Energy Efficiency Prospect of Power Electronics: Example: Welding Inverter

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ABSTRACT

Energy resources are available in various forms and it is being used by people in various ways. Its efficient conversion to usable form reduces global warming and creates less environmental hazards. Electrical energy (EE) domain makes an attractive means to make energy available to the end users at any location. More and more applications use it. It is cleanest form of energy to use. Like all other means of energy usage, it has also grown by improving the efficiency and reliability of constituent components such as generator, transformer, motor, lighting equipments etc. Achieving E^2 of different components does not, necessarily, optimize the utility of EE. Process efficiency, process innovations are major goals to be achieved.

Better understanding of applications and processes has resulted changing pattern in load behavior to achieve E^2 and most importantly, the performance. As a natural course, more and more non-linear loads have been connected to the passive electrical grid. The grid looses control to support large non-linear loads as the compatibility between source and load is reduced. The changing relation between source and load needs a system that creates compatibility between them. Power electronics equipments (PEEs) exactly meet that requirement. Performance, E^2, reliability, compactness, ease of usage, better economics etc. are key inherent features modern PEEs offer. This article details the multi-dimensional role played by PEEs in the EE domain and create certain definite hope in terms of energy balance and better environment to live in. As a case study the importance of welding inverter is detailed here.

Abbreviations: AE: Arc efficiency, ATLE: Across the load efficiency, AWE: Arc welding equipment, CMT: Cold metal transfer. DSP: Digital signal processor, E^2: Energy efficiency, IHE: Induction heating equipment. GMAW: Gas metal arc welding, GTAW: Gas tungsten arc welding, SMAW: Shielded metal arc welding, T & D: Transmission and distribution.

INTRODUCTION

Energy is defined as the capacity to perform work. Resources of multiple origins are available for energy. Multiple avenues are also in place to use energy. There is lack of understanding about the physical importance of energy. For example, we purchase it in 'kg' for our cooking, in liter for transport, considers our reserve in BThUs, barrel, kg/M^3 etc, and pay most energy bills in units (kWh). Similarly, welders may be indifferent to energy concerns while performing similar welding operation either using electrical power source or oxy-acetylene torch. Its better understanding can help humankind channelize its usage in better ways.

Most of energy sources are not readily usable. Conversion and/or refinement are necessary. Better conversion efficiency reduces losses and emission of polluted gases. Traditional coal fired power stations operate at 30 – 35 % efficiency where as latest coal technology known as integrated gasification combined cycle or IGCC [1] generates electricity with efficiency level above 60 %. Though there is significant improvement, the scope of further saving is still large. Energy loss at any stage or location has multiple impacts such as – (i) depletion of reserve, (ii) ecological balance s. a. CO_2 emission etc,(iii) energy cost and (iv) poor life cycle of equipments.

Increase in life expectancy has resulted in population growth, particularly in developing countries. More people are moving to urban areas. More urban areas are, as well, being created as part of civic development process. The per capita energy consumption in urban areas is more. Energy consumption is on the rise. In such a civic transition process, the energy infrastructure, the utility system etc should provide E^2. The ideal mode of energy for urban areas should be in some form that does not pollute ambience and consumers should be at ease to use it and it should be energy efficient.

It is difficult to define E^2 in simple expressions due to its diverse nature of existence and means of usage. Applications decide pattern of energy consumption and so are their means to achieve E^2. Domestic and commercial loads are different than industrial loads. Multiple inputs may decide industrial processes. The pattern of energy usage of developing countries is also different than that of developed countries. For example [4], industrialized countries consume less than 10 % of EE for lighting loads, where as some developing countries consume as high as 86 % for similar loads. Developed countries have successfully adopted energy efficient lighting system. The energy needs for people staying in torrid, temperate and frigid zones are different. People staying in hot and humid atmosphere need energy for ambience cooling. It is other way round in cold countries. Such load pattern varies [23] with seasonal changes as well. The quantum of energy required also changes accordingly. Prevailing weather, geographical location, available energy sources, technological advancement, the existing load pattern and the infrastructural, industrial and economic growth process of a country decide the energy demand. Therefore, the policy for attaining E^2, in general, is country-specific.

Developing countries are still struggling to make energy available to all citizens and in many places even basic energy needs are yet to be met. It may not be the right approach to meet demand by increasing capacity only. Efficient usage of energy preserves energy. The increase in energy consumption in developed countries is less noticeable because the increase in load demand is being offset by increasing E^2 of various equipments/loads. Inertia to adopt new energy efficient methods and/or technologies hinders developing countries to have control on ever increasing demand in energy, control ecological balance and improve sustainability issues. Various factors are involved such as i) availability of technology, ii) initial cost for change, iii) pay-back period, iv) reliability etc. The energy extracted for use by increasing the efficiency of existing sources, transmission systems and loads is called 'efficiency resource'. After adopting such means, developed countries have successfully achieved the means of creating the energy balance and they have kept environmental issues under control. It would prevent fast depletion of reserve. Alertness to implement the technical innovations for creating E^2 to enhance sustainability has given developed countries a definite edge in creating better ecological balance. E. g. wide (voltage and current) range acceptance of low to medium frequency energy efficient (Fig. 1) Trench Field Stop or Soft Punch Through IGBT [2] in Drives, UPS, Traction, STATCOM etc since its introduction into the market has been immediate with remarkable results. The use of NPT IGBTs is mandatory in certain high frequency applications.

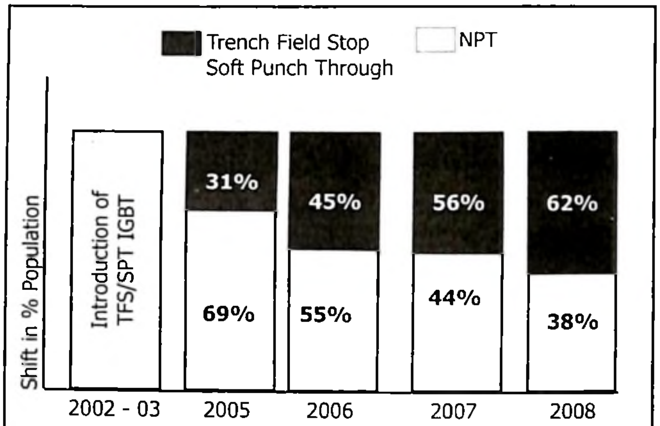


Fig. 1 : Adaptability to technical innovation

Sustained effort is required to look for alternate and affordable energy sources. Traditional energy reserves such as coal and oil are depleting fast, and they pollute environment. Wind energy, solar energy and fuel cells etc have emerged as possible alternates. Energy available from such sources has to go through major conversion or refinement processes. Growth of these sectors is slow and they are costly alternatives. They may need some more time to mature. Lack of alternatives has forced the energy users to look into the way traditional energy reserves are being used. The potential of saving is large. Saving avoidable energy waste would help create a virtual reserve called efficiency reserve. Such reserve is possible at origin such as generator end, transmission systems and at load ends. Creation of such reserve is less costly and is more eco-friendly. Improvement in efficiency in energy usage would create more impact as it would save energy, produce less ambience heating and create less environment problem. Saving energy by efficient means would generate relief in immediate terms. Finding non-polluting energy avenues would solve energy problem as long term solution.

