USING ESSENTIALS OF APPLICATION ENGINEERING CONCEPT FOR DESIGNING INDUSTRIAL SYSTEM DRIVES

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Abstract: Two thirds of the electric energy production (amounted in 2009 at 20,300 TWh) is used by industrial system drives (ISDs) performing at 80%…20% overall efficiencies. There is large variety of ISDs not performing efficiently or failing with downtime production losses. For an average efficiency of 55% the waste energy with ISDs is estimated at 8,860 TWh. One of the reasons is that proposed Five-Essentials-of-Application-Engineering (5EAE) concept is not applied or taught at tertiary education level. This concept is focused on specific ways of thinking outside the box. It employs sustainable and consistent approach when retrofit or new designs options are taken into consideration. 5EAE requires that any ISD shall match the followings: downstream conditions, upstream conditions, environmental conditions, reliability and efficiency indicators and conditions of business sustainability. Use of 5EAE requires strong technical background reflecting deep expertise in a single area, usually technical, complemented with a broad working knowledge of multiple areas of inquiry, establishing a professional as capable of interacting with various facets of the application. Proposed concept is an ideal method to prepare practicing engineering graduates for the global economy requiring broader knowledge in collateral fields. This approach fosters individuals with a deep technical understanding coupled with broader knowledge in the fundamentals of engineering design, innovation, business, leadership. Such training prepares professionals for success negotiating the corporate, global world of industry. The paper presents 5EAE fundamentals with case studies, highlighting also thermal pollution resulted from poor performances of ISDs and conservation potential obtainable by promoting 5EAE concept.

1 INTRODUCTION

Scientific and official documents stress that energy efficiency improvements can play a key role in both assuring a sustainable energy future at all levels of industrial activities and mitigating climate change through socio-economic development as mentioned by Intergovernmental Panel on Climate Change (IPCC, 1996) and re-defined by Federal Energy Management Plan (DoE, 2004). World Climate Summit in Durban-South Africa (WCS, 2011) concluded "that changing unsustainable patterns of energy use is a key area for global action to ensure the survival of our planet".

This paper is about two primary topics: industrial system drives (ISD) and ways of thinking/education.

It proposes a new Concept of 5 (five) Essentials-of-Application-Engineering – 5EAE, (Pitis, 2006, Pitis 2007) which would enable engineers, consultants, designers, manufacturers, and end-users to consistently design and evaluate any design or retrofits of power converters (PC) and/or industrial system drives (ISD).

The paper addresses the need of syllabus opportunity by employing 5EAE concept – that is a subject not being taught in tertiary education. To date there are no specific references on this subject. The concept is focused on specific ways to think outside the box. Examples are used to a large extent to show how these thinking approaches have led to better solutions in the past. In this context, such solutions tend to contribute to improvements in how we build and manage future industrial systems drives of various types.

The 5EAE concept has already been successful applied in designing and manufacturing integrated industrial system drives (IISD) in mining and heavy industries in South Africa (Pitis et al., 2007).
As a new concept, 5 EAE produces several collateral benefits: 1) An increased technical and economic performance of processes, 2) The defusing of incipient energy and economic crisis, 3) An improvement of environmental conditions, and 4) The creation of jobs in industries. Consequently, 5 EAE can be used as a model for improving a company's corporate policies and/or utilities, and government energy policies.

1.1 Basics of Industrial Systems Drives (ISD)

There is a large variety of power converters (PC) and industrial system drives (ISD) which require a sustainable and consistent approach when retrofit or new designs options are taken into consideration. From an economic standpoint, sustainability concepts favor high-efficiency systems, as an energy-efficient system translates into higher effective productivity. This outcome is achievable through a comprehensive approach to design, which includes energy engineering to inform the design process.
The simplest ISD configuration is defined as chains of "i" number of PC, as shown in figure 1, performing:

