Practical Reliability, Availability And Acceptability Aspects Of Modern Arc Welding Equipment

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The role of smart engineering process is to optimize its resources such as energy, material, labor, time to yield desired quality engineering goal etc. Arc welding equipment is engaged to feed its process to produce mechanical joints having diverse characteristics. Inverter technology provides multitude of benefits virtually to each entity associated with arc welding process. Still its acceptance among users, though gradual, is slow. India is in real upsurge in creating its infrastructure. The demand on welding equipment will be great. Hence, efficient system of welding should be in operation. This paper intends to clear wrong notions that inverter technology has inherent problem of reliability and availability that acts as hindrance for its acceptance in arc welding process.

INTRODUCTION

Since the start of electrical domain as avenue to channelize energy for joining metals (arc welding process), there has been increase in process diversity. Diversity in arc welding process has further widened the diversity in welding equipment. The energy efficiency parameters of each process to meet similar goals are quite different. This is due to difference in degree in compatibility of source feeding the arc load. All around diversity offers complex process learning. Modern welding equipments are used to improve compatibility index of the process.

Equipments installed in any engineering process should be equipped to handle its load diversity. Peculiar characteristics of arc welding load need large ratio of open circuit to load voltage, as shown in Fig.1. Moreover, comparatively small range of nominal power rated arc welding equipments (2kW - 18kW) feeds the process (Fig.2) with much wider load (0.05kW - 18kW). Specification of joint decides the power required from equipment. Generally, 15kW rated equipment possesses poor energy efficiency parameter while feeding low power arc load such as at or around 100W (0.7%) of rated power). On the other hand, it is difficult to install arc-load specific equipment in a manufacturing process where diverse welding conditions exist. Therefore, it can be stated that one arc welding equipment should be equipped in such a manner as if it is an integration of many load specific equipments. Arc load characteristics are also diverse as shielding gas, arc length, electrode and parent metal all have individual as well as collective influence. Therefore, availability of installed equipment is of paramount importance.

Due to its existence for several decades, legacy of prevailing arc welding rectifiers and welding transformers is large. It brings in large inertia to any process changes needed. However, as they operate either at 50Hz or 300Hz respectively, they lack ability to control high speed weld pool dynamics. E.g. CO_2 shielded weld gap needs (4) source should regain control on arc within 50 s of arc extinction, or, control of high speed droplet transfer (200Hz) etc. In order to offset short-comings in arc control characteristics, there has been unavoidable increase in process diversity such as in, welding methods, shielding gas compositions etc. Productivity and weld quality issues looks for power source (e.g. chopper) with an ability to handle fast dynamics of arc load. To

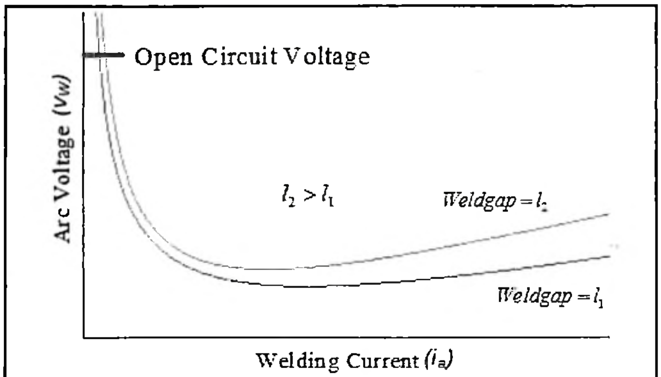

Fig. 1 : Non-linear Characteristics of welding arc

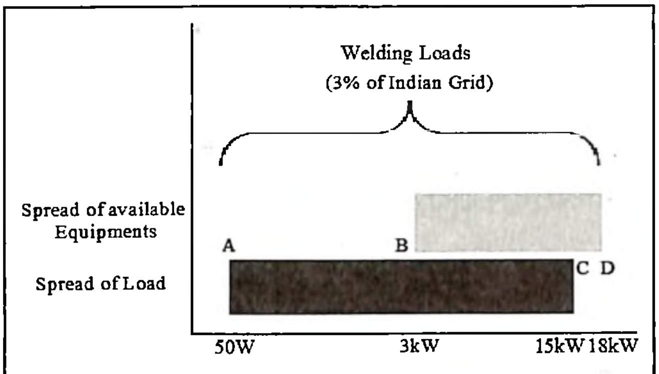

Fig. 2 : Poor loading profile of arc welding equipment

handle, as well, concerns on energy efficiency and environmental issues high frequency inverter (1,2) based power sources form an essential entity of the process. Introduction of inverter is capable of making source (1,2) compatible to load to achieve -

i) energy efficiency
ii) process efficiency
iii) better functionality
iv) improved quality
v) ease of welding
vi) increased automation flexibility
vii) better environment
viii) generation of fumes and particulate matters

Still, availability issue, for long, has kept most Indian users away. Developing countries and India, in particular, has seen, till recently, slow acceptance of inverter power sources. Though, high power equipments are increasingly being deployed in much harsher environments. Inverters for traction applications and converters for hybrid or electric vehicles are some examples. Cost-benefit analysis (1, 2) was sidelined initially. Initial cost, reliability and availability issues have long been concerns for growth of inverter technology. High initial cost has also been an issue in small sector industry dominated process. Have those parametric status been favorably shifted, of late ? Is reliability or availability a major issue any more? Can acceptability parameters be properly defined for welding equipments? Can acceptability parameters be properly defined for welding equipments? This article re-looks into the those criteria in togetherness of arc welding equipment by taking into consideration gains through quantifying goodness factor or impact factor of evolving process and associated equipment. It covers reliability and availability issues of equipments vis-à-vis their performance. Section 2 covers the impact the modern arc welding system creates. Section 3 discusses acceptability criteria. Section 4 details operating environment of the process. Section 5 elaborates reliability and availability aspects while section 6 discovers major failure mode of equipment. Finally, section 7 details the road map for further improvement.