The need for energy that does not pollute dense areas i.e. the load centers is a necessity. The energy available through EE domain makes an attractive means to such end users, at least.

It is extremely user friendly and it is easy for transport to any distant consumer. However, the process of electricity generation causes large CO_2 emission. Electricity generation contributes 41 % of total CO_2 emission [3] into the air. It is important to optimize the usage of EE. Like all other means of energy usage, it has also grown by improving the efficiency and reliability of constituent components such as generator [1], transformer, motor [6], lighting equipments, [4] home appliances etc. Better understanding of applications and introduction of new processes has influenced the load behavior significantly. More and more non-linear loads have been connected to the electrical grid. The dynamics of load is also continuously changing. The operating point of the load in a particular application may not be fixed. Non-linear load with flexible operating point create problem on electrical infrastructure as source and load needs a system that generate compatibility between them. Incompatibility issues reduce the efficiency of the system. The infrastructure is forced to remain under utilized. PEEs exactly fill that void space. Performance, E^2, reliability, compac-tness, ease of usage, better economics etc are key inherent features modern PEEs offer in EE domain. The role of PEE is many – performs designed function, creates energy reserve, improves power delivery capability of the grid etc. The scope in creating E^2 is more in developing countries as less energy efficient measures are in place. Even in USA, now, [8] PEE can save more than 15% of their grid energy. PEE's role in process innovations has also created scope of further efficiency enhancement. This article details the multi dimensional role played by PEEs in the EE domain and create certain definite hope in terms of energy balance and better environment to live in. It plays active role in every aspect in EE domain such as redefining existing loads for energy and process optimization, power factor correction and STATCOM, HVDC transmission, Drives, computers, HVAC etc – to name a few. The article would touch upon such aspects from E^2 point of view and at the end one vital industrial process i.e. arc welding and its PEE will be covered.

ENERGY IN ELECTRICAL DOMAIN

Significant portion of world's total energy (> 40 %) used is consumed through electrical means. EE is not naturally available. It is converted form of energy. More power stations can easily be connected to the grid to boost its availability to the users. T & D lines, across the country, make EE available to far away loads. Easy access to EE has resulted in growth of wide range of electrical loads. EE has minimal environmental impact. A typical source to load diagram in the EE domain is shown in Fig. 2. Passive elements are involved for power flow. Some elements, particularly in load, could be non-linear

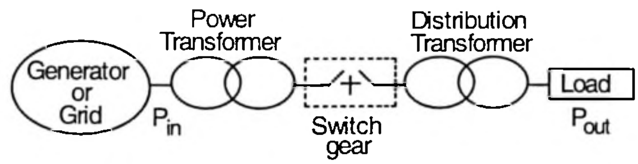


Fig 2.0 : Electrical Energy Flow Diagram

such as AWE. EE is being consumed by products as well as by processes. Process loads, mostly, are for industrial use. Source controls output behavior of appliance loads directly. Efficiency of such products should be high to ensure E^2. Some loads such as electrical motors (torque and speed), IHE (power and frequency) have two parameters to define the load. Proper control is needed to optimize such loads. Process may involve diverse inputs. Compatibility is an issue with diverse inputs. Maximizing process efficiency is complex activity. E g. though all welding (GMAW, GTAW & SMAW) inverters boast for good efficiency at the equipment level, GMAW would create better productivity i.e. process efficiency than others. It can be easily put into automated line. It is ideal to have E^2 products help optimizing process efficiency. ARE, AC drives, IHE are some examples in this category.

Electrical Load: The load is the extreme end of EE connectivity where final conversion or transformation of EE takes place for end use. The eventual load (Fig. 3) could be mechanical, lighting, heating and cooling, or process load. Loads such as DC motor, computers etc. need transformed EE. In each load category large diversity exists. Diverse load characteristics in each load category make the process of standardization difficult. Components of pure electrical infrastructure are passive. In a passive system, load variation mostly means change in power demand. Fine control with passive elements is difficult. Controls become inefficient. Equipments are, generally, bulky and costly. The performance

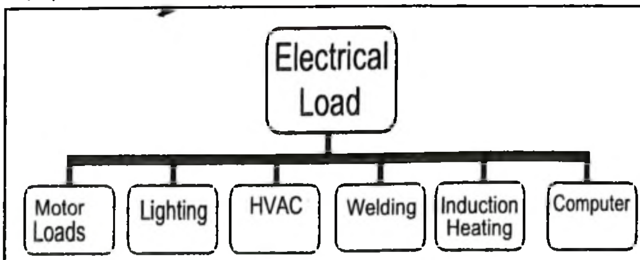


Fig. 3 Load and application spread

parameters of load are critical for system efficiency as power loss component in load has cascading effect till source i.e. generator. For example [9], 1W saving at processor level creates a total saving of 2.84W at the facility. Each load need to be efficient to make its cascading impact minimal. Following parameters of load influence E^2 of the system – i) efficiency, ii) displacement power factor (dpf), iii) distortion power factor (DPF) and iv) harmonics. They are detailed below. The efficiency of a load at power P_{Out} is defined as

$$\eta = \frac{P_{Out}}{P_{Out} + Loss} \quad \text{------(1)}$$

The efficiency of electrical system (facility) for same load is

$$\eta_{System} = \frac{P_{Out}}{P_{Out} + \sum Losses} = \frac{P_{out}}{P_{in}} \quad \text{----- (2)}$$

$$\sum Losses = f(Loss, I, pf, harmonics) \quad \text{-----(3)}$$

Power factor of an equipment or system is

$$pf = Cos\phi = \frac{kW}{kVA} \quad \text{--------(4)}$$

The current drawn by load in 3-phase system is

$$I = \frac{P_{OUT}}{\sqrt{3}\eta V Cos\phi} = \frac{P_{Out}}{\sqrt{3}\eta V pf} \quad \text{--------(5)}$$

$$Loss\ (copper) = P_R = I^2 R \quad \text{-----(6)}$$

R is resistance of T & D lines, transformer and generator. Po or pf and poor efficiency increases PR. Non-linear loads and reactive elements contribute to pf. Non-linear loads such as controlled rectified DC, magnetic saturation, CFL lamps etc introduce harmonics as mentioned below:

$$THD_i = \frac{\sqrt{I_1^2 + I_3^2 + I_5^2 + ---}}{I} \quad \text{-----(7)}$$

where I_1 is fundamental component of current. The harmonics [7] incur extra losses in the system and create problem of voltage regulation at the load end as shown in eqn. (8).

$$V_{load} = V_{source} - IZ_{series} \quad \text{--------(8)}$$

Uncertain load behavior, poor efficiency (Eq. (1)), poor pf (Eq. (5)) and large THD_i (Eq. (7)) demand much more power from grid than the load needs and make grid inefficient s. a.

$$P_{in} \approx 2L\ 2.8P_{out} \quad \text{-----(9)}$$

Some important loads in EE domain are discussed below.

