An advanced computation system to solve electromagnetic problems in arc furnaces

FNM analysis is an aid to furnace design and, combined with instrumentation to determine real-time arc parameters, can be used to improve control of the EAF

The Finite Network Method (FNM) solves electromagnetic problems on electric arc furnaces making it possible for the first time to accurately and rapidly calculate the distribution of the electromagnetic field and current, energy and power densities in furnace components as well as the momenta and impedances of the high current. The FNM analysis alone is an aid to furnace design and, combined with an instrument developed to continuously determine real-time arc parameters, can be used to improve control of the EAF. **By Abbas Farschtschi***

ELECTROMAGNETIC field calculations are a necessary instrument for planning, design, modification and optimisation of all electrical systems.

Field calculations are used for planning new systems as well as for optimisation of the electromagnetic properties and for process control of existing equipment. The electric arc furnace is a complex system where several physical domains play a part which influence each other.

To tackle and analyse physical problems, electromagnetic field theoretical investigations are required. The simulation of mechanical properties of arc furnaces with the help of numerical methods is common practice. In contrast, numerical electromagnetic field calculations are currently not used for EAF design as far as is known by the author. What modelling has so far taken place contains no real field calculations but rather only estimations of these; or the models are only valid for parts of the EAF and then only under very simplified conditions. The results of such calculations have only very limited validity and are not really helpful because important effects are not considered.

Finite-network-method

Because analytical solutions of field problems and also the common numerical methods (such as Finite Element Method, Finite Differences Method, etc) do not lead to satisfying solutions, a special algorithm was developed by the author, the so called Finite-Network-Method (FNM).

For the first time a useful numerical method for modelling of arc furnace electrical systems has been established with the FNM algorithm[1 to 10]. The FNM method is applicable to all arc furnace geometries and allows the simulation of the electromagnetic properties of the complete high current system including the charged material and the furnace structures using a standard desktop computer.

Calculating current density

The complete furnace geometry is modelled using an advanced discretisation method. The first field property – the 3-dimensional current density distribution – is calculated. Simulation of different arc furnaces has been carried out. The results for one such furnace are presented here. The input parameters were the furnace geometry, the properties of the materials used and the secondary voltage (1200V).

The geometry of the furnace was modelled precisely, including the high current cables using the chain equation. Thus the modelled cables have their real physical shape.

The complete arrangement including charge material was divided into about 20 000 volume elements – the black points in **Fig 1** are the centres of these volume elements.

The elements are not uniform in volume. Sections with large geometric changes are simulated using a smaller discrete element lattice. Though possible in principle, the electrode nipples, the furnace shell and surrounding conductive material have not been considered in this simulation. Even with this low order of discrete element choice this efficient calculation method already yields results with high accuracy.

Fig 1 shows the 3-dimensional current density distribution for the complete system using a logarithmic colour scale.

The colour scale indicates that during furnace operation the differences of the current density reaches ratios of up to 1:107.

Knowing the local loads at any point is essential for planning and design and also for the modification of the high current system of an arc furnace.

Fig 2 shows the current density distribution of the busbars (two per phase). The cross section of the busbars shown is located close to the connection point of the busbar and cable. **Fig 3 (a-c)** shows the cross section of each of the three electrode arms determined close to the end of the straight part of the arm.

To get a good indication of the current density distribution between the three electrode

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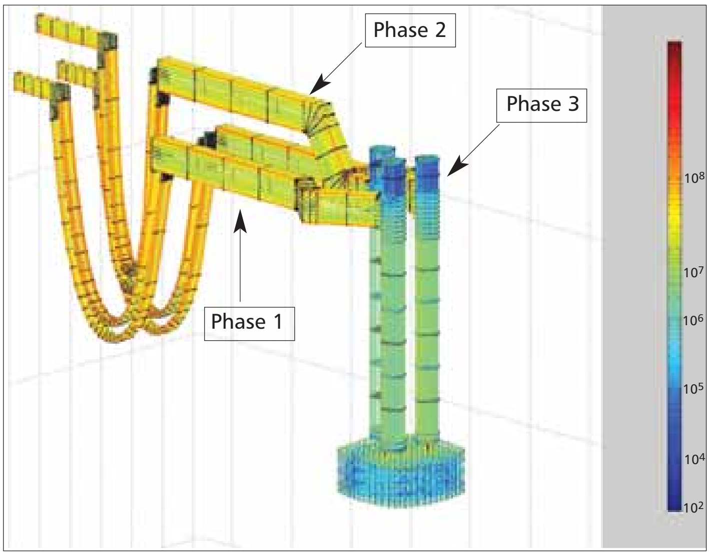