EVOLUTION IN ARC WELDING EQUIPMENTS

The role of arc welding equipment is to feed power to weld gap for making welding joint. The nature of load in arc welding is unique (Fig. 1). Process dynamics (of droplet transfer) is also fast. Moreover, the distance between the equipment and the center of process is variable. Therefore apart from its complex load and application characteristics, the process needs large number long input/output signal lines for proper execution of process. Equipments are liable to frequent movement. Therefore, they should be looked differently than other power electronics equipments.

Traditional arc welding equipments employ control on secondary low voltage side as shown in Fig.3. Such equipments are dominated by large passive components such as welding transformer (TR_1) and smoothing choke (L_1), six high current silicon controlled rectifiers (SCR) etc. Some equipments hardly employ any control. Skill of welder is important there along with other inputs such as shielding gas. Traditional equipments may be categorized as below :

i) Welding transformer
ii) Controlled welding rectifier
iii) Welding rectifier with chopper

In modern welding inverter technology the power control is shifted to primary of high frequency transformer as shown in Fig.4. It enables control on variables of weld gap as well as on grid parameters to establish efficient energy flow mechanism between grid and welding joint. Simultaneously, it achieves optimum performance (2) at the process end. Level of optimization (2, 3) is expressed in the form of goodness factor GF of arc welding equipments as

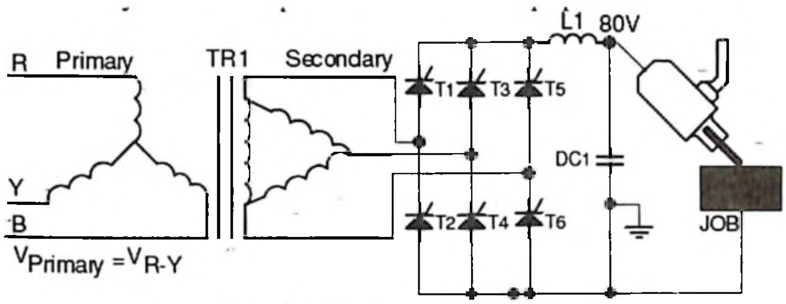

Fig. 3 : Controlled Welding Rectifier

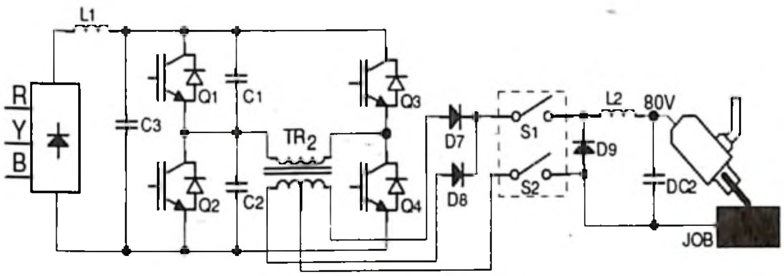

Fig. 4 : Arc Welding Inverters

Table 1 : Overall improvement in arc welding process through evolution

Equipment + Process	η	pf	W (kg.)	τ_s(ms)	GF
400A (SMAW, Rectifier	0.6	0.6	150	20	0.00012
400A (GMAW, Inverter)	0.92	0.95	20	0.1	0.437

Table 2 : Feel of Goodness factor and Impact factor on Process Performance

	SMAW + Rectifier in India	SMAW + Inverter In India	GMAW + Inverter	GMAW+ Inverter in W. Europe
Weld gap power	7.5 kW	7.5 kW	4.2 kW	4.2 kW
Overall elect. eff.	0.37	0.6	0.8	0.8
Energy meter	15 kW	10.6 kW	4.6 kW	4.6
Grid Power used	23 kW	12.5 kW	5.25 k Unit	5.25
Consumption/yr.	23k Unit	12.5k Unit	5.25k Unit	5.25k Unit
Energy saving/yr.	--	32000	125000	125000
Power Factor	0.65	0.75	0.95	0.95
Weight of inverter	150 kg	35 kg	45 kg	45 kg
Fuel Conv. eff.	0.28	0.28	0.28	0.49
Eqv. fuel energy	82 kW	45 kW	18.7 kW	10.7 kW
CO_2 release/yr	19 ton	12.5 ton	4.8 ton	2.75 ton
NO_2 release/yr	19.3 kg	13.2 kg	4.375 kg	2.5 kg
SO_2 release/yr	97 kg	46 kg	15.2 kg	8.7 kg

$$GF = \frac{\eta_{equipment}\, pf}{W\tau_S} \qquad (1)$$

Where $\eta_{equipments}$, pf , W and τ_S are efficiency, power factor, weight and settling time of the equipment respectively. Numerator of (1) signifies how resources or grid power is handled where as its denominator takes care of process optimization. Higher the value of GF better is the energy and process optimization. Table I draws comparative statement (in GF) for shifting from traditional process.

Shift in technology or in method or in both together is guided by definite gains. It may be quantified by the impact factor (IF). In arc welding it may be defined as the ratio of goodness factors of welding equipments of different generations. It is a measure of gain achievable in transforming process with the help of inverter based equipment. It

$$IF = \frac{GF_{GMAW+Inverter}}{GF_{SMAW+Rectifier}} \qquad (2)$$

$$= \frac{0.437}{0.00012} = 3641$$

Maximum value of IF represents overall system gain that includes gain in energy, process, productivity, quality, cost, human factor, environment etc. Table 2 depicts certain directions on impact of higher values of GF on the process.