- **Electrical Conversion** (Transformers - TRX; Variable Frequency Drives – VFD, Starting devices)
- **Electro-mechanical Conversion** (Electric Motors - M)
- **Mechanical Conversion** (Gears, belts, couplings, Transmissions – T, ASDs)
- **Driven equipment, DEE** (Pumps, fans, air compressors, refrigeration, material handling, processes)
- **Monitoring & Controls, Software,** if system is controlled

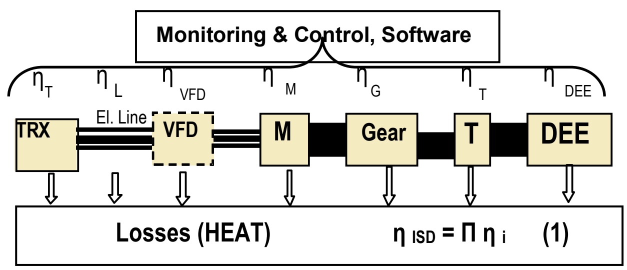

Figure 1: Typical (simplest) series configuration of an Industrial System Drive (ISD), (Pitis, 2007)

Overall efficiency of η_{ISD} is given by Equation 1.
[1] $\eta_{ISD} = \Pi \eta_i$
Typically ISD overall efficiency value is $\eta_{ISD} = 0.55$ with average efficiencies (US-CEEM, 2012) and Mean Time between Failure (MTBF) – failure intensity ($\lambda_i \times 10^{-6}$ [1/hour]) values as shown in Table 1

Table 1- Typical efficiencies, average MTBF, failure intensity ($\lambda_i x10^{-6}$ [1/h]) values* for series ISDs

Equipment	TRX	Line	VFD	Motor	G-box	Transm	Driven	Overall
Efficiency	0.98	0.996	0.97	0.95	0.88	0.95	0.74	0.55
MTBF (10^6h)	12	10	0.08	0.05	0.8	1.0	0.8-1.5	0.58-1.08
$\lambda_i \times 10^{-6}$ [1/hour]	0.0833	0.1	12.5	20.0	1.25	1.0	1.25-0.67	1.74-0.93

*Average values as per (Pitis et al, 2007, Zhadnov, 2011, USA Navy, 1994, USA Army, 2007). Hence wasted energy is estimated at 45 % of the input energy (power).

1.2 Current Characteristics of Industrial Market

The current state of industrial market is characterized by the following barriers:

- The market for subject matter experts for project definition is scarce and innovation is rewarded on an hourly basis.
- Given large variety of ISD, it is difficult to apply consistent energy performance parameters as a design criteria
- Additional cost requirements for system assessments and energy efficiency feasibility studies.

- Experience shows that re-engineering services work, but innovation rate may be low – as knowledge is guarded.

  On the other hand from customer's point of view, the market industry is still divided into two distinct tiers (Pitis, 2007, Pitis et al., 2010):
- Non-discerning product market, CAPEX driven, initial cost usually being the chief driver of the purchasing decision
- Discerning product market - specification and OPEX driven, accepting the concept of the total cost of life cycle costing.

  Different approaches of designing and manufacturing ISD are driven by this market configuration.

1.3 Short Overview of Traditional and New Approaches on ISD Designs

Do-it-yourself Engineering Design (DIYED). This is an old fashion method of using internal resources existent within facility for design and manufacturing specific ISDs. Anecdotally (because of avoiding design expenses, i.e. CAPEX) it was sometimes presented as a "success story" of personnel inventivity.

Catalogue Engineering Design (CED). Traditionally, industrial system drives were designed by consultants using catalogue engineering approach whereby each component of the system was selected based on the design point of the component, not the system. The objective function was (and is still present) the capital expenditure (CAPEX). Minimization of operational expenses (OPEX), power/energy savings specifically are not considered to be relevant, while purchaser department has made "savings".