Fig 1 Three dimensional current density distribution of the calculated furnace
Log scale: (blue) $5x10^2$ A/m^2 – $2x10^6$ A/m^2 (yellow) – $8x10^8$ A/m^2 (red)

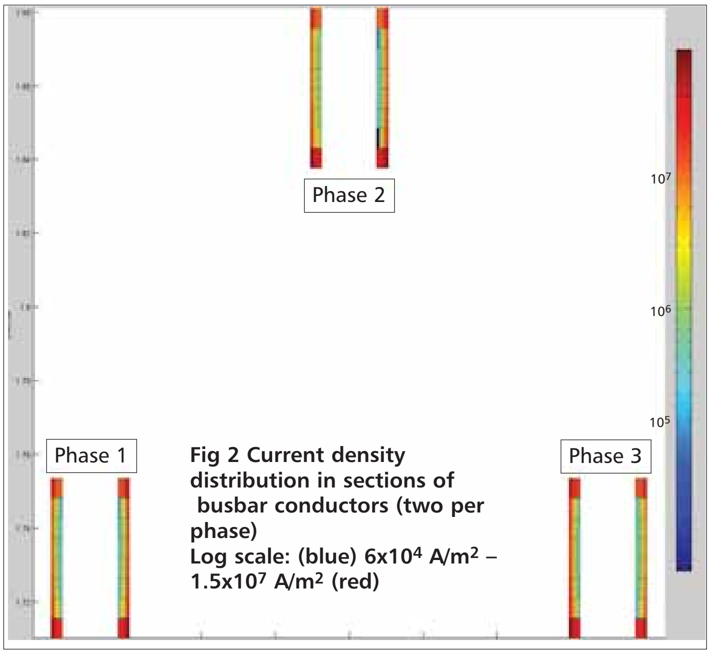


Fig 2 Current density distribution in sections of busbar conductors (two per phase)
Log scale: (blue) $6x10^4$ A/m^2 – $1.5x10^7$ A/m^2 (red)

arms in the region of the thin conductive area the arm boxes are shown together in **Fig 3 (a-c)**. A small discrete element size is chosen to increase resolution.

The current density distribution in the outer copper cladding and steel support of the electrode arm is quite different. These different current density distributions of the three phases are evident in the colour scale. The adjacent sides of the arms have increased current density in the copper as well as in the steel part.

The current density ratios are in a range of 1:103. The skin and the proximity effect is clearly visible in **Fig 3d** (an enlargement of 3a). The skin effect is the current displacement towards the surface of the conductor; the proximity effect is the mutual magnetic influence of the conductors due to inductance, resulting also in current displacement.

Fig 4 shows the current density distribution at two locations of the flexible high current cables. Each phase has four cables, (see also **Fig 1**). The left side shows a section through each of the 12 cables at the end closest to the busbars of the transformer wall and on the right side sections on the electrode arm side of the cables.

The cable sections also clearly indicate skin and proximity effects. It is interesting to note that the current density along the cable length is not uniform but changes with the location. Also the total currents of each cable of a phase are not the same. Calculations for different furnaces show differences of the total currents in a range of 1:2 between the cables conducting a particular phase. These calculations have been proven by measurements.

Fig 5 shows the current density distribution in the three electrodes at cross sections selected at the mid-length of each electrode.

The current enters the electrodes asymmetrically on the side via the copper shoes and exits the electrode at the arc spot. Thus in combination with the skin and proximity effects, the current density distribution over the electrode length is also not uniform. The calculations show this even with a course grid for FNM analysis.

The current density changes along the length of the conductors (busbars, cables, arms, electrodes) and is also not symmetrical about the axis of each, contrary to some statements in the literature.

With regard to the common and standardised one-phase dip tests (two electrodes dipped, one transformer phase voltage) these conditions have been simulated as shown in **Fig 6** with electrode phase 3 lifted.