Motor: Motor loads constitute more than 50 % of EE demand. Application and load characteristics differentiate the need of a particular motor and its capacity. Induction motors (IM) are most common. Common torque characteristics are

$$T_1 = K_C,\ T_2 = K_V\omega \ \text{ and } T_3 = K_I/\omega \quad \text{-----(10)}$$

Where K_C, K_V and K_I are constants and is motor speed. IM has narrow stable operating zone and its E^2 is high at nominal speed and torque. Two parameters (torque & speed) of load decide operating point of IM in four possible ways (Table I).

Table 1

	Case 1	Case II	Case III	Case IV
Torque	Constant	Variable	Fixed	Variable
Speed	Constant	Fixed	Variable	Variable

AC motors, in conventional EE domain, do not possess good control characteristics to improve E^2. This has led to application specific motor design leading to increase in diversity of motors being manufactured in the industry. Starting torque [6] also influences motor selection procedure.

Voltage unbalance is common in developing countries. It increases copper loss and torque pulsations. Under voltage also increases copper loss. Large unbalance reduces the life of motor leading to frequent repair. It reduces the efficiency of motor further. Loads that need good starting torque are met by oversized motors. Oversize motors reduce efficiency and pf. Poor pf draws more current (Eq. (5)) resulting increase in more system loss and reduction in capability of power delivery of the grid (Fig. 5). In order to achieve close to application specific optimization, in a passive system, the motors are manufactured as per Table II.

Table II

NEMA Grade	Starting Current	Locked Torque	Breakdown Torque	Operating Slip s
A	Large	Normal	High	Low
B	Normal	Normal	Normal	Normal
C	Normal	High	Normal	Normal
D	Low	Very High		High

Diverse characteristics have created IM selection procedure complex. AC motors have poor wide range efficiency and pf.

The major losses in AC motors are: i) Stator loss, ii) Rotor loss, iii) Magnetic loss and iv) Stray loss. Energy efficient motors [6] have reduced stator and stray losses. However, they remain inefficient while operating on unbalance voltage, at higher slip and with light load.

For precise control (e.g. speed and/or torque) DC motors are traditionally preferred. DC motor offers good starting and control characteristics as the field and armature are de-coupled

$$Torque = T = K_T I_a \quad \text{---(11)}$$

$$\text{and } Speed = N = K_N V_a \quad \text{-----(12)}$$

where K_T and K_N are DC motor constants, and V_a and I_a are armature voltage and current respectively. Drooping speed torque characteristics make DC motor ideal for control. However, DC motors need more maintenance. The AC-DC conversion process introduces large THD and poor DPF.

Lighting: Second major electrical load (approximately 19% of total electrical energy, globally) is lighting [4]. Only 5% energy is converted for our use in traditional incandescent lamps. The rest is used for heating the ambience [5]. Large loss makes them less reliable. There have already been a lot of improvements in E^2 and lumen efficacy of electrical lamps as shown in Table III. Fluorescent lamps, however, inject a lot of

Table III		
Type of High Sources	Efficiency (%)	Efficiency (lm/w)
Incandeseem light bulb	5	15
Long flourescent tube	25	80
CFI	20	60
White LED	50	150
High pressure sodium Lamp	45	130

harmonics and they are poor pf load. Poor pf reduces systemE2 [6] and its power deliverability [7].

Electrical Infrastructure: Generator, T & D lines and transformer form major part of infrastructure in EE domain. Its role is to feed the load with proper voltage for proper utilization of load. Under voltage causes degradation in motor's performance while over voltage causes magnetic saturation in transformers and also causes reliability problems in certain loads such as lamps. The infrastructure is costly. It should be

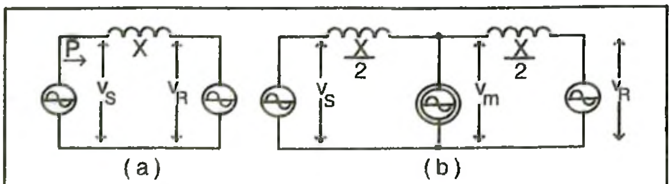
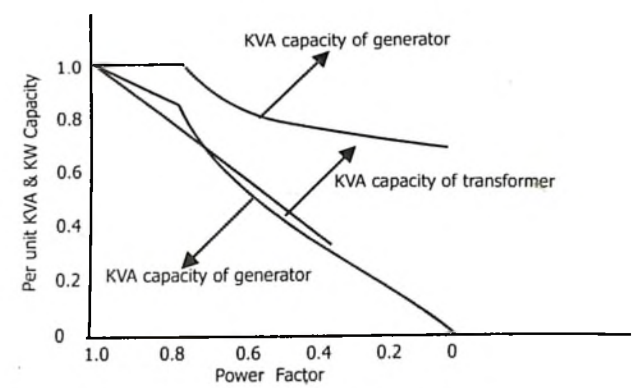


Fig 4 : Simple Grid Connection Diagram

robust, dynamically stable, reliable and available. Its proper utilization is important. Fig. 4a is a simple model of a generator linked to an infinite bus by reactance X. One simple example is shown in Fig. 4a where ' v_s = VSinwt S = ', v = VSin(wt − δ) R ' and 'δ' is load angle. The power transmitted 'P1' is expressed as

$$P_1 = \frac{V^2}{X} Sin\delta \quad \text{-------(13)}$$

Electrical loads with diverse characteristics make optimized power delivery of mains frequency infrastructure difficult. Inefficient and poor pf loads reduce the power handling capacity of electrical infrastructure [6, 7] as shown in Fig. 5. The maximum capacity of infrastructure is decided by its nominal rating (Eq. (13)). Their capability of power delivery is also decided by external factors such as temperature rise in generator and transformer etc. The temperature rise depends



Fog. 5 : Effect of Power Factor on Generator and Transformer

on incurred loss. Prolonged overheating reduces their life. Poor pf with large harmonics reduces the power delivery capacity of these equipments resulting under utilization. Additional facility calls for large infrastructure cost, energy waste etc. It is difficult and complex activity to implement E^2 in large installations.