For example, GF is more in last two columns. The table is created for a fixed deposition rate of 2.5 kg/hr. To make things simple, the duty cycle of equipment is ignored. First column of Table 2 represents the prevailing situation in India where as 3rd and 4th column depict near ideal arc welding situation - one in India and other in Europe (3, 6) respectively. It suggests that just money saved through reduced energy bill is capable of introducing three new prevailing Indian arc welding systems every year. Alternately, if life of Inverter for GMAW process is n years, equivalently it gives birth of 3 (n-1) SMAW rectifiers. Furthermore, there is multitude of benefits such as better weld quality with productivity, less environment pollution (at source as well as at process end) etc. The prevailing system in India exhausts resources at much faster rate. Consider a hypothetical situation where one inverter (life : n years) and one rectifier (life : n_1 years) are employed. In n years of life, the inverter based system, through energy saving prospect alone, creates room for 3 (n-1) rectifiers free of cost. It means one inverter of life n years is capable of equivalently generating indirect life of n+3 (n-1)n_1 years. Therefore, through IF, the normalized reliability (R_N) of modern equipment with respect to rectifier is

$$R_N = \frac{n + 3(n-1)n_1}{n_1} >> 1 \qquad (3)$$

Where numerator denotes life of inverter transformed equivalently into rectifier's reliability, and denominator is normal life of rectifier. Value of R_N >> 1 means inverters creates more benefits to user. Hence, through performance, life of modern equipment is boosted considerably. If any literal similarity is drawn, it can be stated that life span of both Swami Vivekanand and famous mathematician Ramanujan was reasonably short, not their contributions. Alternately, enhanced life, through IF, of modern process is

MTBF (Modernprocess) = KIFn : K<1

Apart from performance, thermal rating of modern power electronics equipments, though it may sound ironical, is superior. Let us consider a loading condition (300A) for a 400A rated equipment in SMAW. The corresponding weld gap power is 9600W. Consider efficiency of inverter and rectifier to be 0.94 and 0.7 respectively. The loss in inverter is 610W and that in rectifier is 4110W. The designed thermal resistance for allowable temperature rise (ΔT) is expressed as

$$R_{th} = \frac{\Delta T}{P_{Loss}} \qquad (4)$$

If ΔT is considered as 60°C (for hot spot temperature 110°C),

R_{th} (Inverter) = 0.1

And

R_{th} (Rectifier) = 0.01445.

It means welding rectifier, ideally, needs liquid conduction cooling for its continuous operation at 300A where as convection cooling is sufficient for inverter. However, the heat generation centers for rectifier have large mass i.e. heat capacity and have large thermal time constant ($_c$). Therefore, the dynamic equation (transient thermal impedance) of R_{th} is

$$R_{th}(t) = R_{th}(0)(1 - e^{-t/\tau_c}) \qquad (5)$$

Thermal tripping mechanism would take action when R_{th}(t) > 0.01445. Large thermal time constant of rectifier transformer (TR_1) and choke (L_1) may lead to formation of higher hot spot temperature leading to reliability problems. Excess loss in large passive components increases probability of higher hot spot temperature. In general, every six degree rise in hot spot temperature reduces the life of TR_1 or L_1 by a factor of two. Insulation materials are prone to crack after facing repeated temperature cycling. They, subsequently, become less liable to movement. Thermal time constants for loss making entities in high frequency inverter are too small as mass involved is comparatively negligible. Ideally, all inverters could easily be made continuous duty rated (similar to motor drives etc) at nominal rating.

ACCEPTABILITY CRITERIA FOR EVOLVING PROCESS AND INNOVATIVE TECHNOLOGY

Acceptability criteria towards process innovations are guided by following criteria :

1. Process improvement
2. Cost implication
3. Reliability of performance
4. Availability and maintainability of process
5. Difficulty in process learning
6. Inertia or attitude towards accepting new process

Let us take one beautiful example of implementing acceptability criteria. Nearly 70% of electrical loads fed through power electronics equipments fall under motor drives, uninterrupted power supplies and power quality applications. These applications employ medium frequency inverters where conduction loss in IGBT is dominant. Out of 4% total inverter loss, IGBTs contribute 1% of it. In general, PT (punch through) or NPT (non-punch through) IGBTs have long been used. However, if Trench Field Stop (TFS) IGBT (its $V_{CE(sat)}$ drop is much less), is used in place of PT or NPT. IGBT, it is possible to reduce IGBT loss by 25% of similar inverters. Reduction of IGBT loss improves total inverter efficiency by 0.3 - 0.4%. However, improvement, of apparently small efficiency saves several GWh of energy globally. Moreover, cost of IGBT in each inverter is reduced by

