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The Network Analyser - Solving Electrical Networks in the "Olden Days"

By David Hutton

The sad death of member Roger Christy in January 2015 reminded me of my time operating the AC Network Analyser at Electricity House in Bristol in the mid-1960s.

Planning and Technical Engineers needed to carry out load flow and fault level calculations to plan and design high voltage electrical systems and to set up protection systems to secure the network in the event of faults.

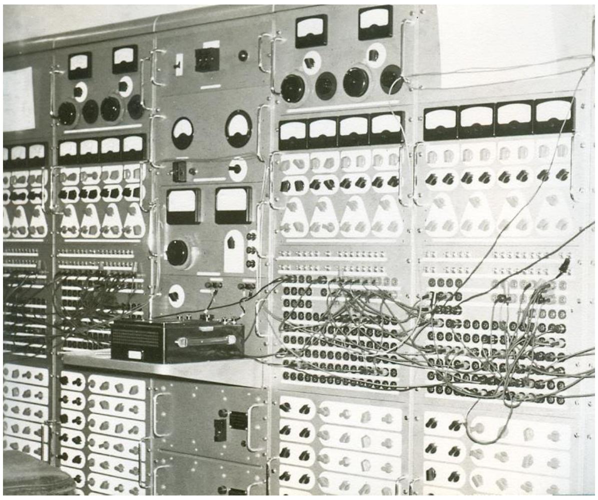
For radial low voltage and 11kV systems this is quite simple and Ohm's Law will enable power flows, losses and fault currents to be easily calculated. Interconnected networks at 33kV, 132kV and above is another matter, with active (MW) and reactive (MVAr) power flows to be taken into consideration. Nowadays, powerful computer programs are available to carry out these calculations, but 50 years ago, computers were in their infancy and did not have the capacity to carry out the complex calculations required. This is where the Network Analyser came into its own!

The Analyser was basically a means of making a model of an electrical network, to apply model loads and to measure the model current flows. In the early days the network analyser was of the DC type with all impedances represented by resistors and a DC voltage was applied to the model network. The currents flowing in the model network could then be measured and scaled up. This type of analyser would give reasonable results as long as the X to R ratio of all the lines etc, were of the same order.

As time went by more sophisticated analysers were developed until a full AC Network Analyser became the norm. These were of two types, either direct impedance or conjugate impedance. In the direct type, resistance on the system is represented by resistance on the analyser, inductance by inductance and capacitance by capacitance. In the conjugate type resistance is represented by resistance but inductance on the system is represented by capacitance and capacitance on the system is represented by inductance.

The SWEB AC Network Analyser was of the conjugate type and operated at 50 hertz. The advantage of the conjugate type was that it saved space as a capacitor unit was smaller than an inductor unit to give the same reactance. On the 132/33kV networks to be studied, very few shunt capacitance reactance units needed to be represented. Although the phase shifts would be different from a direct impedance analyser, the metering on the analyser would allow for this.

On a Network Analyser the impedances of lines, cables, transformers and generators are represented by line units which can be calibrated in per unit values to represent the R and X values. Per Unit values are explained later on. Similarly, power system loads are represented by load units which can be calibrated in per unit to the relevant P (MW) and Q (MVAr) values. Each load unit had a built in tap changer so that the load can be kept constant during a network study. The SWEB analyser had 48 line units and 20 load units. To complete the system the analyser had 4 generator units, 8 auto transformer units, 8 shunt susceptance units and a large patch board so that all the units could be connected together to form a model of the power network. The analyser was fully metered and volts, amps, power and reactive power could be measured at any point on the system. It was physically large and took up a room on the ground floor of Electricity House.



To carry out a network study the first thing to do was to convert all the network constants to per unit values. Per unit values are explained later on. The benefit of using per unit values is that transformer ratios can be neglected. The relevant line and load units are then calibrated and connected to form the network. In the case of load flows, the current and P and Q flows can be measured and tap change positions noted to keep busbar voltages at the required value – 33kV or 11kV.

A set of readings would be taken for the normal operating condition and then for various outage conditions. The results would be recorded on a system diagram. The removal of a transformer or circuit may affect the busbar voltages and so transformer taps would be adjusted to bring the voltage back to the required value. Further sets of readings would be taken for each possible system configuration. The results of a simple load flow study are shown in the **Appendix**.

In the case of fault studies, fault currents and busbar voltages can be measured and also phase angles. Asymmetrical fault studies can be carried out by setting up the symmetrical component networks and measuring the symmetrical component voltages and currents.

This was a very time consuming exercise. It could take at least a day or so to calibrate and connect all the units to represent a large 132/33kV network. It would then take about half an hour to set up and take a set of readings for each operating condition. Assistance was usually provided by a Student Engineer as part of their Head Office training as I had done some years earlier when Mike Tuckett was in charge of the analyser.

