Search for Establishing Nationally Integrated Optimum Arc Welding Process

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ABSTRACT

Arc welding process is an integral part towards building basic infrastructure of India. India consumes alarmingly large quantum of energy in arc welding process. Moreover, the quantum of energy need is steadily growing - making it virtually insensitive to both - growth in technology and process innovations. Globally, energy efficiency parameters, for example, of evolving arc welding process are not uniform as there is phase lag for modern technology and innovative processes to reach places. Welding professionals play a key role here. Optimization in arc welding process intends to reduce stress in facility by drawing minimum energy, maximizes productivity with requisite quality, simplifies process learning, reduces local and global impact on environmental parameters etc. It will be detailed in this article that understanding of different loss centers in energy flow helps evolve right technology to embrace right method or technique to simultaneously achieve energy and process efficiency, weld quality, and maintain balance in environment. Modern high-frequency power electronics equipments, as if, re-discover the process to generate better productivity with energy efficiency, reliability, compactness, better economics etc. They meet all the characteristic requirements of optimum weld gap dynamics. This article discusses a futuristic, yet very much real, scenario for India by interlinking all constituent elements of arc welding process. The aim is to define compatibility among them. Compatibility issue intends to inherently reduce diversity of the process.

INTRODUCTION

An engineering process is characterized with productivity and quality. Arc welding process (process of joining metals), so long, was no exception. However, significant amount of energy with high intensity is consumed in welding. Weld gap consumes [1] nearly 1340J to melt just one gram of steel. It is important to understand and establish proper energy flow diagram between resources and process. Traditional arc welding process possesses poor compatibility (Fig. 1) compared to other electrical loads. Application and loading specific equipment does not exist for majority applications. All inputs to the process are mobile as locations of load centers (weld gap) are not fixed. It restricts use of narrow range of welding equipments e.g. (3kW ≤ P ≤ 18kW i.e. 1:6) to feed much wider range of weld gap loads (0.05kW ≤ P ≤ 15kW i.e. 1:300). Large ratio of load range to equipment range (60:1) has made equipments bulky and less portable. Equipments are forced to operate at light loads that tend to generate poor energy efficiency. Light load behavior of arc welding equipment is special. Poor compatibility issue has inherently escalated the life cycle cost of all constituent elements of the process. More number of equipments, than perceived, along with welders is deployed to deposit metal at joints to complete requisite welding function nationally.

Initially, evolution in arc welding took place locally - around the weld gap. There has been gradual increase in process diversity to handle large range of inputs (material, gas, thickness of metal etc.) and process parameters (current Ia, welding speed, wire size, shielding gas composition) to achieve desired productivity along with necessary and varied quality engineering parameters of welding joints. It was

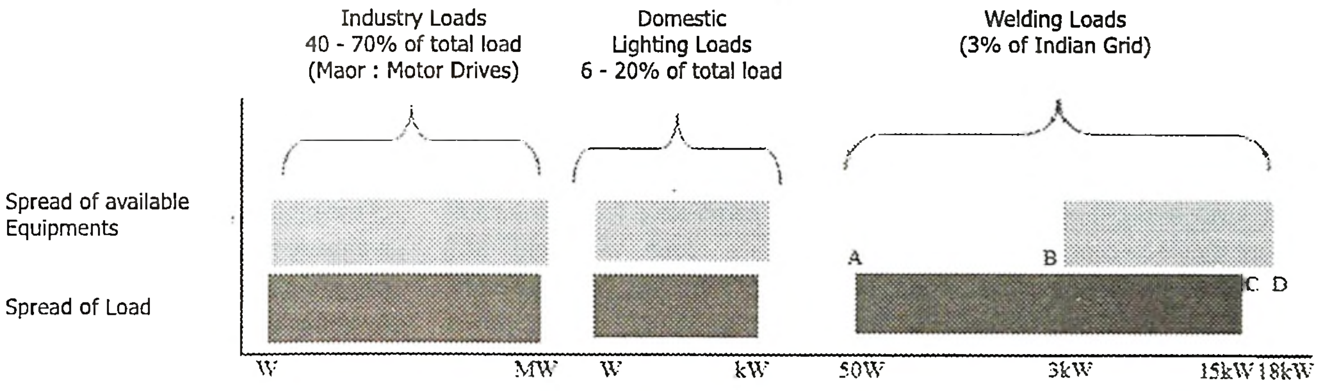

Fig. 1 : Spread in weld gap loads is pooly supported by welding equipments

dealt with through proliferation of welding methods or techniques such as SMAW, GTAW and their derivatives etc. Deposition rate [2] may drastically change with methods. Gains in process efficiency includes quality and environmental aspects such as better weld bead shape, penetration and generation of reduced fumes, spatters and particulate matters. However, simultaneous existence of large process diversity towards meeting one objective i.e. making welding joint could be risky. Process learning becomes complex. Large companies handle complex process learning better than small scale players. Stricter quality standards bring maturity of a process faster. However, it makes process more complex for learning. Automotive industry has shown better process learning. Ironically, quality engineering parameters in arc welding are not rigidly structured for majority of applications. This has led to wider acceptance of simpler and inefficient methods using inefficient technologies. The mechanism for feeding energy to weld gap changes with adopted method. Traditional equipments feeding a process have poor energy efficiency parameters [4, 8] for wide range applications. Quality, productivity, environmental issues [3] and energy efficiency parameters change with methods and or techniques applied. Quantum of grid energy consumed towards making a joint could be different in each different method. Process diversity affects efficiency parameters of integrated process. Overall energy efficiency parameter of a process is influenced by industrial fabric of a nation. Process learning at national level becomes difficult if small scale industries are dominant players in fabrication line. The benefits of evolution of arc welding process in totality have not yet reached global users uniformly.

Arc welding is energy intensive process. The process may be characterized the manner energy is fed to weld gap. Externally, any energy loss depletes reserve, releases greenhouse gases and causes warming [6]. Energy efficiency parameters of a process affect both passive grid and active equipment. Ideally, the grid should be more than insensitive to any process evolution and its growth. It is possible when the grid feeds process with minimum current. It requires both process and equipment to be energy efficient. It is quite true for developed world [8]. Such trend is yet to be seen in India. India's present energy need for arc welding is large (Fig. 1) and the demand is growing at 10 -12 % annually. It is more than that [5] in high-growth information technology sector. Influence of modern technology is yet to be felt. Presence of large diversity has made it difficult to quantify and nationally integrate the energy need for arc welding. Alternately, approximate figure of national metal deposition rate (kg/hr) should be available. Improvement in energy efficiency saves energy. Saving energy through efficient means would generate both short (efficiency reserve) and long term (utilization) relief. Furthermore, inefficient welding processes emit more fumes and particulate matters in the shop floor.