Energy Efficiency Catalog Engineering Design (EECED). Commodity prices, government policies and utilities programs influenced catalogue engineering efforts by promoting or even mandating energy efficient components. Since the 1990s the market start being influenced by minimum energy performance standards (MEPS) which have impacted energy efficiency of the components specified to support a lower total cost of ownership.

Energy Management Engineering Approach (EMEA). A newer trend of retrofit activities is often carried out at the mid-life equipment renewal stage based upon re-engineering existing systems for higher efficiency, often supported through incentives by utilities and government. However, industrial system drive improvements were still dominated by component approach, and not by applications, for example: Variable frequency drives (VFDs) and Premium motors are limited in their impact as supply-side solutions for ISD; therefore VFD are not optimized for their application, but mimic throttling devices they replace.

Great advancements in power electronics at the beginning of this century enabled the nearly universal application of variable frequency drives for variable torque and variable power applications. This enabled the elimination of mechanical fluid flow controls, such as: throttling valves, inlet and outlet dampers, and guide vanes. Various VFD manufacturers continue to provide free software assessing energy savings on variable torque/power applications with as few as 4 (four) input values.

Ultimately, the perceived solution for a mechanical system's energy efficiency remains electromechanical in nature, based on the segregation and minimization of system losses, but not necessarily system performance. In many cases EMEA is costly in the project development phase and in the final capital cost. This field approach to ISD efficiency requires expertise and materials with uncertain outcome in terms of energy efficiency.

OEM dedicated designs (OEMDD). This is an application/system approach type inspired from commercial and residential applications. The concept of load "modulating" electric input power according to mechanical load requirements in conjunction with use of reduced number of components of the power train (IISD method) emerged on the market as the ultimate concept of energy savings with increased reliability of systems. It is promoted by Integrated ISDs (IISDs) that are system performance orientated.

The emerging trend of increasing flexibility, adaptation, and autonomy of embedded control and information systems is the driving force behind the evolving systems paradigm. Evolving systems are systems with flexible model structure that adjust to changes which cannot be solely handled by parameter adaptation.

Evolving intelligent systems develop their structure and knowledge representation through continuous learning from data and interaction with the environment. They exploit synergies between two powerful concepts – real time data granulation and machine learning – with model structure that may include regression models, neural networks, fuzzy, and/or stochastic models.

2 BASICS OF FIVE ESSENTIALS OF APPLICATION ENGINEERING CONCEPT

Practical applications encompass a wide range of systems with variable parameters and structure, and multiple operating modes. However industrial systems do have in common some characteristics that are addressed by use of 5EAE concept. 5EAE defines basic concepts of designing (selection) and/or assessment criteria applicable to any integrated ISD.

This paper proposes new approach in designs/retrofits of ISD by employing the 5EAE concept – a subject not being taught in tertiary education.

Engineering is nothing more than planning based on knowledge instead of guesswork. In this sense, everyone in design, service, maintenance, and technical sales work is his (or her) own engineer, every day. Using application engineering principles requires an appreciation of the role of industrial processes in business sustainability and risk assessment. Proper selection of PC or ISD design does take some fundamental knowledge, requiring a strong technical background.

When selecting a PC for a specific application or when designing or retrofitting ISD, **5** (**Five) Essentials** of what is called **Application Engineering (5EAE)** must be taken in consideration (shown in Figure 2):

- **#1 EAE: Matching downstream conditions** (electrical or mechanical load) is the most important and the most complex tenet of the five Essentials to be considered.
- **#2 EAE: Matching upstream conditions** means the PC or ISD must comply with incoming electrical or mechanical power conditions while also considering its influence on the incoming power.
- **#3 EAE: Matching environmental conditions** means the equipment must not be destroyed by its surroundings. Conversely, it must not, in turn, inflict environmental damages.
- **#4 EAE: Matching efficiency and reliability indicators** enable the end-user in planning repair and maintenance (R&M) activities, preserving system performances, with reference to alteration or rapid deterioration system performance during its lifetime, and therefore minimizing operating expenses. Reliability is the reciprocal of failure, and failure is a random event mainly influenced by heat transfer and power losses, therefore efficiency can significantly influence reliability.
- **#5 EAE: Matching conditions of business sustainability** Using life-cycle costing methodologies to establish total cost of ownership (both capital and operating costs) promotes energy efficiency options. Business sustainability requires mutual benefits to the OEM ("premium" rewarded for value added system) and the customer.