The Network Analyser was a great teaching tool as you could get a "feel" of a network and see how it responded to various network conditions. You were able to "tweak" tap changers and see how that affected power flows, in particular reactive power. Something you can't easily do with a load flow print out from a computer.

Alan Kitley took my place as the operator and then as computers became more powerful the Network Analyser became redundant and it was moved to the Redland Training Centre and then I think it was given to a Technical College. We then used the CEGB set of Power System Analysis programs via a link to their computer system in London. Now it can all be done on a lap-top!

So why did Roger Christy's passing remind me of my days in the analyser room? As I have explained, it took some time to carry out the system studies and so the Planning or Technical Engineer who wished to study a network would come to Head Office to be involved with the studies, view the results and then make changes to the network as thought necessary.

In the case of load flow studies he would already have some idea of a possible reinforcement to relieve a system overload, such as an extra 33kV circuit or additional 33/11kV transformer. These new items could be added and fresh load flow studies carried out. New system demands could be added to represent future loads taken from the load estimates and to see when the next stage of reinforcement would be required.

As Roger worked in Cornwall Group as a 33kV Planning Engineer he would send the network parameters to us and then when we had set up the analyser, he would come to Bristol to work with us and probably stay for a week. This was the start of a long friendship of some 50 years.

Per Unit Notation – read at your peril!

All power system problems are solved using per unit or percentage notation, for example 0.2pu or 20%. That is, all impedances of lines, cables, generators, transformers and loads are brought to a common base. At first sight it seems rather stupid to alter all the line constants to a system from ohms to a dimensionless quantity and then to use the same network equations as if real ohms had been used in the first place.

However if we look a little more closely at per unit notation, two base quantities are used. One is base MVA, usually 100 and the other base is taken as the voltage at which the relevant part of the network is operating – 11kV, 33kV, 132kV.

If the base voltage is V_{ph} and a voltage V that has been measured is to be represented in per unit form, then:

$V_{pu} = V/ V_{ph}$

If the base MVA is G and the base voltage V_{ph}, the base current can be calculated as:

$I_{ph} = G/(3xV_{ph})$ and hence per unit current is given by:

$I_{pu} = I/ I_{ph}$

Similarly for impedances – $Z_{pu} = Z/Z_{ph}$

Now

$Z_{ph} = V_{ph}/I_{ph} = V_{ph} \text{ x } 3xV_{ph}/G = V_{line}^2/G$

$Z_{pu} = ZG/ V_{line}^2$

Similarly for R and X.

For most networks a base MVA of 100 is used.

So for an impedance of 10 ohms at a base line voltage of 33kV and a base MVA of 100

$Z_{pu} = 10x100/33^2 = 0.918$

Apart from the ability to alter the effective size of numbers, there seems little advantage in using per unit notation. However, the real advantage becomes evident when power transformers are considered. If per unit notation is not used, then care must be taken to ensure that the turns ratio of the transformers is taken into consideration.

Consider a 33/11kV transformer of impedance one ohm supplied from an infinite source and supplying a line of impedance one ohm and on the end of which is a 3-phase short circuit. For simplicity, the impedances are taken as resistive.

To find the 33kV fault current using real ohms we need to know the total impedance of the circuit. This will involve "reflecting" the secondary impedance through the transformer. Hence the total impedance is

$1+1x3^2$ = 10 ohms and the 33kV phase current is 19,050/10 (V_{ph}/Z) = **1,905 amps**.

Using per unit notation at 1 base of 100MVA the per unit impedances are:

Primary impedance = $1x100/33^2$ = 0.0918

Secondary impedance = $1x100/11^2$ = 0.8262

Total per unit impedance = 0.918

Per unit fault current (V_{pu}/Z_{pu}) = 1.0/0.918

= 1.09

At 33kV 1.0 per unit current = 1,750 amps

Fault current = 1,750x 1.09 = **1,905 amps**.

Hence by using per unit notations, transformer ratios can be neglected and in complex networks this is of great use.

A Confession!

You may wonder how I have remembered all this after 50 years. Well back in 1967 I was the Chairman of the Graduate & Student Section of the IEE in Bristol and the first talk of the season was always the Chairman's Address and so I wrote a paper called "Solving Electrical Networks". It covered more than that covered in this article and was published in the IEE Student's Quarterly Journal in December 1968 and I still have copies. If you were a Student Engineer around that time you may still have a copy!

Other operators of the Network Analyser you may know or remember were:
Mike Tuckett, Barry Poole & Alan Kitley.
Barry went on to operate the CEGB analyser in Bristol which was of the "direct type", operating at high frequency and this reduced the size of the inductor units.
Mike Tuckett went on to set up the Engineering Computer Team and later on, I and David Peacock joined him.

Appendix

Typical Results from a Load Flow Study

Two 132/33kV substations operating in parallel through a simple 33kV network

The second study show the changes in power flows following the loss of a 60 MVA transformer

I = amps, P = MW, Q = MVAr and G = MVA