average Linear Polarization Resistance

It was identified that the relative corrosion rate increases with decreasing frequency. At very low frequencies (7E-5 Hz) the polarization resistance was similar to DC, while at a low frequency of around 3Hz it was observed that the polarization resistance was very similar to the one obtained at 60Hz. A higher value for polarization resistance leads to a lower sensitivity to corrosion.

Based on this experiment, a frequency of 3Hz would provide most of the energy savings observed when powering the OSP network with DC while maintaining the low corrosion rate benefit of a traditional 60Hz powering system:

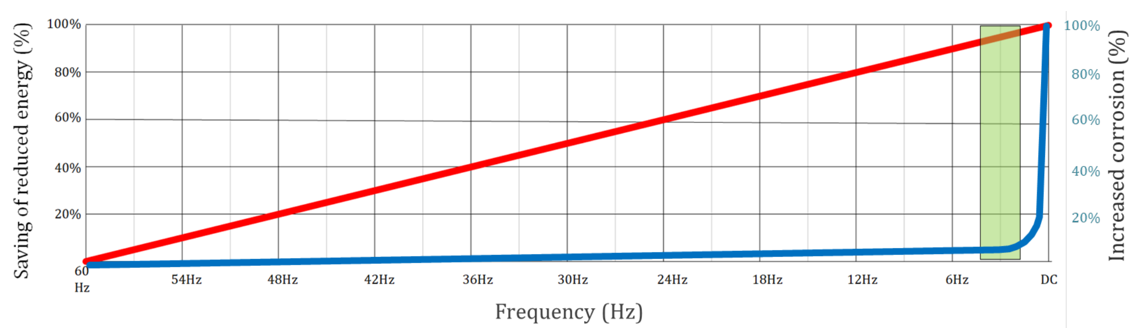

Figure 7 – Energy Consumption and Corrosion vs Frequency

Indeed, low frequency AC (LFAC) transmission for power systems was first introduced in 2000 [7]. The primary advantage of LFAC transmission is that by operating the system at a frequency lower than 50 or 60 Hz, the transmission line reactance can be significantly reduced, thus extending power capacity.

The use of LFAC has been present for a century in railway systems in Central and Northern Europe. Offshore wind power plants are more recently adding up to this technology. The outcome of cables operating at low frequency is decreased charging current, consequently reduced generated reactive power, leading to the increase of the maximum active power that can be transferred in the cable. In particular, for 16.7Hz (1/3 of the 50Hz used in Europe), such active power increase is around 20% [8].

3.2. Surge Protection vs Power Frequency

As stated in section 2.2.2, both common mechanisms to protect network active devices from surge damages (SIDACtors® and GDTs) require zero-crossing voltage of the supplied power.

At the standard north American grid frequency of 60Hz, there are 120 zero-crossing voltages per second (one every half cycle), or one every 8.3ms.

At the suggested 3Hz frequency, there would be 6 zero-crossing voltages per second, or one every 166.6ms.

The capacitors in the input rectification and filtering stage (see Figure 3) of the SMPS' of the active devices in the HFC OSP act as temporary energy accumulators. Since the current that flows through them is proportional to the rate of change with time ($\frac{dV(t)}{dt}$) and current cannot be infinite, the voltage between the plates of the capacitor will drop slowly.

This means that in cases when the surge protection is reset (goes back to high-impedance mode) within a few 60Hz cycles, in most cases the active device will stay operational at every moment since its power need will have been provided by the capacitor. This might not be the case with 3Hz, as the 166.6ms between one voltage zero-crossing (or multiple if the surge protector takes longer to reset), might completely deplete the energy accumulated in the capacitor and shut the active device down.

In order to minimize the chances of active devices shutting down, Technetix has filed for a patent technology that monitors at all times the current supplied by the network standby power supply and if a sudden change is detected, switches from the normal 3Hz operation to 60Hz immediately and during a few seconds until the current is stabilized to reset the surge protectors as quickly as possible.

4. Case study

With the purpose of verifying the theoretically estimated savings in a safe, quick and as realistic as possible environment, few proof of concept prototypes have been developed with commercially available high-efficient SMPS adjusted for a 63/89V_{DC} output and a low power consumption IoT microcontroller to monitor the key parameters and drive the switching speed (3Hz vs 50/60Hz) of an H-bridge electronic circuit.

A test set-up was put together with a 5-amplifier cascade (four trunk amplifiers and one line extender) connected via 1,625ft of 75Ω tri-shield coaxial RG11 cable with a 77% braid. Power analyzers were connected to both the input and output of the device under test (DUT) to compare the performance. 10mΩ shunts were added to every connection to accurately measure the current flowing through each network piece.