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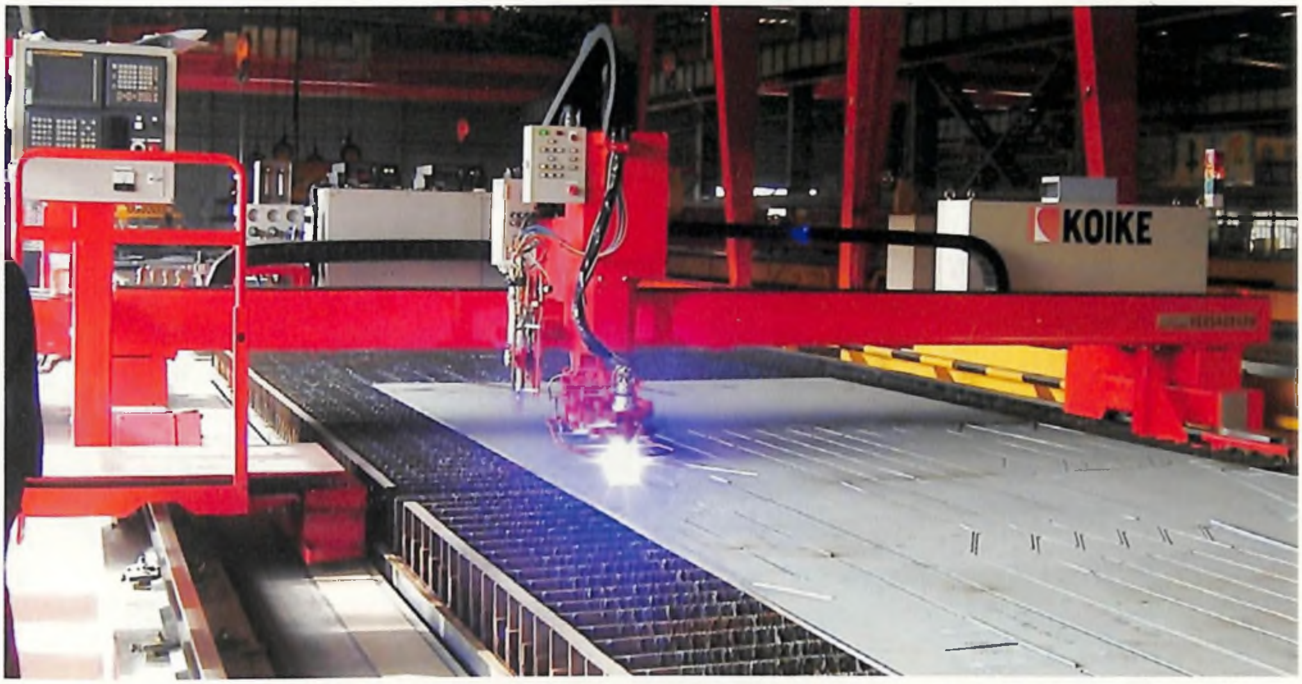

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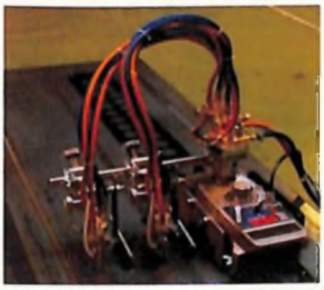

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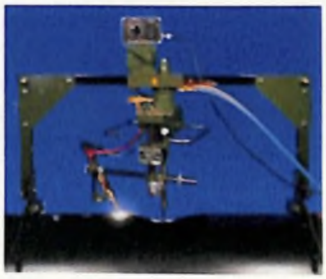

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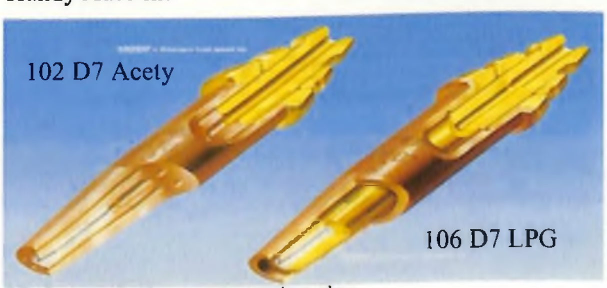

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20%. Two-front benefits i.e. in energy efficiency and cost, apparently look marginal, have propelled the global power electronics leaders to take note of this IGBT seriously. It is noticeable by the surge in sale of TFS IGBT as shown in Fig.5. It took just 4 - 5 years, in a linear way, for the IGBT to move from physics of development to matured market penetration. It can be commented that only a few handful IGBT manufacturers help save several GWh of electrical energy globally.

Let us consider another example - arc welding method. Arc welding involves multiple inputs and each input has gone through evolution phase. There are two major centers of benefits - method or technique and in energy flow channel centered around equipment. Due to lack of sophisticated equipments in initial days, evolution in techniques was more prominent and gradual. The acceptance of gradually evolved process in developed countries, as shown in Fig.6, has been in concurrence. All developed countries have moved ahead in parallel and accepted better welding methods. Japan, for instance, rarely uses constant current (CC) characteristics for arc welding. CV processes are productive, energy efficient and are suitable for all metal all position welding. Acceptance of productive methods almost in concurrence to their development phase could be related to the continuous effort put to educate end users.

The level of benefits in energy, performance and cost (1, 2) is increased many fold if modern arc welding equipments is deployed in the process that uses better methods. Therefore, their acceptability to control energy flow to maintain arc is beyond doubt. Unfortunately, the penetration level of inverters in India is less than 10% and

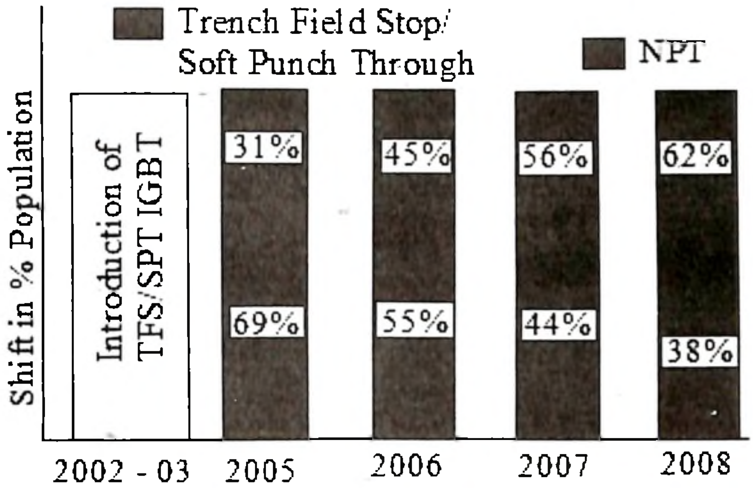

Fig. 5 : Implementing acceptability criteria : Small gain, large integration - huge benefits