It is interesting to see that the two phases which lead the short circuit current induce eddy currents in the raised third phase. Thus the third phase is heated (causing losses) which has to be considered in calculating impedances or inductivities.

A common practice at the design stage is to neglect the permeability of the steel parts of the high current system (and around it) and to assume constant current densities. Due to the physical-mathematical complexity of the eddy current problem the complete calculation of the real distribution of current density has not been performed by others and thus also the influence of the steel and skin and proximity effect has been neglected. Thus possible measures to improve conductor positions and cross sections have not been applied.

If this non-uniformity of the current density distribution or if different currents of parallel conductors (cables) are not considered, this means if the local electrical conditions of the conductors are not respected then over -or under-design of parts or of the complete system may occur.

The FNM approach enables these problems to be examined in detail and as a result optimise design which can save on construction materials used as well as enabling higher furnace currents to be used at the same transformer voltage thus increasing furnace power.

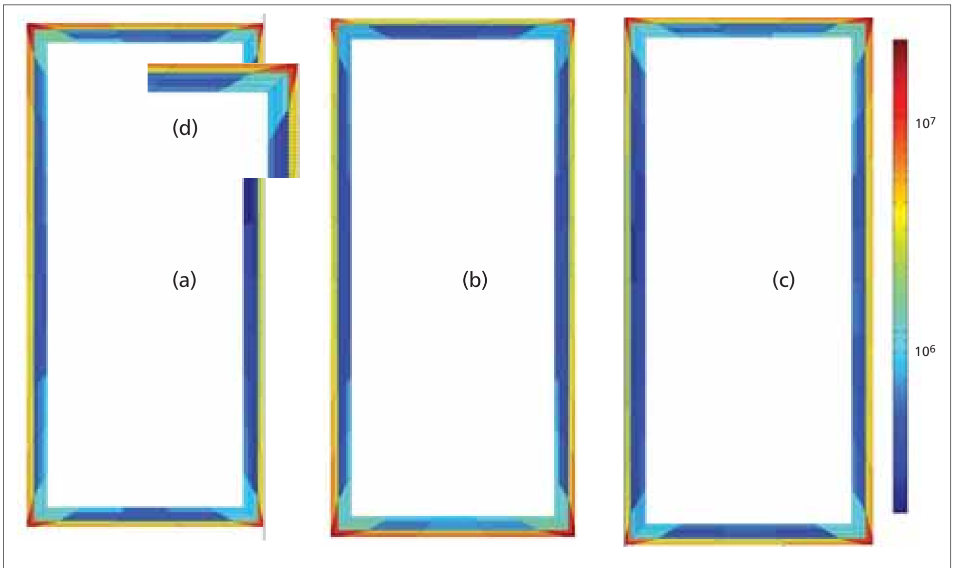
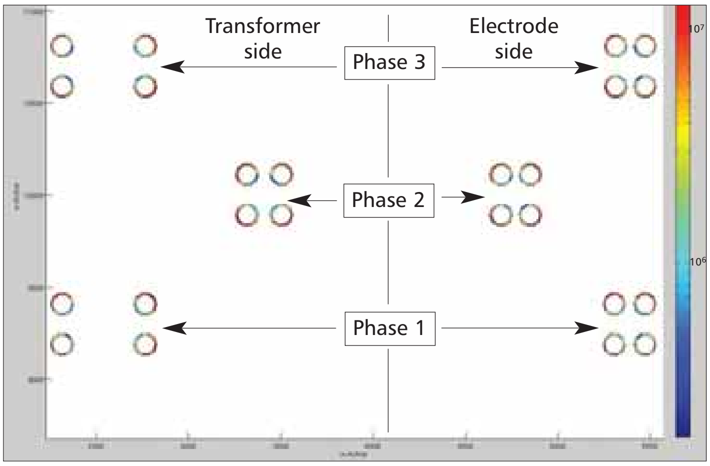


Fig 3 (a-d) Current density distribution in cross-section of each electrode arm at similar locations. Log scale: (blue) $1x10^5$ A/m^2 – $2x10^7$ A/m^2 (red)

Power & energy densities

The FNM system was used to calculate the power distribution for the furnace configuration previously described.

The power density is proportional to the square of the current density and thus the power density ratio for the high current system of this furnace reaches values of $1:10^{14}$ based on the current density ratio of $1:10^7$. These large local variations in current density lead to very large local power density values which may cause problems due to local over-heating.