Characteristics of arc welding load are different than other loads, say, of Fig. 1 as process makes an important center for optimization of energy flow. Welding process (method) and its compatible equipment are continuously evolving to establish compatibility between source and process. An efficient method optimizes the process and there by reduces energy demand whereas efficient equipment reduces stress on grid vis-à-vis improving its reliability and availability. Equipment helps in process innovations as well. When evolution in process and that in equipment moves in synchronism, it yields better compatibility. Process diversity is inherently reduced. Reduction in diversity, such as in computer industry, helps integrate the optimum process at national level easily. Energy efficient equipment should be compatible to best welding method to widen functionality of the process. Can best of both be used for energy and process optimization? This article establishes that optimization of complete arc welding process needs to establish energy flow through a sequence of cascaded stages each behaving like a resistance for energy and process efficiency, weld quality and have minimal impact on environment at source and at shop floor. Section 2 discusses prevalent Indian arc welding process. Section 3 deals with evolution in process around weld gap. Section 4 idealizes energy delivery mechanisms in a cascaded system for wide-range dynamic loads. Section 5 introduces a term goodness factor in arc welding to gauge compatibility. Section 6 defines implementation means to establish compatibility through inverter technology. Finally, section 7 approximately quantifies gains at national level.

ENERGY EQUATION OF PREVALENT ARC WELDING PROCESS IN INDIA

Complex nature of energy input to existing diverse arc welding process has made it difficult to quantify the global impact of total arc welding process on grid, environment etc. Weld quality, productivity etc are local issues. Though inverter technology makes slow but gradual in roads, SCR based equipments still dominate arc welding process in India. Complex non-linear and wide range weld gap loads along with pertaining perception of poor reliability and availability issues of inverter technology have hindered the spread of inverters. Here, availability of power source is critical as single equipment feeds many point loads (Fig. 1). Energy efficiency parameters for such loading pattern are poor with old SCR technology. India, for example, consumes alarmingly large power (≈ 3500MW) at equipment level [4] for arc welding applications. The demand is growing at 10 - 12% annually. In order to gauge cumulative impact on energy, all arc welding loads are connected to a hypothetical isolated grid [8]. Large centralized energy distribution network in India also incurs large loss. Cascading arrangement of energy flow from source to process is shown in Fig. 2. Power loss (P_{Loss}) at process end has cascading impact (1) on source i.e. $P_{Loss\text{-}total}$, as

$$P_{Loss-total} = \frac{P_{Loss}}{\prod_1^r \eta_i} = \frac{P_{Loss}}{\eta_{System}} \qquad (1)$$

where η_i is efficiency at i^th stage in r-stage distribution network. Eqn (1) may be simplified for arc welding as

$$P_{Loss\cdot total} = \frac{P_{Loss}}{\eta_{facility}\eta_{equipment}\eta_{Cable}\eta_{process}}$$

where $\eta_{facility}$, $\eta_{equipment}$, η_{Cable} and $\eta_{process}$ are efficiency (η) in facility, equipment, welding cable and process respectively. Equipments feed power " to weld gap [1] to melt metal (M_{Melt}) to make welding joint as

$$M_{melt} = \frac{\eta_{melt}\eta_{arc}V_{arc}I_a}{1340} \qquad (2)$$

Energy conversion efficiency at weld gap is called arc efficiency η_{arc}. It depends [7] on welding method where as melting efficiency η_{melt} varies with welding current (1) I_a, metal to be welded and energy intensity (kJ/mm^2) of the process. Energy efficiency parameter is complex (2) even at process end as it depends on adopted method, productivity (kg/hr), and other input conditions. It is complex process to generalize, quantify and integrate at the national grid level. In order to have feel of the problem, certain assumptions [8] are made to analyze local (around weld gap i.e. shop floor) and global impact. Average deposition rate is considered as basis for energy calculation. Let us consider arc welding scenario of India. Analysis of energy flow in existing Indian process is comparatively simpler as it is dominated by 'constant current' (CC) process such as SMAW (72%) and GTAW (14%). Rest (14%) uses CV process 'GMAW'. GMAW is more energy efficient than SMAW, while GTAW is other way round. Uncontrolled arc length along with long and hot electrode in SMAW cause more radiated heat loss to surroundings. SMAW yields moderate η_{arc} (0.65) [11] as more loss is incurred in wasted heated electrode while being replaced. Power source, meanwhile, is kept under free-running mode. Importantly, welders feel discomfort holding hot electrode holder in high temperature ambience. It restricts metal deposition rate. Average deposition rate 2.5kg/hr [2] is considered. Corresponding weld gap power required is 7.5kW [2]. The popular equipments in India have poor value of both η (0.6) and pf (0.6) at 7.5kW weld gap power.

In electrically coupled cascaded system harmonics and pf make impact on $P_{Loss\text{-}total}$ (1) as well. T & D loss (P_R) [8] varies with size of distribution network (R), pf, η and process efficiency ($\eta_{process}$). In a 3-ph system, with line current I, voltage V and process input power P

$$P_R = 3I^2R = \frac{P^2R}{V^2(\eta_{equipment}\eta_{Cable}\eta_{process})^2 pf^2} \qquad (3)$$

Efficiency of T & D ($\eta_{T\&D}$) lines is expressed as

$$\eta_{T\&D} = \frac{P}{P + P_R} = \frac{V^2 \eta_{equipment} \eta_{Cable} \eta_{process} pf^2}{(V^2 \eta_{equipment} \eta_{Cable} \eta_{process} pf^2 + PR)}$$

$$= f(\eta_{equipment}, \eta_{Cable}, \eta_{process}, pf, R, P) \quad (4)$$

where R is per phase resistance of T & D systems. Though welding cable incurs similar transmission loss, it will be separately covered in details. Poor pf forces grid capacity (MVA) to remain under utilized as

$$MVA = \frac{P_{Grid}}{pf} = \sqrt{3}VI \quad (5)$$

Poor pf and η increases life cycle cost of costly facility. Values of η in (4 and 5) are measured by concerned sources. The value of $\eta_{T\&D}$ for arc welding loads [8] is considered as 0.8.