In a passive system scope to improve efficiency is limited of already large installed equipments. The improvement program, to begin with, should be load driven (Eq. (9)). The scope of improving efficiency is, however, large if loads draw power at their maximum efficiency. The operating point of load shifts in dynamic loads. For example, ARE is specified by its range (say, 3A – 400A), and not by maximum rating only. Loads such as motor drives in HVAC [23] have seasonal variations. Similarly, wide load fluctuations take place in computer applications [9]. The operating point in IM drive is decided by voltage and frequency, and that in IHE is decided by power and frequency. Simultaneous control of two parameters, in a passive network, is difficult. Such loads need active control. Active control based on parametric feedback of operating point makes the system intelligent and efficient.

Efficient electrical network would exist when loads would not disturb the supply grid. Individual loads need to be efficient with good pf and negligible harmonics. The role of PEE is singularly important for improving E^2 of electrical network. PEE improves efficiency of generator (97%), transformer (98%) and T & D lines (94%) by maximizing operating efficiency and pf of load. Next section would touch upon the important role it plays in widening the horizon of EE domain and make EE domain stronger. Widening of EE domain is achieved without creating any environmental issues. Maximizing E^2 help create pseudo-environment indirectly.

POWER ELECTRONICS EQUIPMENT

The maximum utilization of EE is possible when load behaviour is resistive and harmonics are absent. Inefficient and non-linear loads hinder the optimal utilization of the costly, electrical infrastructure. The introduction of power electronics (PE) between load and source (Fig. 6) is capable of solving most of the issues. PE is the technology associated with efficient conversion, control, conditioning of electrical power from its available input into the desired electrical output form. PE controls flow of EE from source to load to achieve

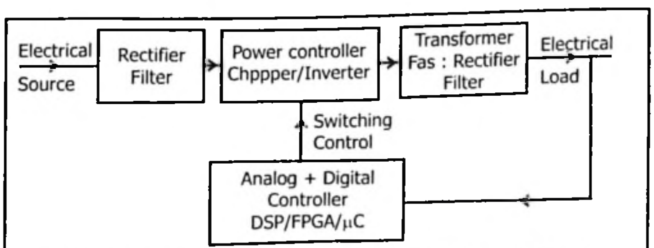


Fig. 6 : Block Diagram of Power Electronics Equipment

i) Source to Load compatibility: The source could be grid power supply, battery voltage, fuel cell or solar output or uncontrolled and fluctuating voltage output of the wind generator. On the other hand loads could be electrical grid, motors, lighting etc. Compatibility issues involve handling voltage, frequency and phase angle matching and load should behave like resistive one and with no harmonics. PEE converts passive load into active one.

ii) Consolidation on performance: e.g. high frequency switching increases control loop bandwidth. The response time of PEE is much superior to the dynamics of any load.

iii) Improvement in function domain.

iv) High efficiency and flat efficiency curve: Modern loads such as SMPS for computers [9], welding etc. are dynamic wide range loads. Good ATLE optimizes the energy usage. Low loss modern PEE has structured loss distribution.

v) Reliability: High reliability products require less replacement. Each replacement cost energy, material etc.

vi) Small size, light weight: They allow the PEE to be closer to the load. Electronic ballast and CFL lamp together make one product. This feature is useful for high current loads such as welding. The cable loss can be significantly reduced.

vii) Low cost: It helps popularize PEE.

Application areas of Power Electronics

1. **Stronger Grid:** By maintaining the mid-point voltage(Fig. 4b) as

$$v_m = VSin(wt - \frac{\delta}{2})$$

The transmitted power (eqn 15) gets modified to

$$P_2 = \frac{V^2}{\frac{X}{2}} Sin\frac{\delta}{2} = \frac{2V^2}{X} Sin\frac{\delta}{2} = 2P_1 \qquad \text{----(14)}$$

The transmittable power gets doubled. Addition of vm reduces power system oscillations, improves robustness feature [19] and enhances its availability. This is achieved through a PEE such as static var compensator (SVC) or STATCOM. HVDC transmission also helps reduce T & D losses.

2. **Widening the base of EE:** PEE is equipped to integrate non-polluting non-conventional energy resources to the electrical grid and thereby it creates wider base of EE domain.

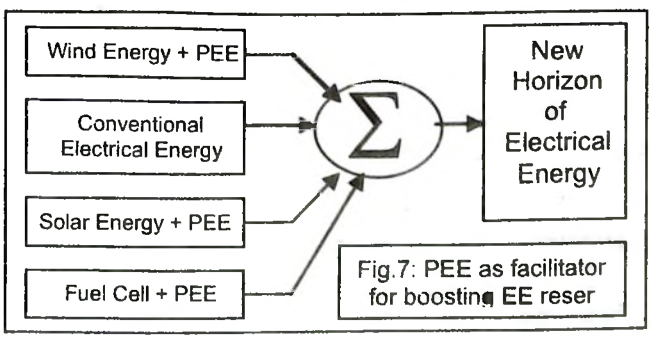


Fig.7: PEE as facilitator for boosting EE reser

The growth of this area would enhance the energy reserve greatly. The energy extractable from non-conventional energy resources does not have robust parametric behavior matched with electrical grid. PEE is in a position to create the bridge so that solar energy [21], fuel cell and wind energy sources are connected to the electrical grid to widen EE domain as shown in Fig 7. India generates 7% of EE through wind energy and USA plan to feed grid 10% of its EE from solar source in next ten years. With more energy pumped into grid from non-conventional sources, the emission of green house gases would be significantly under control.

3. **Drives:** Two decoupled inputs controls (Eq. (11) & Eq. (12)) are required for controlling two outputs such as speed and torque of DC motor. Unified field theory has helped deriving decoupled equations for control of IM leading to evolution of field oriented control approach for AC drive [20] (ASD). This has been realized in power electronics. It is equipped to control starting torque, operating speed and torque of AC motor and have large efficiency. The stalled torque can be made equal to maximum torque. AC motor with the help of ASD can adjust any load characteristics with just change in parameter setting. ASD with feedback from process achieves large process efficiency such as in HVAC [23]. ASD along with energy efficient motors brings following benefits

a) feeds motor with balanced voltage

b) Optimally (efficiency, pf and harmonics) handles shifting of operating point (speed and torque)

c) No need of oversize motor

d) IM with ASD eliminates DC motor and DC drive. It reduces one class of motors i.e. less diversity. AC Motor diversity is also reduced as one motor with ASD meet all applications in that power range. Efficient process could be in place to handle mass production of motors.

e) The grid system efficiency is improved.

f) Reliability improvement at each stage is achieved.