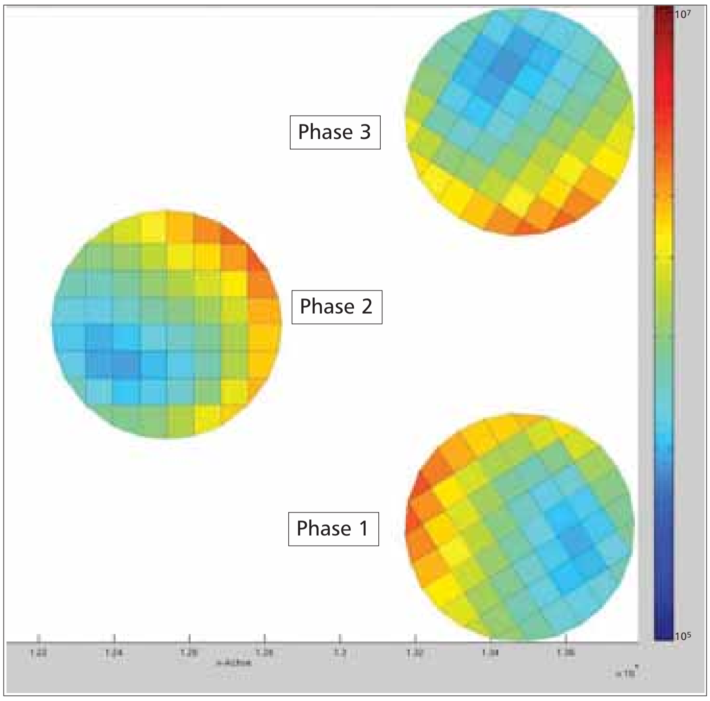


Fig 4 Current density distribution in the four flexible cables per phase; section parallel to electrode arms below the connection of cables with conductors and electrode arms (left transformer end; right electrode end)
Log scale: (blue) $2x10^5$ A/m^2 – $2x10^7$ A/m^2 (red)

Fig 5 Current density distribution in the three electrodes at cross sections selected at the mid-length of each electrode
Log scale: (blue) $1x10^5$ A/m^2 – $1x10^6$ A/m^2 (red)

All conductive material surrounding the high current system is subject to induced eddy currents generated by the time variant fields. These eddy currents are magnetically coupled to the impedances of the high current system and thus influence the electrical behaviour of the furnace. They also generate considerable heat losses which up to now have not been calculated nor considered. Subject to these eddy current heat losses are the furnace shell with the water cooled panels, the roof, the off-gas elbow and all metallic materials close to the high current system. Very high current densities lead to hot spots that can reach temperatures that visibly glow.

For the first time it is possible to calculate the current and power density distribution and thus the energy-loss-distribution of all the elements of the furnace periphery and also of all the conductive elements. Here the influence of these losses on the impedances can be simulated and accordingly measures taken during design to reduce such undesired influences.

It is known that temperature fields can be simulated by means of electrical networks. The FNM system generates an electrical network to determine the current density distribution. Therefore it provides an ideal starting point to combine both fields in order to determine the temperature distribution of the furnace parts of interest based on the power density distribution.

Impedances & inductances

The impedances are the most important properties of an arc furnace. They rule the electrical operating behaviour of the furnace and also influence how economic the melting process is.

In general, the inductivity depends on the spatial permeability distribution, on the current density distribution of conductive loops and on the geometry of these loops. The accurate calculation of the inductances considering these factors has not been performed for arc furnaces by others to date because of the high complexity involved. Analytical and conventional numerical calculations do not yield usable results because they depend on physical and geometrical simplifications.

As a result of such inaccuracy in calculations sometimes costly reactors are installed to increase furnace inductances which are too low and additional loops are installed on the middle phase power supply to improve symmetry.

This can be avoided if the inductivities of the arc furnace are accurately calculated in the design phase to optimise the overall furnace configuration.

The FNM system enables all important electromagnetic properties of the high current system to be determined and also that of surrounding metallic parts (including taking into account skin –and proximity effects).

The FNM calculation was applied to several furnaces and the calculated results were found to be highly accurate. The results are not presented here for space reasons.