For clarity, elements of facility such as generator and transformer etc are assumed to have ideal η and pf. Influence of harmonics is also ignored. Fall in η with percent loading and reduced pf is ignored for simpler representation. With this, the Indian isolated welding grid would look like that in Fig. 2. The equipments feed 1743 MW cumulatively to national weld gap load. Hence, industry demand of total deposition rate in India is 581 ton/hour. Comparison between output and various loss centres are shown in Fig. 2a. The grid feeds (Fig. 2b) 4510MW (3 % of national grid) for melting load 216MW through welding. Alternately, for each watt consumed in melting, 71.5W (equivalent) worth of coal is burnt. Compatibility between source and process is poor (Fig. 2b). A part of HAZ, however, is required for proper welding quality. The life cycle cost of electrical infrastructure is large as installed grid capacity (MVA) is not fully utilized. Each loss segment of Fig. 2a contributes differently. Total power loss depletes energy reserve, causes environmental issues and warming [6] and escalates life cycle costs of different energy infrastructure entities. Losses in process, further, cause weld quality problems, local warming, generation of dust and particulate matters, discomfort to welder and poor productivity. In addition, more loss in equipment increases its size and reduces its reliability estimate.

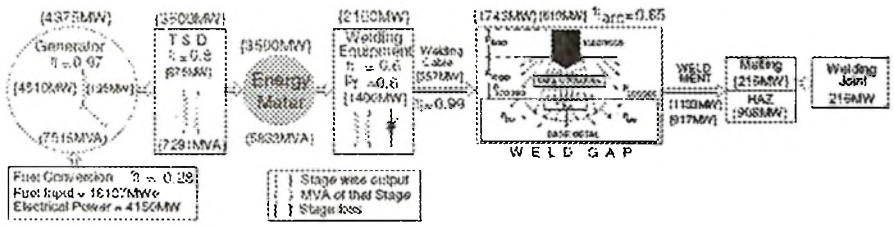

Fig. 2 : Energy flow in hypothetical Indian Arc Welding Grid

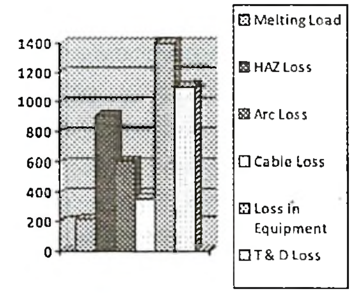

Fig. 2a : Output vs loss comparison

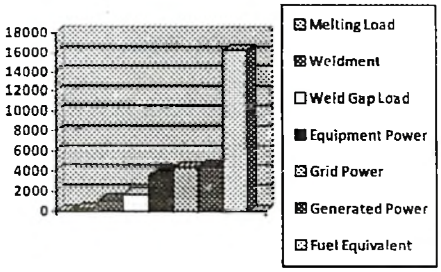

Fig. 2b : Resource to weld gap energy flow

WELDING CABLE

Welding is large-current load. Still, the role of welding cable is ignored in most applications. It performs dual role in modern arc welding processes carries large current from equipment to weld gap at different job locations and meets, as well, the rise time (di_a/dt) requirement of fast dynamic process. Rise time is not critical for certain CC loads such as SMAW. Long cable though adds flexibility of use but incurs large integrated loss (≈ 357MW) in Indian arc welding process (Fig. 2). Traditionally, 4V cable drop is considered for deciding cable size as

$$Cabledrop = I_a R_{Cable} = I_a \rho \frac{L}{A_c} = 4V \quad (6)$$

For fixed drop at rated I_a and using (6) we get

$$\frac{L}{A_c} = Cons\tan t \Rightarrow A_c = K_1 L \quad (7)$$

DC power loss in the cable P_{Cable} is

$$P_{Cable} = \rho I_a^2 \frac{L}{A_c} \quad (8)$$

Efficiency of power delivery of the cable is

$$\eta_{Cable} = \frac{P}{P_{Cable} + P} \quad (9)$$

The value of η_{Cable} (9), say, at 200A () is 0.83. Weight (W_c) of cable increases with L as

$$W_C = \sigma A_c . L = \sigma K_1 L^2 = K_2 L^2 \quad (10)$$

where ρ, L, A_c and σ respectively are resistivity, length, area and density of welding cable.

Any job site ideally needs large inventory of copper cable (10) to meet different physical and electrical conditions. Cable utility, say in SMAW, is optimized if equipment is attached to one set of cable with high η_{Cable} (>0.99) at rated current. Welding methods using periodic current pulses face more problems with long cable. Cable with length L (cm) and diameter d_c (cm) introduces inductance (L_c in nH) in weld gap circuit as

$$L_C = 2L(\ln\frac{4L}{d_c} - 1) \tag{11}$$

Inductance of cable (L_c) and that of inverter output (L_3) affect t_r and t_f in pulsing current loads (say P-GMAW) as

$$t_r = \frac{(L_3 + L_C)}{(R_{Cable} + R_{Col})} = t_f \tag{12}$$

E.g., apart from incurring large transmission loss, a 50M, 50mm^2 welding cable may introduce t_r or t_f around 3.3ms to current pulsing applications. It would make impact on functioning of the process, fume generation in particular [3]. Benefits of welding process such as P-GMAW are compromised if L is increased.

Compact light-weight equipment is more flexible [8] than long cable (10). Large saving (≈ 350MW) is possible if cable loss at nominal loading is restricted to less than 1%. Light weight (W_C) equipment is portable and it simplifies cable sizing for energy efficient and P-GMAW process.

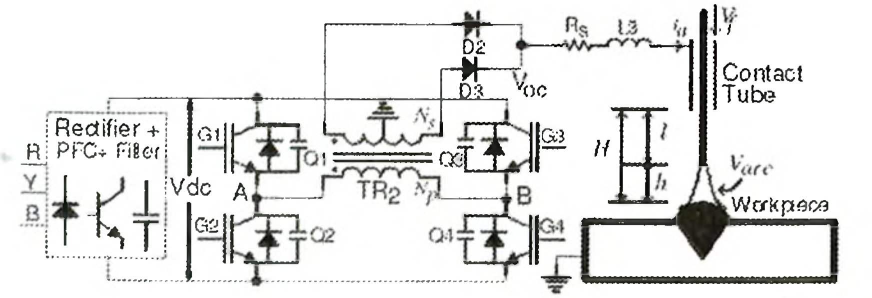

Fig. 3 : Power Circuit Diagram of GMAW Process

EVOLUTION IN ARC WELDING PROCESS

As discussed in last section, in India serially connected cascaded energy delivery mechanism for traditional processes (SMAW, GTAW) makes large overall impact. Processes mostly follow CC characteristics where arc voltage is uncontrolled. Though both generate acceptable weld quality for most applications, they have poor productivity and energy efficiency parameters. SMAW, in particular, lacks automation flexibility and produces large fumes and particulate matters and poses welder discomfort [2]. Therefore, metal deposition rate is further restricted.