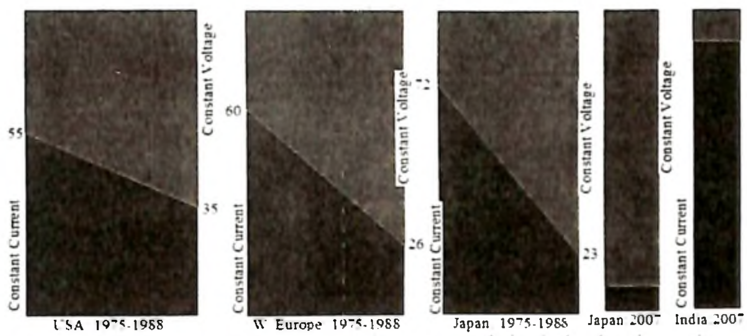

Fig. 5 : Acceptability is in concurrence with gradual evolution in developed countries

that of inverter based GMAW process could be less than 5%. India has just entered the upward surge in infra-structure development. In its present technological status, the demand on energy towards welding expected to be large and growing. This needs to be addressed. Hence, acceptance of modern process holds key.

One of the reasons of modern process and equipment being ignored is that the energy cost in arc welding is considered to be insignificant (< 2% of the total process cost C_1). Comparative statement on process costing is shown in Fig. 7. However, the role of equipment or energy (1, 2) in the process is catalytic in nature. They help reduce the process cost drastically from C_1 to C_2 ($C_1 > C_2$) as shown in Fig.7 by improving productivity, consuming less energy and shielding gas, reducing quality cost, reducing waste in the form of spatter etc. E.g. increased productivity reduces labor and energy cost. Labor cost is main contributor to process cost. Labor cost is main contributor to process cost. Cost benefit, alone, can fit the bill as acceptance criteria as explained in column 1st and 3rd of Table 2.

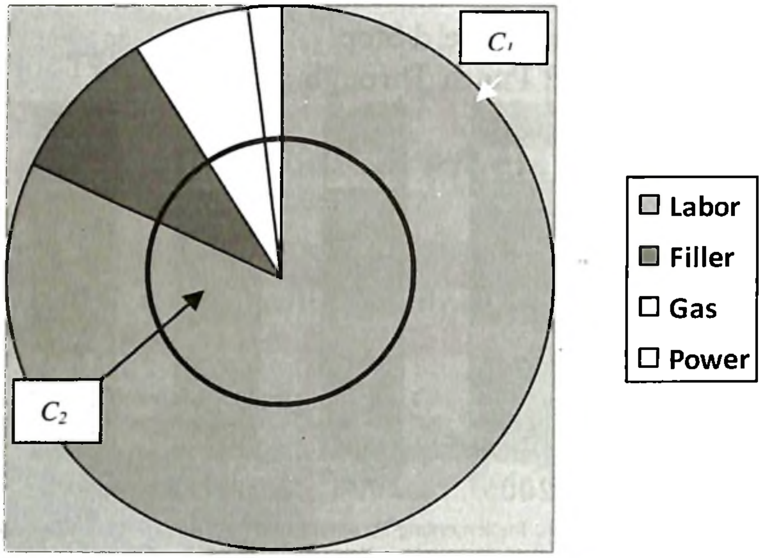

Fig. 7 : Costwise impact of energy on process is negligible

ENVIRONMENT AROUND ARC WELDING EQUIPMENT

The transition from welding rectifier to inverter from circuit point of view is large as inverter actively controls the dynamics of weld gap. Component count, mostly active, in inverter is much more. Interconnecting cables and connectors are more as more protection measures are necessary. Pin count in inverter could be ten-fold. Therefore, environment around may play critical role. It is known that, arc welding equipments possibly face one of most difficult operating conditions. The prevailing conditions outside the equipments play critical roles in creating certain failure modes. The conditions may be categorized as follows :

1. Electrical operating conditions : Welding equipments have traditionally faced basic power quality problems as they are connected to sources ranging from national grid to small diesel-generator (DG) set. The equipment design should take care of voltage and frequency fluctuations, voltage unbalance etc. Rectifiers are robust as, for example, gate drive for SCR is current sensitive. Operating range of gate trigger current is $0.2A \leq I_G \leq 3A$ i.e. 15:1. On the other hand, inverters mostly use IGBT as switching device whose gate is voltage sensitive. The operating range of gate voltage (V_G) is narrow ($15V \leq V_G \leq 20V$) i.e. 1.33:1. Modern inverters, however, are devoid of this problem as control and gate drive circuit have been fed through internal DC-DC converter.

2. Hazardous ambience : In this field of metal working air around equipment contains small metal particles. Moreover, coastal areas offer hazardous ambience as salt content in air is more. They can cause failure in circuit. PCB with more pin count invites problems.

3. Mobility of the equipment : Positions of welding joints are not fixed. Hence, either the joint locations or equipments are mobile. Due to differences in weight, the handling of inverter is worse than that of rectifier. It will be detailed in section 6. Handling of inverters is poor as their weight is close to pay load capacity of a healthy worker. Movement of rectifiers is comparatively less, or, mechanized system is employed to move them.

4. Process connectivity : Equipments are connected to the process directly. Large number of interconnecting wires (mostly mobile) is required for most arc welding processes. Interconnecting signals are more for modern multi-functional inverters (8, 9). Any loss of signal in interconnecting cables results a complaint, though the equipment is healthy.

During the initial days of introduction of welding inverters, factors (1 - 4) contributed failures in a large way.