Quantitatively, large [1] energy saving (50%) is possible with energy efficient motors fed by ASD. It amounts to a gain close to 20 % of total EE. The E^2 program for ASD is ever active. Intelligent power modules with trench field stop or soft punch through IGBT enhances E^2 of drives further. TFS IGBT with SiC anti-parallel diode makes future of ASD bright.

4. **Lighting:** CFL lamps are energy efficient and have good efficacy. They still pose two problems. Traditional ballasts are bulky and make audible noise. Secondly, they draw current rich (78%) in harmonics [7]. CFL lamps with integrated electronic ballast (PEE) solve both the problems. Integrated CFL easily fits into existing infrastructure. The energy saving prospect is 75% at lighting load [8]. This is equivalent to 14% of total EE. Implementation of energy efficient means for lighting is simple and cost effective. LED is fast emerging as contender for future lighting and it has long life. PEE helps produce and drive such LEDs for lighting, signaling, indication etc to improve E^2. Installation of PEE in motor and lighting loads can save 34 % of total EE.

5. **Making PEE stronger**: Power density of PEE is moderate. Parameters such as td-off of IGBT trr of fast diode etc create hindrances [18] to use full potential of PEEs. Switching frequency of PEE is restricted due to increased losses. Moreover, single crystal silicon based power switching devices [11] is more or less a saturated field. Their acceptability in aerospace and automotive industries is less as well. SiC is a superior contender to replace silicon based power switching device. They operate till 350 deg C, have better thermal conductivity, voltage rating and incur much lower losses (including switching losses). Moreover, SiC diodes when connected anti-parallel [14] to IGBT, E^2 is further enhanced. Wide spread use of SiC devices would make PEE more robust. IHE (a PEE) [15] forms an integral part of SiC crystal [12] growth for production process.

6. **Influence on Process:** With wide operating range (frequency in particular) modern IHE is equipped to cater many process applications. The IHE has helped improve E^2 (kg/kWh) billet heating, melting, forging (Saving: >25%) etc. Other prominent applications are induction cooker (25%), cap sealing (Saving: >40%) (for food, pharmaceutical and oil industries), engine valve hardening for automotive industry,

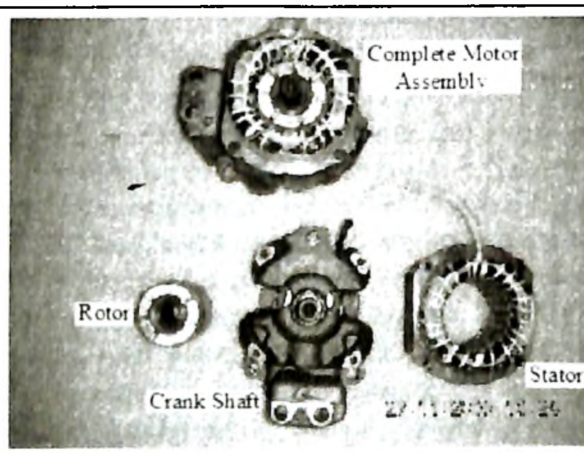


Fig. 8: Induction Heating in Shrink Fitting Application

shrink fitting (Fig.8) for motor manufacturing (Saving: >50%). All are mass produced processes. Large energy saving through process innovations is possible. IHE makes the process clean, energy efficient and eco-friendly. Achieving process efficiency through energy efficient PEE makes the process optimal.

ARC WELDING

In India AWE consumes app. 3000 MW (2.1%) of total EE. Multiple inputs such as energy, shielding gas, electrode material, metal and its thickness to be welded, wire feed speed, orientation of the joint etc come together in a proper way to make a good welding process for joining metals. Large parametric inputs driven by quality engineering needs of welding joint make the process complex and diverse (fig. 9)

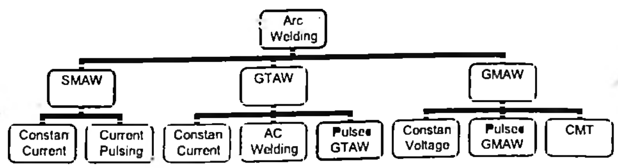


Fig. 9: Application areas of arc welding equipment

AWE feeds energy to arc welding process. It should be electrically efficient and ensure process compatibility i.e. it should meet productivity with requisite weld quality. High productivity directly enhances E^2. Table IV lists down certain comparison of regularly used rectifier based welding modes.

Need for water-cooled torch makes GTAW more inefficient. On the other hand, GMAW boasts for large AE (i.e. proportion of arc energy transferred to the work piece) and is ideal for automation to boost productivity. Maximizing E^2 in arc welding means need for more installations of GMAW welding equipments. It follows constant voltage' (CV) characteristics and has compatibility problem with highly non-linear weld gap load. It is difficul For passive component dominant GMAW to meet the fast load dynamics in real time as shown in Fig. 10. The short circuit currents at each droplet transfer (point A, B and C) are different from other current peaks. So is the frequency of droplet transfer. Reduced frequency (at E & D of Fig. 10) dynamically changes the mode to 'globular transfer' (Fig. 9). They increase spattering. Spattering is loss of energy and loss of nearly usable material. Need for after-weld quality control hampers productivity. GMAW is categorized by the mode of metal transfer as shown in Fig. 9. Each mode has

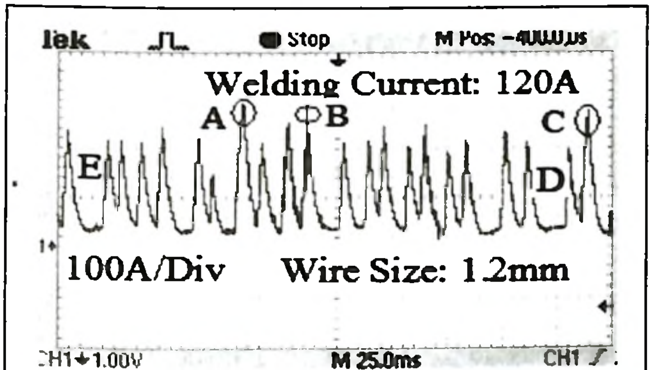


Fig 10: Current Dynamics in GMAW

Table IV

	SMAW	GTAW	GMAW
Arc Characteristics	Constant Current (CC)	Constant Current	Constant Voltage
Electrode Type	Consumable rod	Non-consumabl	Consumable wire
Equipment	Simple	Complex	Complex
Arc Efficiency in %	60 - 70	45 - 60	85 - 95
P_{in}/P_{out} = 1/weld (Eq.(9))	4.69	6.08	3.57
% of load share	49	22	29
Scope of automation	Poor	Good	Good
Process efficiencv	Very Poor	Poor	Good
Appliation Criticality	Suitable for outdoor appln. & small business simple process	Good for thin metal welding & welding of Al. Mg.	Suitable for everywhere all positions and for all metals

limited current range and they need different process inputs such as shielding gas. The development of AWE should lead to wide current range GMAW equipment with good control dynamics.