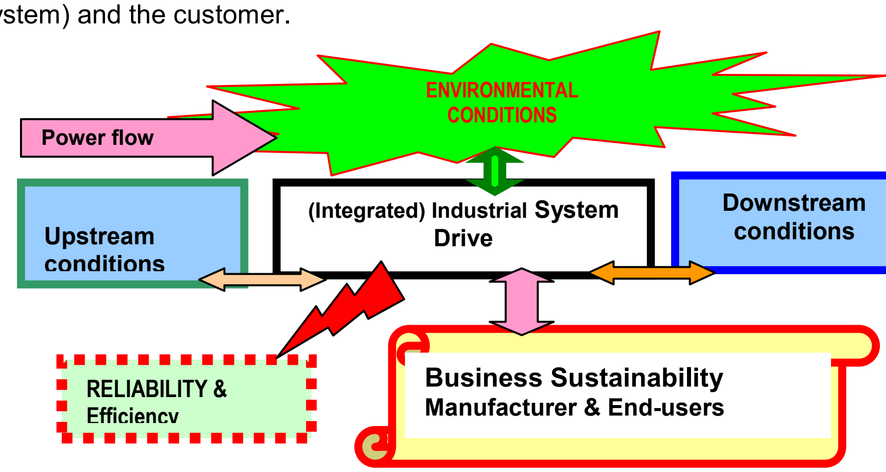

Figure 2: 5EAE defines basics of design and/or assessment criteria of any ISD (Pitis, 2007)

Systems' performances improvement and increased reliability indicators with optimized management aiming OPEX reduction are an obvious corollary of the 5EAE.

3 DISCUSSION ON SALIENT FEATURES OF 5 EAE CONCEPT

The objective of the 5EAE concept is to minimize power losses and environment impact, maximizing IISD global efficiency and incorporating its reliability indicators. It is a step forward on design methodology that minimizes production cost in terms of energy intensities of production such as kWh/production unit.

As obvious corollary of 5EAE concept, it was found that higher performances (efficiency) and high reliability indicators are possible to be obtained by using any of 3 (three) methods:

- **Eta method:** Maximizing efficiencies of PC but keeping the same configuration of the power chain.
- **Wire-to-process method**: Reducing the number of PC in the power chain (increasing ISD reliability)
- **IISD method**: Use of Integrated Industrial system drives and OEM designs of dedicated IISD

In particular, based on previous South African experiences in mining industry have been proven that OEMDD (IISD methodology) represents a reliable solution to the present economic and environmental crisis that persists, in part, due to a misunderstanding of the efficiency opportunity.

In addition, compliance to 5EAE, the use of IISD designs will enable the followings:

- Employ premium efficiency products and controls in IISD designs (Eta);
- Maintain high efficiency values over large range of loads (Eta);
- Reduce the number of power converters in system – shorter power train (Wire-to-Process);
- Process automation and performance optimization (IISD);
- Properly matched power converters during design and retrofit (performance optimization) (IISD);
- Stability of high efficiency values of PCs over large range of loading profiles (IISD);
- Performance stability after maintenance and repair (IISD);
- Target lowest cost of ownership (OPEX) through life-cycle costing (IISD).

4 EXAMPLES OF NON-COMPLIANCE TO 5EAE CONCEPT

By definition, integrated ISD must be in full compliance with 5 EAE. By contradicting the 5EAE, business may become less competitive and exposed to financial risk. Minimum values of power savings obtainable with IISD may be assessed by analyzing impacts of non-compliance with the 5EAE.