COMPARATIVE STATEMENT OF PREDICTED RELIABILITY IN DESIGN OF WELDING EQUIPMENT

The shift from basic rectifier to inverter is a complex one. Complex weld gap load, harsh environment, two-transistor forward converter as topology to begin with, high initial cost and above all poor availability accounted for slow acceptance of new inverter technology. Particularly, in reliability, designer is concerned with designing a product or equipment to last as long as possible without failure. In maintainability, the emphasis is on designing an item so that a failure can be repaired as quickly as possible. The combination of high reliability and high maintainability yields in high system availability. Process people are mostly concerned about availability of each item connected with the process. It is defined as the probability that a system is operating satisfactorily at any point in time *t*, when subject to a sequence of "up" and "down" cycles. In other words, availability is a combination of reliability and maintainability parameters. Availability A(t) is improved when reliability R(t) i.e. mean time between failure (MTBF) is high as

$$A(t) = \frac{MTBF}{MTBF + MTTR} \quad (6)$$

where MTTR is mean time to repair. Average value of MTTR depends on nature of failures, availability of stock of requisite components and expertise and promptness to clear faults. Ideally MTBF should be high for these products. To make welding equipment 99.5% available with average MTTR of 24 hrs. the required MTBF of the equipment is 4776 hours. If MTTR is reduced to 12 hrs, A(t) increases to 99.75%. MTBF of an equipment alone depends on design capability where as MTTR depends on modularity in design, redundancy in critical segments and maintainability parameters of either manufacturing or service provider company. For example, MTTR is virtually zero for hot swappable redundant power supplies. Redundant equipment also improves availability criteria. If two equipments have availability A_1 (99.5%) and A_2 (99.5%), the system availability A is

$$A = A_1 + A_2 - A_1A_2 \quad (7)$$

$$= 0.995 + 0.995 - 0.995^2 = 99.9975\%$$

Poor deposition rate and duty factor force a fabrication site to procure more number of SMAW equipments, thereby instilling certain degree of inherent redundancy. On the other hand, modern arc welding technology (5) is guiding the arc welding process towards either reducing process diversity or allowing the process to migrate towards multi-functional arc welding equipments (8, 9). Either of them will reduce equipment redundancy. In such situation, equipment should possess high reliability i.e. MTBF. Hence, power source product design is critical factor in arc welding process to have high dependability.

Arc welding inverter with different functional blocks is shown in Fig. 8. Modular design helps reduce MTTR to enhance A(t). Presence of more blocks is to cater more functions. Function space of inverter is inherently wider.

Each block may consist of circuits and or software. Reliability of circuits depends on many stages such as design, procurement, production and testing. Software reliability is design centric. Moreover, software does not have problem any ageing. Software blocks do not add pin count as well. Software incentive design is, therefore, preferable. Otherwise, each hardware circuit consists of large number active and passive components (parts). Pin count increases in hardware design. Part count, nature of parts and their prevailing values of stress factors decide product's failure rate as per MIL-217F. Both rectifier and inverter include three types of components. They are

(i) small signal active and passive components : they mostly are part of different blocks

(ii) Active power components

(iii) Passive power components

Failure rate $_i$ of i^{th} component (or block) depends on its base failure rate $_{bi}$ and applicable stress factors (eqn. 8, 9, 10). Failure rate of low power component (say i^{th}) in any functional block or printed circuit board is expressed as

$$\lambda_i = \lambda_{bi}\pi_T\pi_E\pi_Q \quad (8)$$

Where

$_{bi}$: Base failure rate of i^{th} component

$_T$: Temperature acceleration factor

$_E$: Factor to take care of environment

$_Q$: Quality factor based on test and inspection

Eqn. (9) for components handling large power such as SCR (10) or diode or DC link capacitors is modified as

$$\lambda_i = \lambda_{bi}\pi_T\pi_E\pi_Q\pi_R\pi_S \quad (9)$$

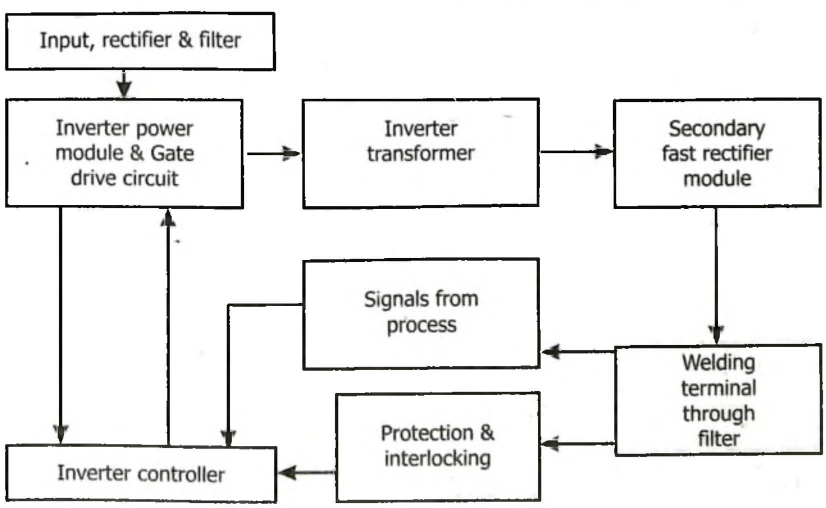

Fig. 8 : Basic block diagrams of modern welding equipment

Where

$_R$: Current rating factor

$_S$: Voltage stress factor

High frequency inverter could add another stress factor in its power switching devices i.e. Insulated Gate Bipolar Transistors (IGBTs) in the form of from switching loss. In hard switching applications current through IGBT is suitably adjusted to take care of it.

$$\lambda_i = \lambda_{bi}\pi_T\pi_E\pi_Q\pi_R\pi_S\pi_{SW} \quad (10)$$

Where, $_{SW}$ is stress factor due to switching loss. Soft switching inverters incur negligible switching loss, therefore, its value may be neglected.

Equipment's failure rate $_{ec}$ and reliability estimate R(t) are related to block failure rate ($_{Bi}$) as

$$\lambda_{eq} = \sum \lambda_{Bi} \quad (11)$$

$$MTBF = \frac{1}{\lambda_{eq}} \quad (12)$$

And

$$R(t) = e^{-\lambda_{eq}t} \quad (13)$$

Reliability R of n-block modular system with individual estimate R_B and in absence of any redundancy is expressed as

$$R = \prod_1^n R_{Bi} \quad (14)$$

Reliability study for each block is important. Some blocks are common to many power electronics products, all types of welding inverters included. Process learning for such blocks gets simpler as old MTBF data is transferable to new design (13). It helps reduce design cycle time as well.