Conventional GMAW process is energy efficient and is more productive as well compared to SMAW and GTAW. GTAW has inherent problem [24] of initiating welding arc as well. GMAW is suitable for wide current range applications, all-metal-all-position welding and it possesses automation flexibility for further enhancement in productivity. Duty factor of constant voltage (CV) equipment is more than three-fold that of SMAW counterpart. It is dominant process in developing world [4]. Self-regulation feature [16] of CV process maintains constant average arc length (h). Its high energy intensity arc yields better η_{melt}, and consumable wire with small stick out (l) generates better η_{arc} (0.85) [17]. It is important to briefly elaborate the GMAW process. Schematic power circuit diagram of GMAW process is shown in Fig. 3. The dynamic equations for non-linear weld gap in GMAW [16] are expressed as

$$V_{oc} = R_s i + L_p \frac{di}{dt} + i\frac{\rho l}{A} + V_{arc} \tag{13}$$

$$V_{oc} = \frac{dV_{DC}}{n} \tag{14}$$

$$S_m = K_{01} I_a + K_{02} I_a^2 l \tag{15}$$

$$\frac{dl}{dt} = S_f - S_m \tag{16}$$

In steady state, $S_f - S_m = 0$

$$H = l + h \tag{17}$$

where 'd' is PWM duty cycle of inverter, n is N_p/N_s, S_f and S_m are feed rate and melting rate respectively;

K_{01} and K_{02} are constant. Three major modes of metal transfer exist in conventional GMAW process dip or short-circuit, globular and spray. Though momentary, metal transfer changes [18] arc length (i.e. change in arc voltage, ΔV_{arc}). The values of ΔV_{arc} [18] in different welding modes are

i) in presence of weld pool oscillation: < 0.5V

ii) spray transfer: $0.5 \le \Delta V_{arc} \le 1.0$

iii) globular transfer: $1.0 \le \Delta V_{arc} \le 8.0$

iv) short-circuit transfer: $\Delta V_{arc} \ge 8.0$V

Large slope (dI_a/dV_{arc}) in CV characteristics causes sharp change in I_a for small ΔV_{arc}. I_a has major influence in arc welding in wire melting and metal transfer, penetration, bead formation, arc stability, arc rooting, spatter, and mechanical properties of joint etc. Large swing in I_a takes place in (iii) and (iv) to effect droplet detachment. Waveforms of weld gap variables at 150A and corresponding welding joint are shown in Fig. 4 and Fig. 5 respectively. Out of phase V_{arc} and I_a indicates droplet transfer is passive. Smooth metal transfer in dip transfer demands meeting too many parameters in real time such as

i) maintaining constant short-circuit frequency (Fig. 4)

ii) minimizing standard deviation of short-circuit current amplitude

iii) profile control of I_a such as dI_a/dt before and after droplet detachment

iv) arc stability i.e. ensuring minimum current post short-circuit

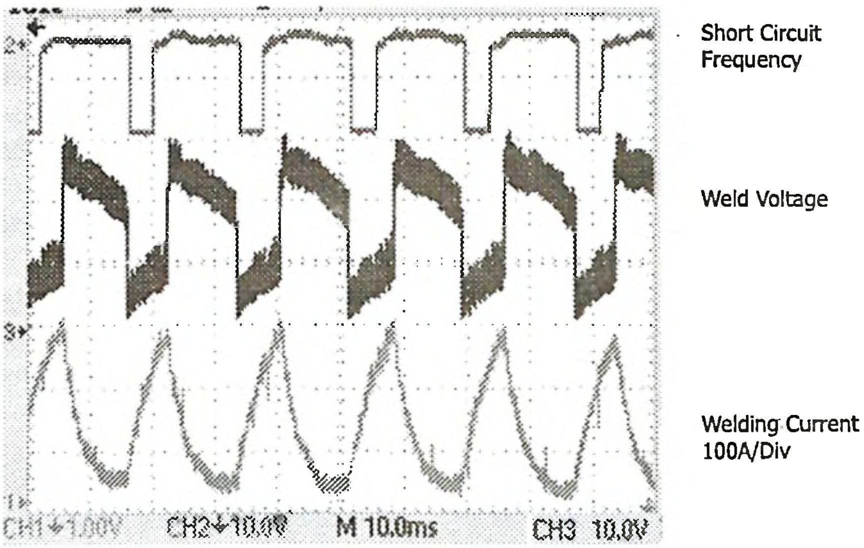

Fig. 4 : Waveforms of GMAW in dip transfer

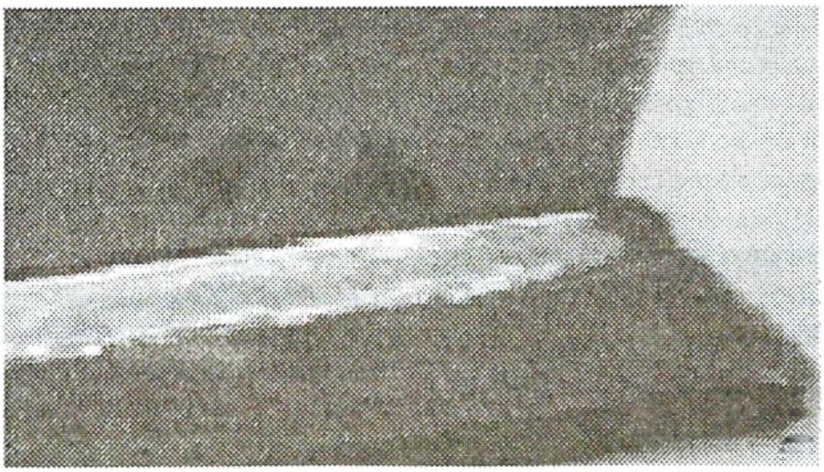

Fig. 5 : Welding joint at 150A under dip transfer

The condition for droplet detachment in P-GMAW is

$$I_p^2 T_p = Cons\tan t = D \tag{18}$$

$$I_a = \frac{I_p T_p + I_b T_b}{T_p + T_b} \tag{19}$$

D is detachment parameter. I_b provides requisite arc stability. The metal transfer rate in P-GMAW ($M_{P\text{-}GMAW}$) is more (20) than GMAW (M_{GMAW}) process as

$$M_{P-GMAW} = M_{GMAW} + \beta l X(1-X) I_e^2 \tag{20}$$

i.e. $\eta_{melt}(P-GMAW) > \eta_{melt}(GMAW)$; where $I_e = I_p - I_b$ and β is constant, and,

$$X = \frac{T_p}{T_p + T_b} = \frac{T_p}{T} = fT_p \tag{21}$$

One drop per pulse (ODPP) mode [21, 22] is preferred as it achieves better control on droplet size 'v' as