EMF distribution & momenta

Accurate electromagnetic force (EMF) and momentum calculations are only feasible when applying a three-dimensional field calculus. Approximated calculations which neglect important effects do not lead to useful results.

Under the influence of magnetic forces caused by the currents in the electrodes the electrode-arms move in axial and lateral directions. Furthermore bending momenta and torques act on the mechanical system caused by asymmetric current density distributions.

These effects have not been considered to date by others. Oscillations in the arms and electrodes influence regulation of the position of the electrode which can lead to increased electrode consumption (breakages, loss of nipple, etc). Nevertheless these oscillations have not been considered in their full complexity so far.

The electromagnetic forces and momenta are also the cause of movement of the high current cables. The connecting points (on both sides) of the cables are subject to shear-forces which can also twist cables if they are strong enough. The root cause of these excentrical acting forces are the skin – and proximity effects. The forces can be accurately calculated with the FNM system.

Electromagnetic compatibility (EMC)

The high currents used in arc furnaces generate strong magnetic fields. People and electronic equipment close to the furnace are exposed to these fields.

The FNM system allows the fields (field strength, magnetic flux density) to be calculated in the areas adjacent to the furnace, such as the control room. Based on the results protective measures can be taken.

FNM to plan & modify furnaces

Planning and modification of a furnace is restricted by several criteria. To avoid hot spots, the current and power density as well as branch currents should be ideally equal at all points of the high current system. Impedances should be symmetrical, have minimal dependence on the position of the electrode arms and be small but retain a minimum value. Other criteria are not considered here. Many different requirements have to be considered, containing degrees of freedom such as the furnace geometry. The FNM simulation of the alternatives yields the best solution for the construction of the high current system, considering all criteria and physical effects. The FNM system does these calculations in approximately 50 minutes per run using a normal desktop computer. An optimised algorithm to increase the speed of the calculations has already been developed and awaits implementation.

Measurements for arc furnaces

To determine the real arc power and radiation/wear index measuring the arc voltages and currents is crucial. Measuring the arc current is comparatively simple using standard high current detectors. In contrast, to measure the real arc voltages is much more difficult and only possible in an indirect way.

The author has developed an instrument that enables the arc voltages and other relevant values to be determined. The system has 15 galvanically separated inputs with differential amplifiers to measure the secondary voltages of the three electrode currents (via Rogowski coils or current clamps), generated by the three primary voltages.

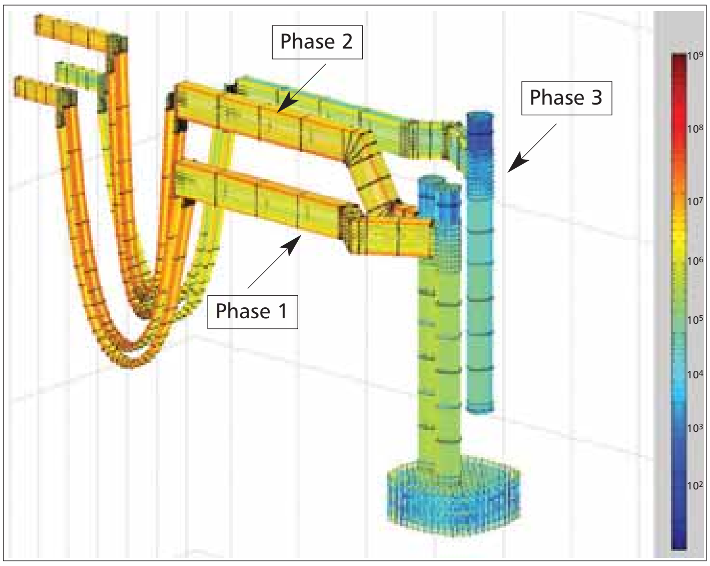


Fig 6 Three dimensional current density distribution at one-phase short circuit calculation (only phase 1 and 2 are carrying current) Log scale: (blue) 1x10^2 A/m^2 – 1x10^9 A/m^2 (red)

It has a further six inputs to record other values of interest, eg position of electrode arms.

All 15 secondary voltage values are measured in real-time to derive the RMS average and other relevant values. The measured data is stored on CF memory cards and can be exported via an USB port. Thus further evaluation of the raw data is possible using analysis software. The memory of the cards is sufficient to store 15 input signals over four hours using a 100μs sample time. Alternatively, the card can be used to record a long term measurement over a month using a sample time of 20ms. The instrument is portable and weighs only 4.7kg.