Arc welding is, mostly, a large current process where mechanism of energy transfer to the molten pool is important. AWE controls energy flow to the weld gap. The configuration of arc welding load is different than other electrical loads as shown in Fig. 11. E2 of the process depends on i) loss in equipment, ii) loss in welding cable, iii) loss at weld gap and iv) mode of integration of energy leading to creation of weld pool and loss in electrical infrastructure such as generator, transformer etc. Poor efficiency at any stage would have eventual impact on grid efficiency (Eq. (2) & Eq. (9)). Welding process efficiency (WPE) may be expressed as

$$\eta_{WPE} = \eta_{arc}\eta_{cable}\eta_{int} = \eta_{cable}\eta_{AE} \text{------(15)}$$

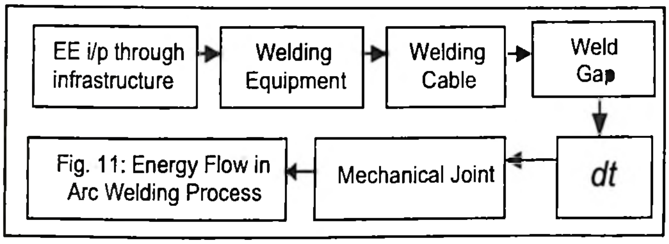


Fig. 11: Energy Flow in Arc Welding Process

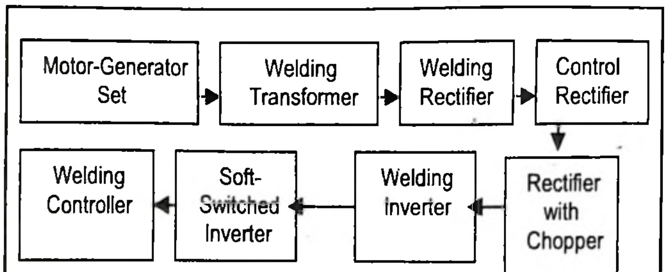


Fig. 12: Evolution of Arc Welding equipment

Where η_{arc}, η_{cable}, η_{int} and $_{AE}$ are efficiency of weld gap, cable, weld puddle and arc respectively. Efficient process reduces the burden on electrical infrastructure (Eq. 5 & Eq. (6)) and on equipment. Proper integration of weld gap power creates good weld puddle and perfect welding joint.

Efficiency of integration is decided by many factors such as shielding gas, loss due to spattering, energy density distribution around the weld joint, heat loss in electrode etc.

AWE can influence the complete welding process to achieve E^2. Better understanding of physics of welding, availability of better components such as power switching devices, sensors, DSP/micro-controllers and evolution of better circuit topologies have helped AWE product line to evolve as shown in Fig. 12. Process innovations need product evolutions in welding. In India and other developing countries, thyristerized welding rectifiers (Fig. 13a) dominate arc welding process. Rectifier is secondary controlled and its transformer (Fig. 13a) TR1 is always energized at Mains frequency causing large magnetic losses. Thyristers $T_1 - T_6$ are switched at 300Hz (six-time mains frequency). Rectifier has fixed topology. Welding inverters are being slowly (Fig. 13b) introduced. Here, the control is in primary and its transformer TR_2 is energized only when welding is performed. Major topological excursions are possible (Table V) to influence the equipment, load and electrical grid. The switching devices $Q_1 - Q_4$ have in-built anti-parallel diodes, and sometimes parallel capacitors for soft-switching [22]. With new switching techniques [2, 22], the inverters operate around 50 – 100 kHz to have benefits of weight, efficiency and bandwidth, and are sufficient for prevailing weld gap dynamics of arc weldingapplications as shown in Fig. 10. The basic equations s a. efficiency (η), settling time (τs) and weight ratio (an important factor) of AWE of two generations are shown below:

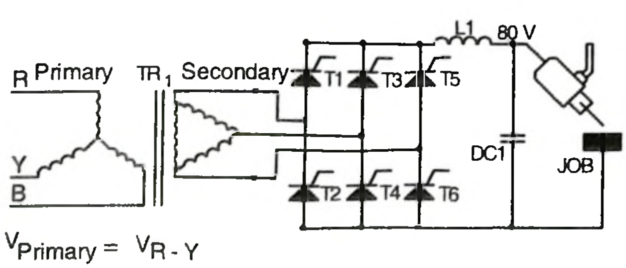


Fig. 13a : Basic Welding Rectifier

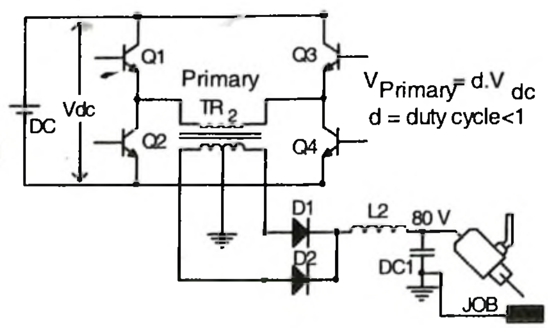


Fig. 13a : Basic Welding Inverter

$$\eta_{INV} = \frac{P_{OUT}}{P_{OUT} + K_4 V_{PWM} + K_5 I + K_6 V + K(I)V + K(V)I}$$

$$\eta_{RECT(max)} \approx 0.65, \text{ and}, \eta_{INV(max)} \approx 0.94$$

$$\tau_{S\text{-}RECT} = \frac{K_{rect}}{f_s} = \frac{K_{rect}}{300} \approx 15mSec$$

$$\tau_{S\text{-}INV} = \frac{K_{inv}}{f_s} = \frac{K_{inv}}{100000} \leq 0.1mSec$$

$$WeightRatio = \frac{W_{RECT}}{W_{INV}} \geq \frac{240kg}{20kg} \geq 24@100kHz$$

The parameter K_1V, K_2I and K_3I^2 are magnetic loss, conduction loss in $T^1 - T_6$ and copper loss respectively in rectifier. In inverter, magnetic and copper losses are negligible. Other loss components are conduction loss, and voltage and current dependant switching losses. Switching losses are negligible under soft-switching technique. Table V lists the improvement in efficiency (max.) among equipments.

Table V

Rect-lfier	Forward Converter	Half-bridge	Full-bridge	Phase Shifted	PS-ZVS	PS-ZVS-ZCT
60 %	83%	88%	88%	91%	92%	94%

PS-ZVS-ZCT based inverter is most suitable for welding as it simultaneously solves three major issues - settling time (S) for controlling process dynamics, efficiency and weight of AWE as shown in Fig. 14.