$$v = \frac{AS_f T}{60} \tag{22}$$

where A and T are area of electrode wire and cycle time (T) respectively. Once proper parameterization is done [22], P-GMAW is implemented through programmed ΔV_{arc} to bring I_p and I_b under close control to achieve smooth spray transfer. For ODPP, I_a and V_{arc} are required to be pulsed in phase (Fig. 7h) to achieve active control on droplet size (v) with defined deposition rate. Equivalent circuit diagram to represent steady state P-GMAW process may resemble as two switchable power sources (Fig. 7g). Steady state equations during peak and background pulsing conditions may be expressed as

$$V_{arc1} = I_b R_{col} + V_{F1} \tag{23}$$

$$V_{arc2} = I_p R_{col} + V_{F2} \tag{24}$$

$$\begin{aligned} E_{Cycle} &= V_{arc1} I_b T_b + V_{arc2} I_p T_p \\ &= P_b T_b + P_p T_p \end{aligned}$$

where V_F is respective anode and cathode drops; E_{Cycle} is energy required in each droplet detachment cycle, and P_b and P_p ($P_p >> P_b$) are base and peak power. Practically, $V_{F1} \approx V_{F2}$, therefore,

$$(I_p - I_b) = \frac{(V_{arc2} + V_{F2} - V_{arc1} - V_{F1})}{R_{col}} \approx \frac{\Delta V_{arc}}{R_{col}} \tag{25}$$

Hence, P-GMAW may equivalently be regarded as process of dynamically modulating resistance of weld gap like

$$\Delta R = R_{Col} = \frac{\Delta V_{arc}}{I_p - I_b} = \frac{\Delta V_{arc}}{I_r} = \frac{\Delta V_{arc}}{\Delta I_a} \qquad (26)$$

Therefore, for P-GMAW, welding controller should be able to

i) Control instantaneous weld gap voltage V_{arc}

ii) Control current profile of I_a as required in peak and back ground durations

iii) Maintain minimum current I_b for arc stability

iv) Maintain zero phase angle between them i.e. negligible t_r and t_f.

Negligible values of t_r and t_f means the controller or equipment should possess small settling time. Fig. 6 [21] is experimental waveform of ODPP that resembles (23) and (26).

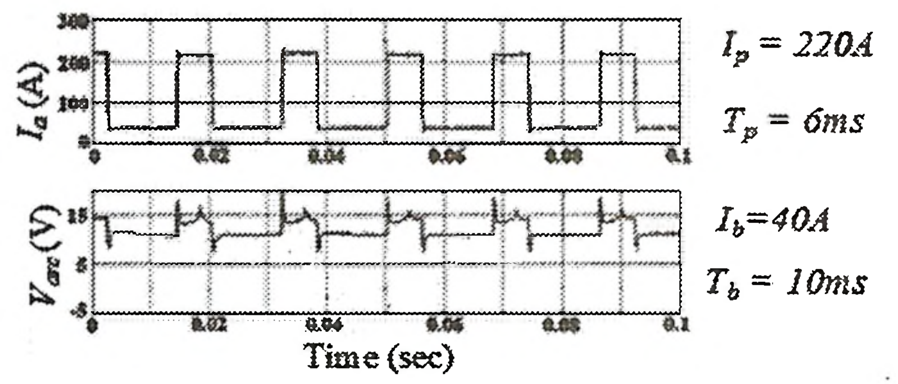

Fig. 6 : In phase weld gap waveforms under P-GMAW

ROOTING FOR IDEAL CHARACTERISTICS IN CASCADED ENERGY DELIVERY SYSTEM IN ARC WELDING

Poor ratio of energy utilized at work piece to resource exhausted (Fig. 2a and Fig. 2b) has made prevailing arc welding process of the developing world, in particular, not compatible to source or resources. It is more critical as equipments are mostly light-loaded (Fig. 1). Generally, compatible process possesses high degree of functional integrity [9]. It depends on multi-stage input-output characteristics of a cascaded system with or without feedback signals. Input-output characteristics may be improved through closed loop feedback control. Ensuring proper control characteristics in a fast dynamical process using feedback needs high bandwidth controller. Proper arc welding process needs to possess control system with fast dynamics for optimum [9] metal transfer. Large controller bandwidth (32) is required to emulate fast changing profile of weld gap parameters. Therefore, integrity [9] of the process may be achieved in two ways either through feedback control emulate desired characteristics and (or) converting the power control network, wherever desirable, to behave like ideal resistance. Pure resistive loads, for example, possess ideal characteristics (Fig. 7a Fig. 7g) as output follows input. Immediate noticeable benefit (Fig. 7b) is that source feeds load with unity pf to enhance the utility (5) of the grid.

Traditional CC equipment uses only one feedback signal i.e. arcing current I_a. It does not possess any feedback to optimize pf and harmonics to make grid compatible to process. Moreover, lack of control on arc length (V_{arc}) allows the equipment to pump uncontrolled energy to weld gap. It results in increase in temperature of arc column T_C beyond its optimal [10] value ($\approx 3000^\circ$ C) to create following problems:

i) More radiation loss in the process,

ii) Fumes and particulate matters are more around welder, more welders' discomfort

iii) Poor energy efficiency

iv) Poor weld quality

v) HAZ area is more

If same source executes pulsing in I_a in certain manner [11], it brings energy and quality benefits to the process. Controlled actuation using PWM techniques is useful to achieve control of output variables that results through time-integration of actuated input. E.g. increase in temperature of a body is result of accumulated power in it. It is used in temperature control of oven [12], in SMAW [11] and in flow control for smooth positioning [13, 14] of pneumatic actuator etc. Power pulsing i.e. simultaneous pulsing in voltage and current enhances η of equipment feeding resistive circuit at light loads [15]. This feature is useful in arc welding (Fig. 1) as high across the load efficiency η_{AL} is pre-requisite. Definite power pulsing is possible if output behaves like a resistive load.

Let us configure cascaded delivery mechanism (Fig.2) into three simple resistive networks such as in Fig. 7a, Fig. 7e and Fig. 7g to depict facility or grid, equipment and weld gap respectively. The resistive network possesses following characteristics (consider source resistance, $r_p \approx 0$):

i) $\angle(V, I) \to 0$ in Fig. 7e and 7f signify that there is no extra harmonics, and pf of respective circuit is unity. They handle respective loads with no circulating current. It means there is no energy storage element in that stage.

ii) $Gain.BW \rightarrow \infty$; it means current rise (t_r) and fall time (t_f) are negligible. Sharp pulses in welding (Fig. 7h) brings more benefits such as fumes are much less, productivity is more, quality is better in P-GMAW.

iii) Resistive characteristics (Fig. 7f) allow power pulsing in equipment to achieve both η and η_{AL} at same high value at any power (current) level (Fig. 7d).