Fig 7 a-c shows the real-time measured arc voltage and current for the three phases.

Combining FNM & measurement for long-term arc voltage

Indirect measurements of arc voltages can only be carried out after the data for the equivalent circuit of the furnace has been determined using short circuit tests.

These characteristic values remain constant for only a short time after these dip-tests as they depend on the geometry which in turn depends on the operating conditions. Thus long-term indirect measurements of arc voltages are not possible due to the changing conditions of the arm positions.

To overcome this problem, the FNM approach can be used to calculate the impedances of the high current system depending on all possible arm positions, fault voltages and/or electrode lengths.

These values can then be tabulated and the table used to control the furnace. Combining the measured and tabulated calculated results can then be used to determine the arc voltages, arc powers and wear index in a continuous manner.

As a result real-time optimisation process control is possible because the arc voltages are the determining parameters of the electric arc furnace. This approach was previously impossible.

Flicker and harmonics

Measuring the continuous arc voltage establishes new possibilities to measure other relevant quantities of the furnace in the same continuous manner. Arc voltages are the basis of flicker and harmonics in the line supply and once measured can be used to further analyse these phenomena and develop measures for mitigation of these disturbances.

Also measuring the reactive power can be performed more accurately and be more effective based on the arc voltage determined and so could improve reactive power compensation. ■

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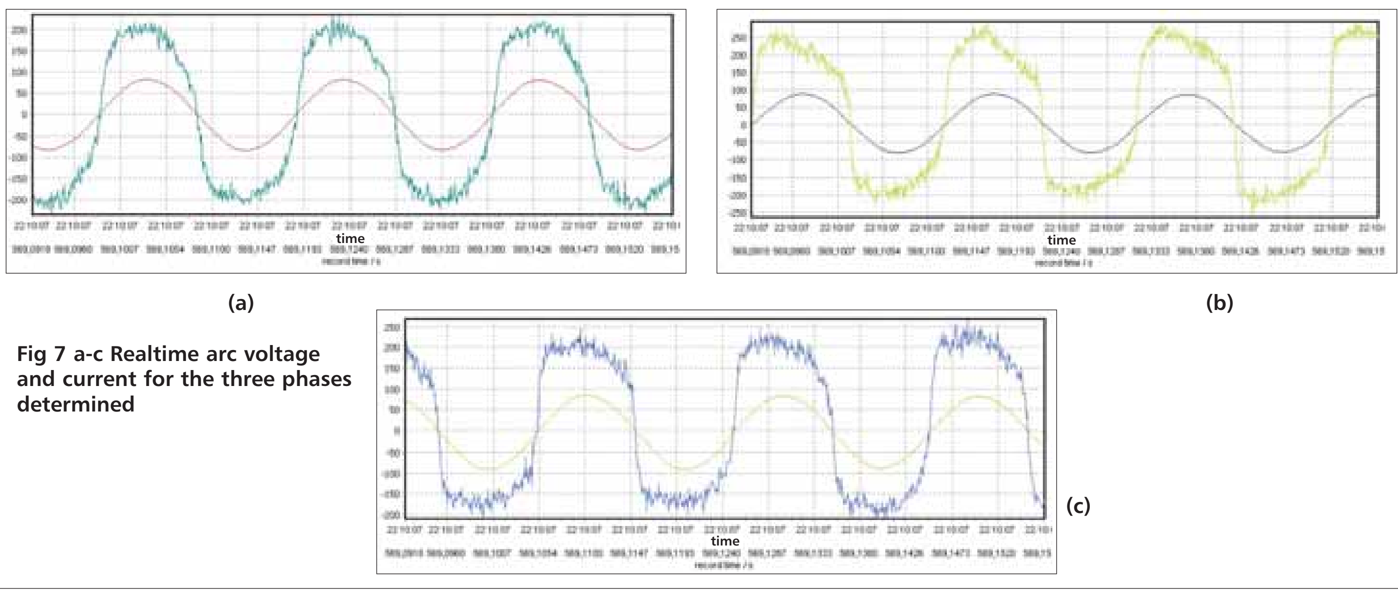

Fig 7 a-c Realtime arc voltage and current for the three phases determined