The block diagram below shows the test set-up:

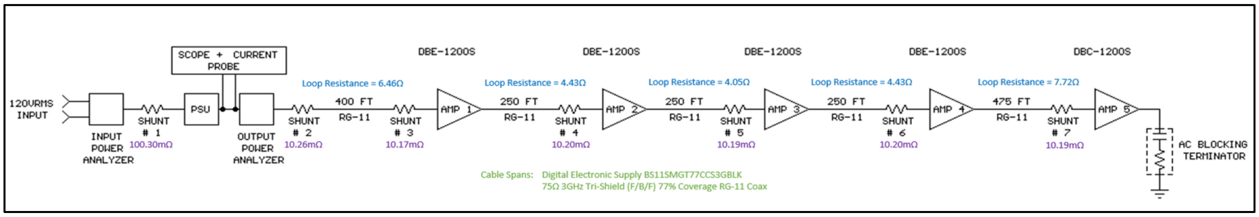

Figure 8 – 5-Amplifier Cascade Performance Testing Set-up – Block Diagram

The following picture shows the laboratory set-up with the prototype being evaluated.

Figure 9 – 5-Amplifier Cascade Performance Testing Set-up - Picture

Four different commercially available power supplies were used as DUT. The first two units (UPS-A and UPS-B) are industry well known network standby uninterruptible power supplies (UPS) with $89V_{RMS}$ quasi-square wave outputs and maximum output rated power of 1,350VA. The third unit (PSU-C) is a non-standby sine wave transformer power supply unit (PSU.) with the windings adjusted for an $89V_{RMS}$ sine wave output. The fourth unit (ASPX) is the smart low frequency AC power supply developed by Technetix with a maximum output power of 1,500W.

The following table summarizes the key parameters:

Table 1 - Smart Low Frequency AC Power Supply Test Results

	Input		Output			
	Input Voltage (V_{RMS})	Input Power (VA)	Output Voltage (V_{RMS})	Output Power (W)	Amplifiers Power (W)	Cable Loss (W)
UPS-A	120	456	89	340	197	143
UPS-B		437		358		161
PSU-C		450		406		209
ASPX		310		267		70

As anticipated, the combination of an improved power factor – since now the power waveform remains flat at 89V over longer periods of time (3Hz vs 60Hz) and therefore the reactive component of the apparent power (see figure 2) - and the fact that less current flows through the cables to recharge-discharge the capacitors in the active devices power supplies, adds up to a massive (more than 50%) reduction in the measured power lost in the coaxial cable.

This impact adds up to the fact that the SMPS' used in the ASPX prototype are significantly more efficient than both the ferroresonant power supplies (UPS-A and UPS-B) and the sine wave transformer (PSU-C). This results in an overall input power reduction of at least 31% (310VA vs 437VA) in the 5-amplifier cascade test set-up.

It can be argued that the selection of RG11 as coaxial cable is not the best representation of an HFC network construction as most of the trunk cables used present a wider diameter and lower loop resistance per unit of distance, or that the number of amplifiers in this test set-up (5) does not represent a typical network segment powered from a single UPS – normally around 20-25.

Both arguments are valid, and the reality is that typical network segments fed by a single UPS in an N+4 (or deeper) architecture spread out not only 1,625 ft as in the test set-up, but normally one to multiple tens of thousands of feet, and also that the higher the number of amplifiers in the segment, the further away the latest ones will be from the UPS, forcing the current needed to power them flow through a longer distance of cable, which increases the power loss in the cable.

5. Future

Technetix, committed to the continuing sustainability performance improvements and to helping the broadband industry reach their sustainability goals, will keep investing and investigating in this innovative energy savings idea and plans to create some additional proof of concept prototypes early in the fourth quarter of current year with optimized SMPS and custom-built control and polarity switch circuitry, that will be made available for interested broadband operators to test in their labs.

In parallel and based on the information harvested during the multiple tests that have been run so far, a mathematical model is being developed to estimate, given a specific network architecture, the energy savings that can be obtained so that the operator can make an educated guess.

6. Conclusion

In summary, this paper presents an energy savings proposal through the replacement of traditional sine wave or ferroresonant power supplies with a more efficient and innovative SMPS-based smart slow frequency AC.

These energy savings can be translated into a sizeable reduction in the electricity bill of broadband cable operators – which typically represents up to 50% of their electricity consumption – with the consequent massive impact in the greenhouse gas emissions reduction and help with net-zero sustainability initiatives OR they can become additional energy available in the network to upgrade existing active devices that are more energy demanding or to power additional ones such as remote OLTs, 5G small cells or WiFi hotspots without needing to add additional service connections to the electrical grid.

Abbreviations

AC	alternating current
CPD	common path distortion
DUT	device under test
GDT	gas discharge tube
GHG	greenhouse gas
HFC	hybrid fiber-coaxial
Hz	hertz
Hz	hertz
K	kelvin
MTBF	mean time between failures
OLT	optical line terminal
OSP	outside plant
PSU	power supply unit
RMS	root mean square
SCTE	Society of Cable Telecommunications Engineers
SLFAC	smart low frequency alternating current
SMPS	switching mode power supply
UPS	uninterruptible power supply

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