Biased power pulsing in weld gap helps the process to dynamically modulate its resistance (26) to maximize its power when droplet is detached. The pulse (base) enables gradual heating of electrode tip. Droplets are not superheated. This lowers the amount of generated fumes and particulate matters etc. Power P is transferred [15] to process with no noticeable fall in η. P-GMAW process follows similar working principle (Fig. 7g and Fig. 7h).

MEASURE OF COMPATIBILITY IN ARC WELDING PROCESS

GOODNESS FACTOR

Welding controller [23] is lone active element in complete energy flow diagram as shown in Fig. 2. The solution to process and energy efficiency problems is linked with designing right equipment compatible to P-GMAW. As discussed in earlier sections, optimization of arc welding process depends on

i) Settling time (τ_s) of equipment to meet fast pulsing in P-GMAW

ii) Compact and light weight equipment to allow reduced cable loss and cable inductance

iii) Unity pf and large η ($\approx$ 1) for reducing loss in facility, equipment etc

iv) Excellent η_{AL} as I_a vary over wide range.

Expression of flat efficiency curve should ideally be insensitive to wide range variable I_a. One way to express it is

$$\eta_{equipment} = \eta_{max} \tanh(xI_a) \qquad (27)$$

Eqn (2) in welding needs the equipment to possess high value of η (η_{max}) and it should remain flat i.e. insensitive to welding I_a. The value of 'x' is chosen to incorporate minimum current I_b ($\approx$ 20A) for arc stability. Hence

$$\eta_{equipment} = \eta_{max} \tanh(0.05I_a) \qquad (28)$$

Or,

$$GF = \frac{\eta_{max} \tanh(0.05I_a)pf}{W\tau_s} \qquad (29)$$

Or,

$$GF = \frac{\eta_{max} \tanh(0.05I_a)pf}{W\tau_s} \qquad (30)$$

where weight of the equipment W and settling time τ_s may be expressed as

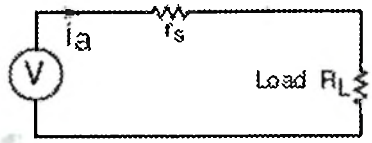

Fig.7a: Resistive power network

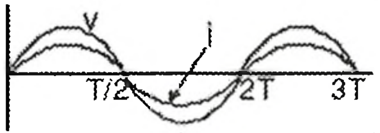

Fig.7b: Has unity Pf and no harmonics

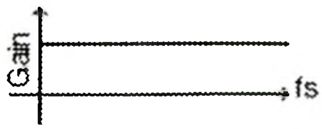

Fig.7c: It possesses good dynamic capability.

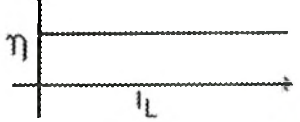

Fig.7d: Yields high and flat efficiency

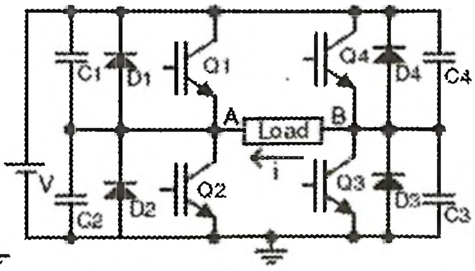

Fig.7e: A typical Power Inverter

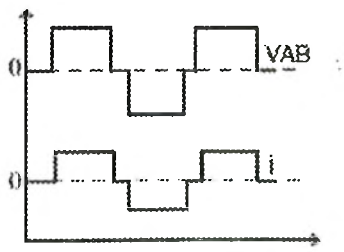

Fig.7f: Output waveforms of modern welding inverter : Resistive

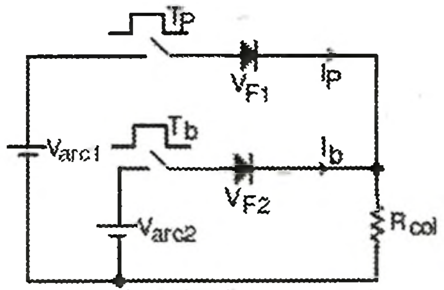

Fig.7g: Equivalent circuit representation of PGMAW process

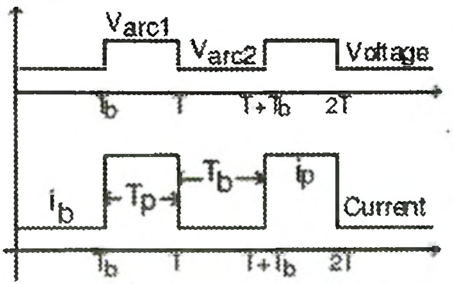

Fig.7h: In phase waveforms of PGMAW emulates resistance switching

$$W = \frac{K_3}{f_s} \qquad (31)$$

and

$$\tau_s = \frac{K_4}{f_s} \qquad (32)$$

Constants K_3 and K_4 depend on inverter topology and controller structure. Numerator of (30) connects facility for compatibility and its denominator is linked to process. Sharp t_r and t_f (both linearly vary with τ_s) in P-GMAW [3] in ODPP generates minimum fumes and particulate matters as no extra tip heating takes place. Using (31) and (32) in (30) we get GF as

$$GF = \frac{\eta_{max} f_s^2 \tanh(0.05 I_a) pf}{K_3 K_4}$$
$$= K f_s^2 \tanh(0.05 I_a) pf \qquad (33)$$

Unity pf and η close to unity at all loading conditions make facility (grid) compatible to equipment. Attaining unity pf through a pf-corrector at input (Fig. 3) converts welding load to grid as resistive as shown in Fig. 8. Rest of the constituent parameters of GF (33) varies favorably with one basic parameter of inverter i.e. f_s. Therefore, solution to both energy and process efficiency program is associated with designing a PF-corrected high frequency welding inverter. Cost, design complexity and η-vs-f_s trade-off are certain limiting factors to maximize GF (33).