The major blocks, from reliability point of view, that differentiate inverter (Fig.4) from welding rectifier are

i) high frequency inverter at the primary

ii) rectifier with DC filter at input and

iii) fast rectifier

iv) more interconnections between blocks

Welding rectifier (as shown in Fig.3) on the other hand has following major components as

i) Low frequency power transformer (TR) and

ii) Large filter choke (L) at the secondary

iii) Secondary phase controlled SCRs

Normally, well designed and properly manufactured transformers and chokes have large life. With sufficient power margin, individual life of these components could be in the range of 15 - 20 years. However, in arc welding applications, these components are designed with poor margins at peak load leading to frequent temperature cycling i.e. Duty cycle. Probability of high hot spot temperature is more. It may damage insulation leading to their early failures. Frequent movement of heavy rectifier enhances failure rate due to generation and propagation of cracks in insulation. With all blocks included, the life of welding rectifier is in the range of 8 - 10 years i.e. MTBF of 24000 hrs.

Reliability parameters of almost all evolved products change favorably over time. It has happened in inverters as well. The phobia of inverter reliability was correct in early 1990. Subsequently, each constituent element has shown sharp fall in over the years. As discussed in (8, 9, 10), reliability can be improved either by reducing or by reducing stress factors. New design concepts or topology have eased the stress factors of power switching components. Technology innovations in packaging, better input materials, joining techniques and better heat removal means together have contributed to reduction in . At a time when IGBT was first introduced into the market (say in 1990s, Fig. 9), SCR was already a matured device as its process learning stage was over. FIT value of IGBT was large in excess of 2000. However, over next few years industry has seen sharp decrease in as shown in Fig. 9. Now, values of of IGBT and SCR are very close to each other as shown in Fig. 9.

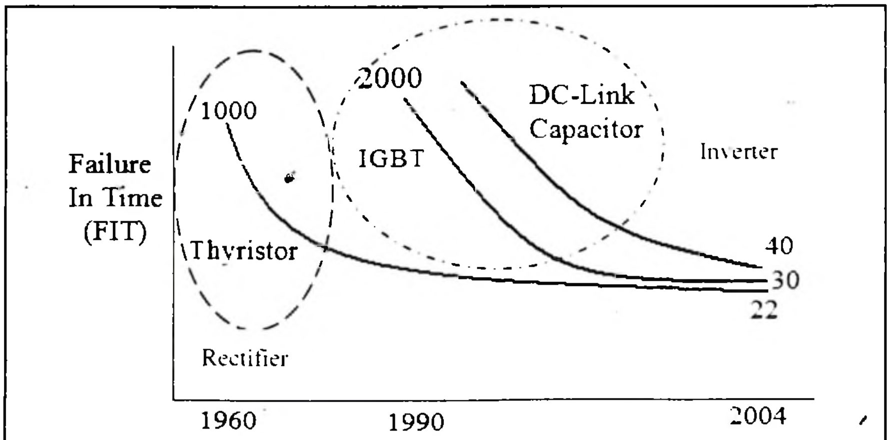

Fig. 9 : Convergence of base failure rate in power components

Let us look at another major component in inverter - DC link capacitor. Improvement in reliability in DC-link capacitors is 3-directional. Emergence of modern inverter topology has seen sharp reduction in its F value (e.g. from 1500 F (electrolytic) to 100 F (PP)). It has resulted sharp fall in $_b$ in DC link capacitors (Fig.9). Secondly, better material (Polypropylene (PP) film) is capable of enhancing the ripple current capability (from 12A (in electrolytic capacitor) to 100A). It has reduced current stress factor ($_R$). Thirdly, migration from low power density electrolytic capacitor to film capacitors has resulted sharp decrease in equivalent series resistor (ESR). There is 60:1 reduction in power loss in DC link capacitors. Added to this, improved layout and packaging (Fig. 10) reduces temperature stress factor $_T$. It boosts inverter efficiency as well. The value $_b$ of film capacitors is very small as shown in Fig. 9. Similar logic is valid for fast secondary diodes. Therefore, failure rate of modern equipment could easily be placed favorably alongside rectifier. Lateral gain in life through impact factor is a separate issue. Likewise, there has been improvement in failure rate in integrated circuits, small components, connectors, sensors, ferrite core materials etc. Therefore, designed MTBF for rectifier as well as that of modern inverter would be close to each other.

INSIGHT ON FIELD FAILURE DATE

Reliability prediction estimates the reliability of equipment as used in field. However, it is difficult for welding inverter to emulate in-service conditions. Therefore, it is extremely difficult to have demonstrated MTBF matching predicted one at product development stage. Wide range load, open circuit and short circuit conditions (Fig. 1) are valid operating points of arc welding loads. Many designed topologies could be sensitive to operating point of weld gap loads. Organizing proper acceleration testing facility for large number of units over wide weld gap loads in diverse process is extremely difficult, rather not feasible. Most welding equipments undergo severe shocks while being transported from one joint to another at field. The magnitude and nature of shocks are difficult to simulate. Therefore, MTBF based on field failure data gives better insight on reliability of welding inverter. MTBF can as well be expressed as