4.1 Non-compliance to EAE #1 (Downstream conditions)

Typically, the most oversized component in an ISD power train is the transformer. Operating transformer loads are loadings in a range of 15%-30% of their rated capacity. It is estimated that correctly sizing distribution transformers will generate approximately 7 % power savings (CSA C802-5, 2014)

The same applies to electrical motors. Usually efficiency of such electro-mechanical power convertors (AC motors) is in direct proportion to its loading, up to 75% loading, when it levels off or decreases slightly. Over the range of 10%-75% of full load – the higher the loading, the higher is its efficiency. Therefore, motor losses can be reduced by selecting the correct size motor for each application. Oversized motors used in power trains frequently occur in various industrial plants worldwide. This phenomenon is often a consequence of various allowances, accumulated during the process of design, project management, construction, procurement, and commissioning of a plant.

Often, selection of electrical motor as part of ISD has the following trajectory for equipment sizing:

- Basic application requirement – basic power P = Po
- 10%...15% contingency added by equipment designer P = 1.1 Po…1.15 Po
- 10%...15% contingency added by project engineer, P = 1.21 Po…1.32 Po
- Increase to nearest available rating, P = 1.33…1.55 Po
- Procurement adding allowance, P = 1.55…2.0 Po

Case study: In a metal mine, a group of 53 (standard efficiency) motors (total power 6,700 kW) are working 24/7 (96.5 % average availability of mining equipment) at average loading of LF = 48%.

Energy consumption on baseline E_B = 6700 kW x 0.48 x 8760 h x 0.965 = 3216 kW x 8454 h = 27.2 GWh

Motors were replaced with right sized Energy efficient motors (total power 3,850 kW) at LF = 75% (Janicijevic et al). Annual consumption becomes E_1 = 24.4 GWh with Energy savings of 2.8 GWh/y.

Reduction in power demand ΔP = 6700 x 0.48 – 3850 x 0.75 = 3216 – 2887 = 329 kW $_{electric.}$

By replacing oversized standard motors with right sized energy efficient motors specific power saving indicator representing power savings per 1 kW installed power is:

C_M = 329 kW/3216 kW = (0.1 kW/1 kW) = 10% efficiency gain.

In case of replacement with Premium® motors, efficiency gain is C_M = 11.7 %, while replacement by use of advanced motors, efficiency gain becomes $C_M \approx 13\%$.

Overall, if correctly sized within ISD, electric motors (Pitis, 20017) and transformers (CSA, 2014) will reduce power demand with about PS_{Mot} = 12%.

4.2 Non-compliance to EAE #3 (Environmental conditions)

Typical examples include for example improper design of equipment enclosures not matching environmental conditions, i.e. actual ambient temperature performs higher values than standard values. The consequences are that many types of equipment run at higher than normal temperatures. As a result additional power is wasted for cooling (HVAC) or improving heat dissipation (heat transfer) – ventilation.
Figure 3 depicts examples of specific components (rotors, electrical contacts, connections and bearings) being damaged due to poor heat transfer resulting in unnecessary down time production loss.

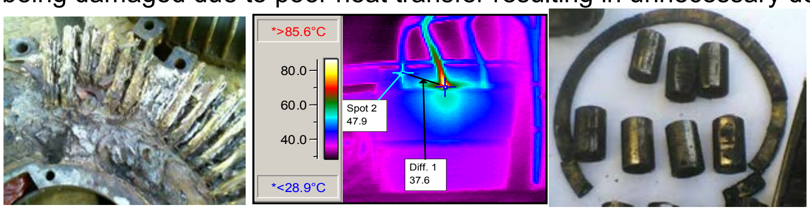

Figure 3 – Samples of damaged components (rotor, connection boxes, bearings), (Pitis, 2007)

It was estimated that, by matching environmental conditions, power savings of about 3.5% can be achieved with electric machinery (transformers and motors), only (Pitis et al 2012)