Due to low frequency operation, the inductance 'L1' in Fig 13a is large and its value is different in SMAW and GMAW equipments where as the value of 'L2' is negligible in inverter based equipments of all modes. The role of passive parameters that influence dynamics is negligible. One equipment can house all three modes of welding resulting in unification of equipments. Particular welding mode is implemented inside the inverter controller as all other components remain same. It helps reduce inventory.

The nature of loading in welding is different than most other EE loads. For example, complete range such as 3A – 400A rated AWE is used to feed weld gap for different applications. Used and specified ranges are same. Moreover, the trend is towards using more and more current pulsing (Fig. 15b). Pulsed welding applies controlled heat at the weld joint. In pulsed GTAW, the magnitude of welding current pulsates between peak and base values (Fig. 15b) but follow 'CC' characteristics. Pulsed GMAW (P-GMAW) [16] is, however, complex process. For such applications, the equipment needs to have good ATLE for E2 as shown in Fig. 15a. Pulsing is severe in CMT [17] technology where base current is zero. PS-ZVS-ZCT inverter achieves good control on current dynamics to avoid spattering in P-GMAW.

Large magnetic loss makes average efficiency (<0.5) poor particularly in pulsing and variable current applications.

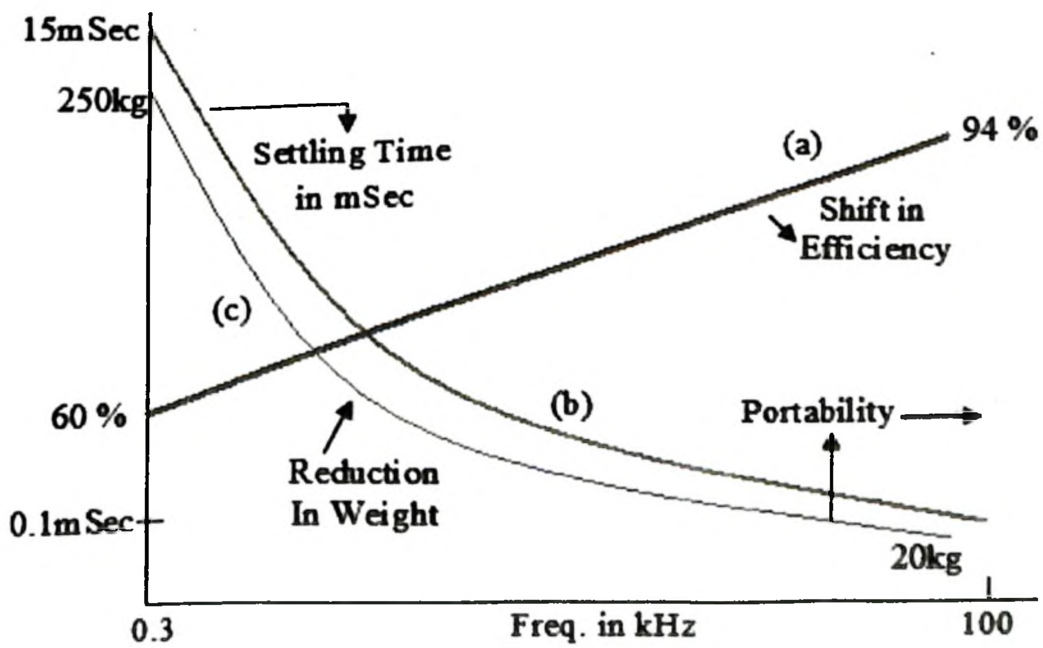


Fig. 14: Major Gain in High Frequency Inverter

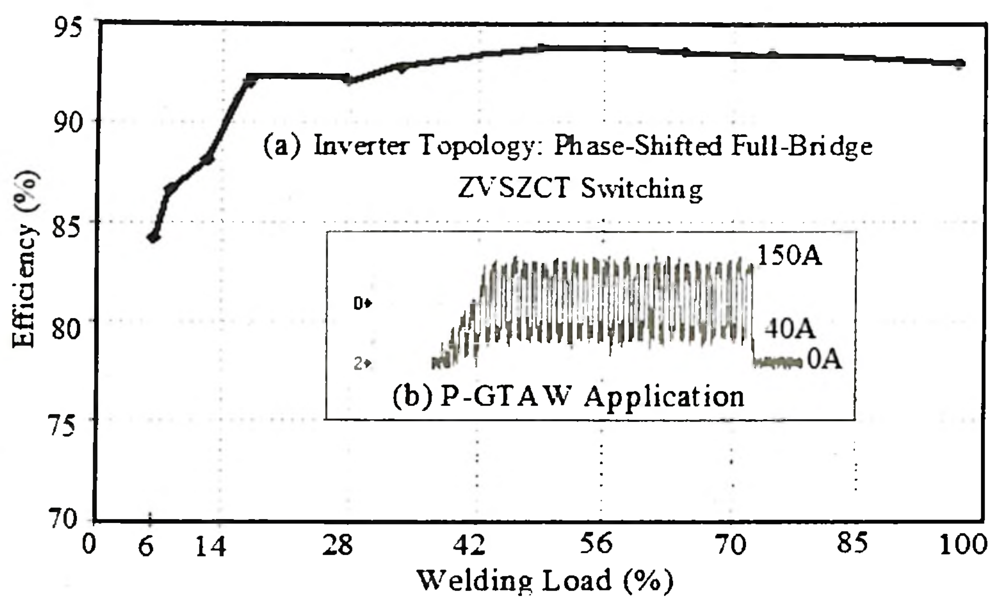


Fig. 15: Efficiency Curve of Modern Inverter

Average AE with welding rectifiers considering all modes is

$$\eta_{AE(av)} = 0.49\eta_{AE(MMA)} + 0.29\eta_{AE(GTAW)} + 0.22\eta_{AE(GMAW)} = 0.65$$

In welding, the load is else where i.e. at the weld gap. Actual power required for welding (cable= 0.85) in India is

$$P_{Welding} = 3000 \times 0.5 \times 0.85 \times 0.65 = 829\,MW$$

Significant loss (671MW) occurs between equipment and weld puddle. For average welding load, the ratio of current drawn (in rectifier and inverter) from mains is

$$x = \frac{I_{Rect}}{I_{Inv}} = \frac{\eta_{Inv(av)} Cos\phi_{Inv}}{\eta_{Rect(av)} Cos\phi_{Rect}} = \frac{0.9 \cdot 0.95}{0.5 \cdot 0.6} = 3$$