POWER ELECTRONIC EQUIPMENT: ENGINE TO MEET COMPLETE COMPATIBILITY CRITERIA IN ARC WELDING

SCR based traditional equipments or welding choppers have long been favored in arc welding process. They employ secondary control operating at low voltage. They are just capable to optimize the process as V_{arc} and I_a are only accessible parameters for control. Absence of control on grid pf incurs large loss (Fig. 2). Shifting control to primary (Fig. 3) using inverter technology gets access of grid parameters. Measured feedback signals of grid voltage and current and their phase angle enhances functional integrity [9] to establish compatibility among various entities of Fig. 2. Maximum achievable GF makes facility and resource compatible to process. As discussed in last section, equipment is portable (31) and process compatible (32) if f_s is large. Its upper bound is limited by cost implication and frequency dependent switching losses taking place inside equipment. Following issues help decide operating f_s

i) worst case arc stability criteria

ii) optimum t_r or t_f for sharp P-GMAW current pulses

iii) minimum length of welding cable

iv) cost-vs-energy and process efficiency trade off

Dynamically, problem of arc stability is worst [10] with 100% CO_2 shielded GMAW process. It experiences frequent short circuits as well. Power source needs to have τ_s around 50 μSec [10] to ensure existence of arc post short circuiting. Arc stability under argon shielded atmosphere (>150 μs) is much relaxed. P-GMAW is better suited under argon shields. On the other hand, fine droplet transfer (22) uses high frequency (≤ 300Hz) pulsing. The values of T_p and T_b are small. Inductance (11) in welding cable (≤ 6M) in P-GMAW may delay current pulses (32) (t_r and t_f (12) to around 250 μs). Inverter with $f_s \approx 100$ kHz is sufficient for optimum τ_s (32) in arc welding. In conventional inverters, η drifts away from optimality due to large switching loss $f_s(E_{on} + E_{off})$ in (34). Therefore, inverter for optimized arc welding process is topology sensitive. The equipment with right topology should possess high value of η_{max} in (28). Its value is restricted as high frequency inverter (Fig. 7e) incur losses of multiple origins as

$$P_{Loss} = f_s(E_{on} + E_{off}) + \frac{I_a^2}{d^2 n^2} R_{eq} +$$
$$P_{L(FW)} + P_{DC-Link} + P_{Misc} \qquad (34)$$

where P_{Loss} is total loss in inverter; first term $f_s(E_{on} + E_{off})$ is switching loss, second term is resistive loss, third term is free-wheeling loss, fourth one is loss incurred in bridge rectifier and filter, and last one is power consumed in control power supply, gate drive circuit and in equipment cooling. Equipment with high η needs less cooling. Forced cooling should be avoided as ambience in welding is full of metallic particles. To satisfy (33), elements of P_{Loss} (34) should be minimized. Procedure to achieve η_{max} using (34) is following:

i) $(E_{on} + E_{off}) \rightarrow 0$: It is also important in arc welding as no-load (E_{on}) and short-circuit (E_{off}) conditions are valid operating points. This condition is, as well, useful [25] for inverters operating at higher DC bus voltage when boost converter is used for active pf correction. Phase shifted full bridge inverter using ZVS-n-ZCS [26] topology yields negligible switching loss.

ii) $\frac{I_a^2}{d^2 n^2} R_{eq}$ is inherently less in P-GMAW as both n and d are comparatively large. It needs less V_{oc} (14). High f_s helps reducing R_{eq} as length of Litz wire is significantly reduced. is minimum with inverter feeding unity pf load true in phase shifted ZVS-n-ZCS topology

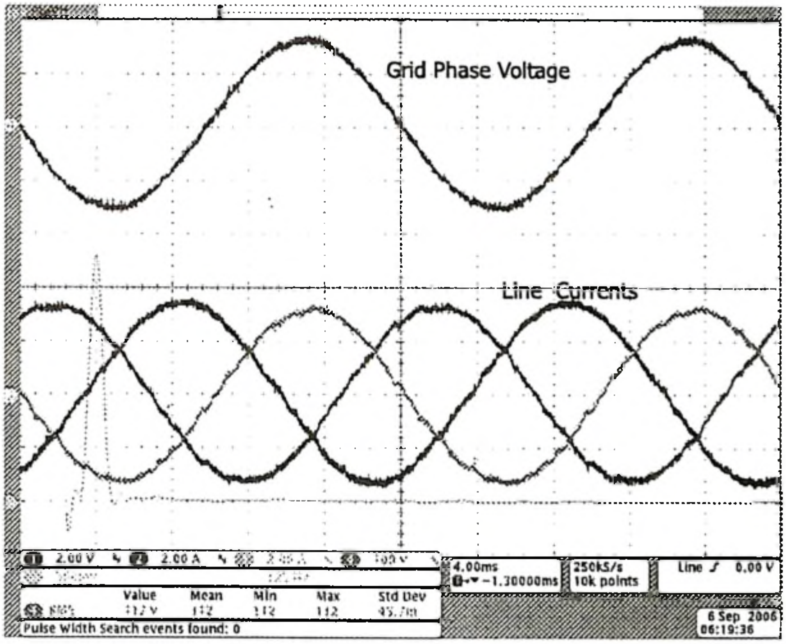

Fig.8 : Current in arc welding grid is resistive

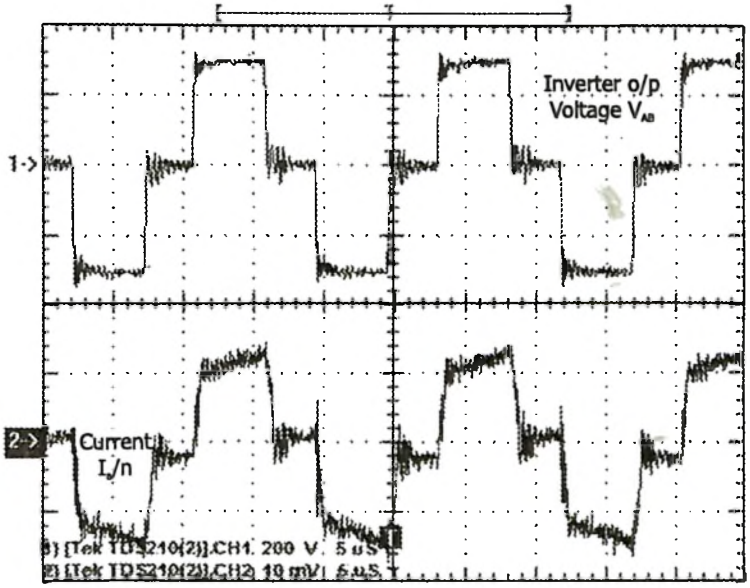

Fig.9 : Load of modern inverter is resistive

.iii) $P_{L(FW)} \to 0$; Means there is no free-wheeling current through anti-parallel diode of IGBT. It is also true in ZVS-n-ZCS topology. Load power factor is unity and output of inverter behaves like a pure resistive network as shown in Fig. 9. Unity pf load draws minimum current for specific output power.

iv) $P_{DC-Link}$ is minimized when DC-link feeds load with minimum i/p RMS current, and by choosing small value in DC-link capacitor with low ESR. RMS current is less for unity pf at source as well as at load. Reactive power fed to DC-link is negligible here.

v) P_{Misc} is less as cooling need is reduced in inverter operating at high η. ZVS-n-ZCS topology requires less gate power [9], and high density logic needs negligible power for control.