4.3 Non-compliance to #4 (Efficiency and Reliability indicators)

ISD reliability indicators are related to their number of components with their individual failure rates compounded. Catalog Engineering Design (CED) approach produces unnecessary high number of PCs of ISD. It is estimated that by reducing the number of components in the power train (use of Wire-to-Process method), a minimum 8% power savings could be obtained (Pitis, 2006, Pitis 2007).
A significant amount of heat is generated by inefficient operation of equipments due to improper specification or the use of general purpose equipment for special-purpose applications. While bearing failures represent about 65 % of rotating machinery failures, there are no specifications on bearing temperature rise. Sometimes equipment manufacturers not provide specific operating, maintenance and repair (R&M) instructions with expected values for system monitoring, repair and tests. As a result, ISD performances “slip” toward lower values, operating closer to an area of performance instability. Power savings of about 2% are estimated by addressing proper R&M activities (Pitis et all, 2012, Zeller, 2011)

4.4 Non-compliance to EAE #5 (Business sustainability)

A potential spanner in works progress has been for decades the declining R&D activity at the OEM levels. One of the explanations is the unbalanced market: non-discerning product market (CAPEX driven) using cost considerations in bid selection (Par 1.2). The second reason is manufacturer’s reluctance to move from general purpose to definite purpose products or dedicated equipments (OEMDD – Par 1.3).
Reputable corporations, mining houses start insisting on dedicated products. It is estimated that by using dedicated equipments and IISD, power savings can be increased by 10-15% (Pitis et al, 2007).

4.5 Case study: Contradicting essentials of application engineering (Pitis, 2007)

Overseas-designed continuous miners (**CM**) have been imported in South Africa for coal mining industry. For various reasons, their declared rated performance of 40,000 tons of coal cut/month has been totally outrun in RSA (currently production figures are ranging between 80,000 and 1200,000 tons coal/month).
After a while, it becomes obvious that some overseas-designed motor powering these CMs were not satisfying the harsh South African requirements, contradicting 5EAE:
EAE#1: Higher volume of cutting coal brought the motors in heavy working conditions (frequent DOL stop/startings and re-closures, prolonged stall conditions, heavy overload conditions) with accelerated degradation and higher failure rates;
EAE#2: Machinery was forced to withstand specific South African power supply conditions as: unbalanced or out of standard voltages, sags and dips, transients, frequency and voltages variation;
EAE#3: Various environmental conditions dirty and acid cooling water blocking or corroding water jackets by-passing thermal protections, ,
EAE#4: Lower reliability and efficiencies on motors and maintenance activities

EAE#5: Lack of co-operation between user and manufacturer/repairer and unions and employer;
The machinery failure rate increased beyond expectation with obvious consequences: high financial losses due to down-time production costs (DPC) of 149…219 kilo-Euro, as shown in Table 2

Table 2: Financial losses generated by failure of a specific CM (Pitis 2007)

Item	Cost	Financial loss
DPC, hourly rate	125 t x 40 E = 5000 E	
DPC loss@ 18h	5000 E/h x 18 h	90,000 Euro
Penalties 10%	500 E/h x 18 h	9,000 Euro
- **New motor**	**120,000 Euro**	
New rotor	10,000 Euro	10,000 Euro
Av. cost repair	Max 60 % of new	40,000 Euro
- **Total losses**		**149,000 Euro**

By using IISD methods in compliance to 5EAE, a new "P" series of cutter motors has been designed and manufactured. Failure rates have been reduced (MTBF = 12 months), with improved efficiency (95.5%).