$$MTBF = \frac{kt}{r} \qquad (15)$$

Where r is the number of failures during field test time t of k units. Table 3 gives some idea on reliability of welding inverters based on field complaints. Data has been generated from field. Except 1000A rated one, all are SMAW equipments and have built-in GTAW capability using lift-arc facility. GMAW and GTAW equipments involve more process interfacing as their operation either needs certain sequence of activities or complex multivariable control. SMAW is more suitable process to study the equipment's reliability alone as it needs minimum interfacing and support. SMAW is more suitable process to study the equipment's reliability alone as it needs minimum interfacing and support. SMAW equipments of three different ratings (400A, 250A and 170A), each type of fifty numbers have been put into service for one year, average eight hours a day. Each fifty numbers have been divided equally into two groups one half for highly mobile applications, and for other half the movement of equipments are restricted. Two more types (130A an 1000A (CV)) of lesser quantity have been tested. First one was for mobile applications while other one was static. Loading pattern is not fully known. Certain man-made failures have been excluded from the data. Equipment loading factor (ratio of welding current to national rating) is more in lower rated equipments. For example, 130A is rated for 100% duty cycle and 1000A and 400A have 100% duty cycle at 60% loading. MTTR for all units are considered same.

Following conclusions can be made from Table 3

i) All units have decent availability

ii) Reliability of fixed equipments are high and is as good as that of rectifier

iii) MTBF of mobile welding inverters is much lower

Table 3 : Influence of mobility of equipments on field failures

	W (kg)	Breakup in MTBF (hrs) : (MTTR : 24hrs)			Availability (%)
		Fixed	Mobile	Average	
400A	40	15k	3.9k	9.5k	99.75
250A	25	18k	7.2k	12.6k	99.81
170A	12	20k	18k	19k	99.87
130A	6.5	25k for all mobile installations			99.9%
1000A	90	15k for all static installations, no failure			>99.84%

iv) Failure rate of heavier mobile equipments is more

v) Failure rate of small mobile units is less

vi) Failure rate of heavy fixed units is less.

Arc welding equipments face one of the most difficult operating conditions. It is clear from field data that weight of the inverter plays important role in field failures. It may be taken as another stress factor $_{M}$. Lower the weight of the inverter better is the overall MTBF. MTBF for fully mobile equipments (130A) is high where as the same is true for static 1000A ones. It means equipments are badly handled if W of equipments is comparable to load carrying capability (P_L) (one third of his/her weight) of human beings. Based on static and mobile MTBF data of Table 3, equipments may be categorized into three types :

1. $\frac{W}{P_L} << 1: \quad \Rightarrow \pi_M \rightarrow \leq 1$

Equipments this condition results high MTBF for mobile installations as well.

2. $0.5 \leq \frac{W}{P_L} \leq 2: \quad \Rightarrow \pi_M \rightarrow >> 1$

Equipments falling in this range are vulnerable as operators find difficulty in moving from one place to other. 400A rated equipments has minimum MTBF for mobile installations.

3. $\frac{W}{P_L} >> 2: \quad \Rightarrow \pi_M \rightarrow 1$

Such equipments (1000A) hardly have any mobility. Static high current units have acceptable MTBF as well.

EQUIPMENT PACKAGING AND HANDLING HOLD KEY

It is clear from the last section that W of equipment is one critical factor for mobile (most units are inherently so) welding equipments. Fortunately, their power range is narrow as shown in Fig.2. Majority of arc welding loads fall under 500A i.e the power rating of equipment is under 19kW. We have also seen in Table 3 that field failure rate of mobile equipment is acceptable if its weight is around or less than 15 kg. i.e. handling is better. The required power density is still decent (15/19) i.e. 0.9 kg/kW. It is an achievable target if we compare the corresponding 2010 target (11) of power electronics equipments in electric vehicle as 12kW/kg.

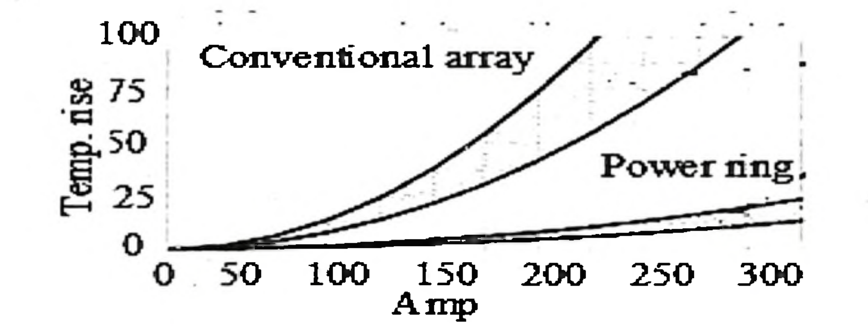

Fig. 10 : Packaging enhances reliability

Equipment for electrical vehicle faces harsher environment both in terms of modular interconnections and mobility. However, there is no human involvement in their handling. Therefore along with design innovations, packaging for these equipments is important as shown (12) in one example figure (Fig.10). There, temperature rise with same material at same output power is drastically reduced with better layout for to achieve improved heat removal means.

Frequency of switching fs of the inverter contributes largely in deciding the size and weight of the equipment. Higher value of f_s aided by soft-switching topology along with better input materials such as in DC-link capacitor help improve the power density. Higher f_s bring in more benefits to the process.

Adoption of better handling means for any product to avoid any untoward failure should be part of process culture. It needs training of personnel involving arc welding process.

If present is good for arc welding process, future is definitely brighter. Power semiconductors will go through a major boost once SiC devices (IGBT, Diodes etc.) are regularly available for production. These devices along with PP film DC link capacitors would reduce power loss in the inverter to a great extent (40%). Importantly, they (SiC) can withstand temperature in excess to 250oC i.e. more than major insulation materials.

CONCLUSION

Cost, performance and reliability of use of equipment decide its acceptability criteria. This article has detailed the acceptability criteria for modern arc welding inverters. It has been established that high performing equipments, through benefits, laterally enhances reliability estimate much higher than existing equipments. Gains for reliability comparison have been quantified.

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