From (eqn. 9) we get, $\frac{P_{R-Rect}}{P_{R-Inv}} = x^2 = 9$

Rectifier contributes more loss in T & D (15%), transformer (5%) and generator (4%). The grid efficiency for welding is

$$\eta_{grid(Rect)} = \frac{P_{out}(Rectifier)}{P_{in}} = \eta_{RECT(av)}\eta_{T\&D}\eta_{Trans}\eta_{Gen}$$

$$= 0.5 \cdot 0.85 \cdot 0.95 \cdot 0.96 = 0.387$$

i.e. $P_{in} = 2.58 P_{Out} = 2.58 \cdot 1500 = 3870\,MW$

It is 2.7% of Indian grid capacity. The electrical process efficiency (EPE) may be expressed as

$$\eta_{EPE} = \frac{P_{Welding}}{P_{in}} = \eta_{grid}\,\eta_{cable}\,\eta_{AE} = \eta_{grid}\,\eta_{WPE}$$

$$\eta_{EPE} = \eta_{grid}\eta_{cable}\eta_{AE} = 0.387 \cdot 0.85\eta_{AE} = 0.329\eta_{AE}$$

= Say Electrical Welding Efficiency (η_{weld})
= 0.213 for MMA mode of welding
= 0.1645 for GTAW mode of welding
= 0.28 for GMAW mode of welding

$\eta(Rect) = 0.49\times0.213 + 0.29\times0.165 + 0.22\times0.28 = 0.213_{EPE}$

Welding inverter (inv(av) >0.9) being portable is kept close to the weld gap to have (cable =0.985). Its superior control helps maximize AE (0.95), reduce losses in electrical infrastructure.

The grid efficiency with inverter in GMAW mode is

$$\eta_{grid(inv)} = \frac{P_{out}(Inverter)}{P_{in}} = \eta_{INV(av)}\eta_{T\&D}\eta_{Trans}\eta_{Gen}$$

$$= 0.9 \cdot 0.94 \cdot 0.98 \cdot 0.97 = 0.805$$

$$\eta_{NPE(inv)}(GMAW) = \eta_{grid}\eta_{cable}\eta_{arc} = (0.804)(0.985)(0.95) = 0.752$$

$$P_{in}(GMAW(inverter)) = \frac{P_{Welding}}{\eta_{NPE(inv)}(GMAW)} = \frac{829}{0.752} = 1102\,MW$$

The prospect of saving is **2768MW** i.e. **1.94%** of grid power.

$$ProcessGain = \frac{\eta_{NPE(inv)}(GMAW)}{\eta_{NPE(Rect)}} = \frac{0.752}{0.213} = 3.53$$

More than three-and-half fold productivity is possible in GMAW inverter for same amount of grid energy. More gains are possible through automation and other process inputs. Table VI lists certain comparisons between rectifier and inverter at equipment level. It also shows gains for replacing 100K welding rectifiers by inverter counterpart annually.

Large current range is possible in P-GMAW. Welding at very small current does not have much impact on E^2.

Equipment based on DSP generates reference current profile for a particular welding. DSP with elaborate feedback help achieve requisite current profile of weld gap. Such welding

Table VI

Rating - 400A m/c (SMAW)	Inverter	Rectifier	Diference	Difference for 100K equipments (saving)
Efficiency	94%	65%	----	-----
Av. efficiency	90	<50	48	----
Weight	20 kg	240 kg	220 kg	22 mn kg
Cost of metal saved for opting to 100k inverters				App.$ 10 mn
EE saved for producing such metal ((3 unit/kg [13])				66 mn units per year
Energy cost for producing the metal				App. $ 10 mn
Reduction in CO_2 emission in 100K inverters				53460 Tons/Year
Wider Scenario of replacing all rectifiers by welding inverters				
Power Factor	>0.95	0.65	Remark : Large saving at input material energy and of welding process makes welding inverter ideal choice for arc welding applications. It optimizes the losses inside equipment i.e. electrical infrastructure and after equipment i.e. before the weld gap. Quality and productivity ius much higher	
Harmonies	Less	More		
Control	Active	Passive		
Portability	Good	Poor		
Cable Length	Small	Large		
Setting Time	0.1mS	1.5mS		
ATLE	Good	Poor		
Reliability	Good	Poor		
Amb Heating	Less	High		
Total energy saved for replacing all rectifiers				2768MW
Infrastructure cost to build such power plant				$ 3000 mn
Reduction in CO_2 emission (coal fired power plant)				10 mn ton per year
Equivalent of planting trees (each tree 15 M2)[14]				540 mn

inverters may be categorized as welding controllers. The equipment can replace functionality of all three different welding modes. It has helped in bringing the concept of 'unified weld gap characteristics'. The controller is more equipped to be part of innovative processes.

Though welding inverter optimizes EE usage, following example would suggest that process approach is more suitable for E^2 and productivity in welding. Energy consumed for burning one (E7018, 5mm dia.) electrode at 250A is 0.15unit that costs Rs. 0.90 i.e. $0.018. It is less significant compared to cost of labor and material. Hence, basic aims in welding are: i) welding quality, ii) welding productivity, iii) eliminate human welder, iv) E^2. GMAW (P-GMAW) meets all those criteria. Innovative processes in metal fabrication started happening with the introduction of such sophisticated AWE.

GMAW is ideal for productivity and E^2. Metal deposition rate in GMAW is more when base metal temperature is higher. Twin-wire GMAW process creates such environment for welding. One wire pre-heats the metal around joint, while the other wire deposits molten metal. It uses two P-GMAW inverters with one welding torch. Pulsing is applied in 180 degree out-of- phase manner. Tandem GMAW process helps double the productivity with much less energy input from two inverters. Such process saves significant part of energy.

Significant (50 %) part of oil is used in transport [3]. Cars with good fuel efficiency help reduce CO_2 emission. Fuel efficiency is related to the weight of car. E.g. 100kg reduction in car weight increases fuel efficiency by 5% and reduces 6% of CO_2 emission. If this is implemented in 2mn cars every year, 200mn.kg of metal would be saved. It is equivalent to 600mn units (480000 ton of CO_2) of EE saved per year [13]. Thin high-strength steels [10] meet collision resistance criteria for such vehicles. Modern welding controllers (CMT process can weld <0.3mm) are needed to weld such thin metals (<0.6mm) effectively. Welding equipment helps enhancing energy sustainability and also takes care of environmental issues such as CO_2 emission. The role of welding inverter, here, is indirect but very critical to E^2.

CONCLUSION

The large gain in efficiency and its ability to handle fast parametric changes in load have made PEE attractive. PEE improves E^2 of stand alone products and helps EE to be compatible to multi-input processes to yield productivity.

Welding inverters consume small % of EE at load, but save large power at grid level. They achieve gains in three fronts – i) E^2, ii) process efficiency and iii) compactness. Scope of this PEE is beyond its function domain as it helps integrating welding modes into one and unifies characteristics. Weld gap in combination with AWE (PEE) acts as resistive load to grid.

Energy waste and environment pollution are related. Right attitude towards energy usage makes us environment friendly. Use of proper PEE in EE domain is one of them.

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