5 ESTIMATING CONSERVATION POTENTIAL OF A NATIONAL INDUSTRIAL SYSTEM

Consider a typical country with electric energy consumption EEC = 500 TWh/year evenly distributed between residential, commercial and industrial sectors (distribution factor DF = 33 % each).
Theoretical researches and reports performed by utilities, reputable corporations and other organizations indicate potential power savings in [%] of the power flow through industrial systems (as shown in table 3).
Such savings can be obtained at components level as parts of Integrated Industrial System Drives (IISD) (Pitis 2010) in compliance to 5EAE (table 3 columns 3…7).
Typical overall efficiency of ISD was estimated at $\eta_{Av,\ init}$ = 55 %, see Chapter 1, figure 1;
Column 2 in table 2 indicates initial and after improvement efficiency values ($\eta_{Av,\ init\ //}\ \eta_{Av.\ after}$).
The Efficiency incremental (Δ) is estimated as $\Delta = (1 - \eta_{Av,\ init}) \times (\Sigma\ \eta)$ in [%]
New efficiency value ($\eta_{Av.\ after}$) is estimated as, $\eta_{Av.\ after} = \eta_{Av,\ init} - \Delta$
Wasted energy (WE) converted in Thermal Pollution can be estimated as:
$(WE)_{initial} = EEC \times DF \times (1 - \eta_{Av,\ init}) = 500 \times 0.33 \times (1 - 0.55) = 74$ TWh = 63,640 Tcal/y
Average efficiency obtainable by IISD promotion may reach 67 % (column 2) and waste energy becomes:
$(WE)_{New} = EEC \times DF \times (1 - \eta_{Av.\ after}) = 500 \times 0.33 \times (1 - 0.67) = 54.5$ TWh = 46,870 Tcal/y

Table 3: Conservation potential [%] obtainable by applying 5EAE Concept. (Pitis 2013)

Equipment (power converter)	Av. Efficiency $\eta_{Av,\ init\ //}\ \eta_{Av.\ after}$	Estimated Efficiency improvements by compliance to 5 EAE [%]					Total Effic Improvements	Efficiency Increment
		#1	#2	#3	#4	#5	(Σ η)	(Δ)
TRX + lines	97 %//98%	7 %	1.5%	3.5%	8 %	12.5%	32.5%	1.0 %
Motor(VFD)	94 %//95%	12%			Heat:2%		14 %	≈ 1%
Power Train	60.0%//72%	45%					45 %	18 %
Total	55 %//67%	23.5%	1.5%	3.5%	10 %	12.5%	51.0 %	≈ 20…21 %

Therefore for a typical country with electric energy consumption of EEC = 500 TWh/year evenly distributed between sectors, (distribution factor DF = 33 % each) energy losses Δ (WE) can be reduced with about 20 TWh if IISD are promoted: $\Delta\ (WE) = (WE)_{initial} - (WE)_{New}$ = 19.5 TWh/y = 16,770 Tcal/year.
Proposed methodology can be applied at any level: industry, corporation and plant, ISD or even PC.

6 CONCLUSIONS

There is a large variety of power converters (PC) and Industrial System Drives (ISD) requiring sustainable and consistent approach for retrofit and new ISD design options.
The paper describes briefly how 5EAE concept can be used to set up basics of a new design method of the Integrated Industrial System Drives (IISD) already being developed for some industrial applications.

5EAE enables consultants and customers to make consistent decisions on ISD designs or on selection of any PC, while end-users and utility programs can use it for consistently evaluation of any PC or ISD
The paper justifies the need of syllabus opportunity of introducing 5EAE concept – that is a subject not being taught in tertiary education. To date there are no specific references on this subject. The concept is focused on specific ways of thinking outside the box. The concept development is based on author's experience in mining and heavy industries in South Africa, where concept was extensively applied.
Examples of non-compliance to 5EAE are used to indicate how these thinking approaches may led to better solutions. In this context, such solutions tend to contribute to improvements in how we design, manufacture and manage future industrial systems drives of various types.
More information on this concept was supposed to be given in proposed Paper #:52 - The Fundamentals and Practice of Essentials of Application Engineering Concept (1). Because reviewers concerns on developments of this research (based on proposals made by the author), the paper has been withdrawn.

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