Once optimum value of η_{max} is achieved through phase-shifted full bridge ZVS-n-ZCS PWM inverter, power pulsing with large ratio of P_p/P_b (24) in P-GMAW (Fig. 7h) helps flattening η (28) at light loads [15] inherently.

Input pf-corrected phase-shifted PWM full bridge inverter using ZVS-n-ZCS topology [26] is proper equipment for arc welding. Its average η is 0.92 and η_{max} is 0.95. Fig. 9 shows that output inverter current is in phase with voltage. Hence, the compatible power source converts arc welding loads to behave like a resistance as shown in Fig. 9.

There are reasons behind welding rectifiers still dominating arc welding process in India. One major factor is legacy i.e. inertia to change, and other is lack of intent to process learning to enjoy benefits. Learning helps understand integrating impact of all avenues of inputs, in process activities, productivity, quality engineering parameters of output, cost, reliability and availability and impact of process on environment. Availability aspect is critical as single equipment feeds multiple weld gaps (Fig. 1). Comparative study on performance, reliability and availability should be made properly. Reliability is affected if power losses and or surges (thermal, electric) are more. Rectifier incurs 50% loss in it and that for inverter is only 5%. Pseudo-perception is that passive components dominated rectifier withstands more surges. The ratio of thermal time constants (τ_c) of SCR to IGBT is 100:1. However, surge handling capability is decided by the swiftness of action against fault conditions. The ratio of response time for control and protection of SCR-to-IGBT is (10msec/500nsec) 20000:1. Hence, proper IGBT based inverter, even ignoring benefits, is always more reliable, available and suitable for use. Equipment with increased availability reduces life cycle cost. Heavy rectifiers are static where as light weight inverters are casually handled in many installations.

ENERGY SCENARIO WITH COMPATIBLE ARC WELDING PROCESS

Section 2 considered 400A welding rectifier as base equipment. Its pf and $\eta_{equipment}$ at 7.5kW are 0.6, W is 150kg and τ_s is 20ms. Its goodness factor (29) GF_{Rect} is 1.2 X 10^{-4}. However, phase-shifted ZVS-n-ZCS inverter yields pf of 0.95, $\eta_{equipment}$ of 0.92, W of 20 kg and τ_s of 0.1ms. Its goodness factor $GF_{ZVS\text{-}n\text{-}ZCS}$ is 0.437. Measure of compatibility improves by ($GF_{Rect}/GF_{ZVS\text{-}n\text{-}ZCS}$) 3642. It is difficult to quantify gains everywhere at one go such as all round weld quality. However, energy gains are quantifiable and therefore presented here. Impact of energy gains is far reaching. The reformed arc welding grid is shown in Fig. 10. It is obtained by replacing welding equipment of Fig. 2 by ZVS-n-ZCS inverter, and SMAW is replaced by P-GMAW. Average deposition rate of 4.5 kg/hr is considered in P-GMAW [2, 19]. After comparing stage wise data between Fig. 2 and Fig. 10 following conclusions can be made

i) Though users are concerned about energy meter reading as part of process costing, the global impact is much deeper.

ii) Potential of total electrical power savings in grid is 3345 MW. Warming through such large power loss introduces vicious cycle of energy use or waste [8]. Prospect of gain is equivalent to ten medium size power stations.

iii) Saving in fuel (mostly coal in India) is close to 12000 MWe. Accordingly, emission of green house gases is drastically reduced. To counter emission 650 million trees would have been required.

iv) Reduction in loss in welding arc is 513 MW. It would bring comfort level to welder and would generate less fumes and particulate matters. Spatter loss is also less.

v) Reduction in loss in HAZ (264MW) helps improve weld quality.

vi) Reduction in T & D loss with improved grid pf enhances life cycle cost of bulky and costly infrastructure.

vii) Most of all, the demand of integrated arc welding loads on grid has drastically reduced

Laterally, larger duty cycle of CV equipments (> 3-time) improve the utility of each installed equipment to enhance life cycle cost, require less staff around welding. Large reduction in weight in equipment through use of inverter technology helps material saving inside equipment, and needs less energy in transport, manufacturing, servicing and recycling etc.

CONCLUSION

In this article all round impact, baring shielding gas, of integrated arc welding loads have been discussed. Roots for their remedies have also been suggested through maximizing a parameter of arc welding equipment called goodness factor. It is achieved by converting each stage to behave like a resistance load. This approach guides to reduction in process diversity. Reduced diversity simplifies process learning. Combination of modern power electronics inverter with the help of right topology along with optimal welding method are instrumental to minimize energy use, maximize productivity with enhanced quality and have minimal impact on local and global environment. Like quality engineering parameters, constraints from energy crisis, concerns on climate change and other environmental issues would accelerate the process to mature globally. In that, the role of modern

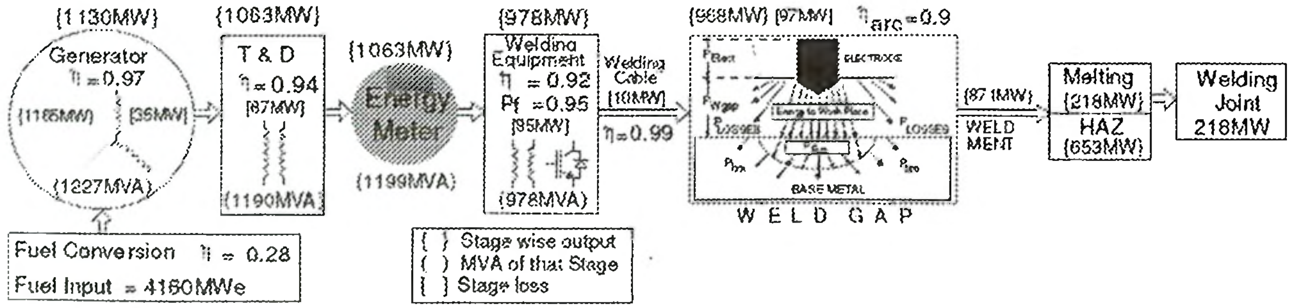

Fig. 10 : Energy flow diagram of compatible of isolated arc welding grid

inverter technology is catalytic in nature. The equipment consumes small power at load end and makes an impact by saving large power at grid. It helps optimize utility of each stage in power delivery mechanism leading to reduction in life cycle cost. Reduction in loss checks warming; increase in efficiency creates energy reserve and reduces green house gas emission.

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