Substation Automation

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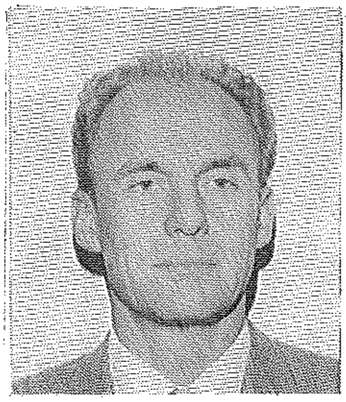

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SUMMARY

Integrating all the control and monitoring functions of a substation into a single, computer-based system offers a significant increase in performance-to-cost ratio over hard-wired systems using descrete components. However, to realise this increase, a certain rethinking of substation design is necessary, and this paper discusses the various changes involved. The essential point is that, in order to obtain the full benefit from substation automation, the user must accept a fairly rigid framework as far as the equipment design goes. In addition to these general aspects, the paper also describes the main features of a recently developed system.

1. INTRODUCTION

The term "substation automation" encompasses two different aspects of substation control. On the one hand, it means the automation of certain control or supervisory functions that were previously carried out manually, such as restoring operations as far as possible after a failure or switching transformers in and out of service according to the loading conditions. But, on the other hand, it means the integration of all control and supervisory functions into a single piece of equipment and executing them within the framework of a data processing system. Thus, substation automation will take on the characteristic feature of all data-processing systems, namely, that the hardware provides a standardized framework, within which the functional flexibility is provided by software. This requires a certain rethinking, almost a change of philosophy, as far as substation design goes, and it provides a point of departure for some very promising developments, both in the design methods and in the actual construction of substations, and these will be the subject of this paper.

However, it is worthwhile to first consider the general implications of going to a data processing based system. Everyone is aware of the fact that raw computing power is becoming less expensive every year, whereas software costs seem to remain about constant, thus shifting the cost of data processing towards the software. And the accepted reason for this is the ever-increasing scale of integration and thereby lower production cost, per function, of microelectronic circuitry. But there is another reason, which is often overlooked, and that is the relative degree of standardization accepted in hardware and software. In commercial computing, where the cost decrease has been most dramatic, there is almost total acceptance of standardized hardware. Nobody would think of specifying to a computer manufacturer how his equipment should be wired or assembled mechanically, or even what colour it should be painted.

In industrial applications the acceptance of standardized hardware is, on the average, much smaller. Instead of being concerned with specifying the performance of his system, the user gets involved in telling the manufacturer how to achieve that performance. And in many cases the user fails to perceive the system aspects at all, and goes right into specification of separate parts of hardware. The result is increased cost and/or poorer overall performance.

In order to reap the full benefits of a software-based control system, the user will have to accept a much higher degree of standardization than is presently the case. This may seem an intolerable imposition on the prerogatives of the substation design engineer, and a first reaction is often to assert that the requirements placed on a substation are so varied that each substation demands an individual design. This paper will show that most requirements can indeed be satisfied within a standardized system, and that the acceptance of such a system does not restrict the creativity of the substation design engineer. On the contrary, it relieves him of a lot of tedious detail work and allows him to concentrate on the much more important system aspects.

2. SUPPORTED FUNCTIONS

Before going further, it is useful to have a clear picture of what functions are included within substation automation as it will be treated in this paper. And in that respect it is important to note that the protection functions are not included. They form a separate system, and operate completely independently of the control system. No matter what happens to the control system, or even if it is taken completely out of service, the protection functions remain unaffected. The protection system sends some signals to the control system, e.g. for event logging or secondary circuit breaker back-up protection, but it does not require any signals from the control system.

In order to satisfy a range of requirements, the control system must be of a modular design. The modularity of the hardware allows for varying substation size, and the modularity of the software allows a choice of functions. Some functions are, however, always present; these constitute the Substation Management Program and are

- Data base updating. All the inputs are scanned, and the data stored in a data base, to which all other functional modules have access. Some inputs, such as circuit breaker status or protection trip signals, are scanned at a high rate, others, such as measured values, are scanned at a lower rate.

- Module control. This part of the program calls the various functional modules as required. It senses changes of state, keeps track of elapsed time, etc.

- Man-machine interface. The system uses a VDU and a simple, functional keyboard to give an operator manual control during service or testing. This replaces the traditional control panel with its switches, pushbuttons, lamps and instruments.

A range of functions are available as software modules, they can be implemented at any time simply by loading the corresponding software:

- Measured values display. In order not to clutter up the single-line diagrams used with the cursor control to operate the various devices manually, all measured values are displayed in tabular form. The grouping and format may be chosen to suit individual tastes.

- Tap-changer control. Voltage control with line-drop compensation.

- Auto reclosing. Single-shot, 100-500 ms time delay, 5-20 s lockout period.

- Loadshedding and gradual restart. Using the input from a frequency transducer, this module can shed groups of feeders at pre-set underfrequency thresholds and restore them whenever the frequency recovers. After a total power failure, the feeders are restored sequentially.

- Loss minimisation. Disconnecting parallel transformers under low-load conditions.

- Thermal load calculation. At high overload conditions, up to 190% of rated load, the temperature distribution within an object such as a transformer or a cable can differ appreciably from its steady state value. The software module calculates the temperature of the most critical points, allowing a maximum economic utilization of the plant.

- Secondary circuit breaker back-up protection. Using the circuit breaker status information to check if a tripped breaker has actually opened after a certain time interval, this function provides a reserve for the normal, current controlled back-up protection.

Finally, some functions require both hardware- and software modules and are therefore called subsystems:

- Sequential event recorder. Up to 256 digital inputs are sequentially scanned and checked for change of state. To each input an alarm and a normal message are allocated which are output together with date and time when the relevant change of state occurred. The time resolution is 100 ms.

- Data logger. Records preselected data on magnetic tape at fixed time intervals.

- Capacitor bank control. Provides power factor correction by switching up to eight capacitors, arranged in two banks of four. The switching routine can be either time-of-day or closed loop VAr control.

- Telecommunication. This facility provides data communication with any remote station using a voice frequency channel.

3. SUBSTATION STRUCTURE

Basically, every substation contains some arrangement of high-voltage equipment, consisting of circuit breakers, isolators and busbars, followed by one or more transformers, and then a similar low-voltage arrangement. ("High" and "low" are, of course, used only in a relative sense.) To the high-voltage equipment are connected a number of incoming lines, and to the low-voltage equipment are connected a number of outgoing lines, as shown in Fig. 1. All of these will be called feeders.

It is now an important assumption of this whole scheme that a universal arrangement can be found which will encompass all substation configurations which are in use in Australia. This assumption allows the cost of producing the software for any particular substation to be reduced dramatically, as will be discussed below. But note that the hardware is not affected by this assumption, nor will it reflect the type of arrangement chosen.

In deciding upon a suitable universal arrangement, one is confronted with four partly conflicting requirements:

(a) Capacity, i.e., the number of feeders and transformers which can be accommodated.

(b) Expandability. If feeders or transformers, which were not anticipated at the time of the original design, have to be added, then it must also be possible to just add to the control system without changing the existing part.

(c) Flexibility. Various configurations, such as single and double busbars, 1½ breaker, etc. shall be included.

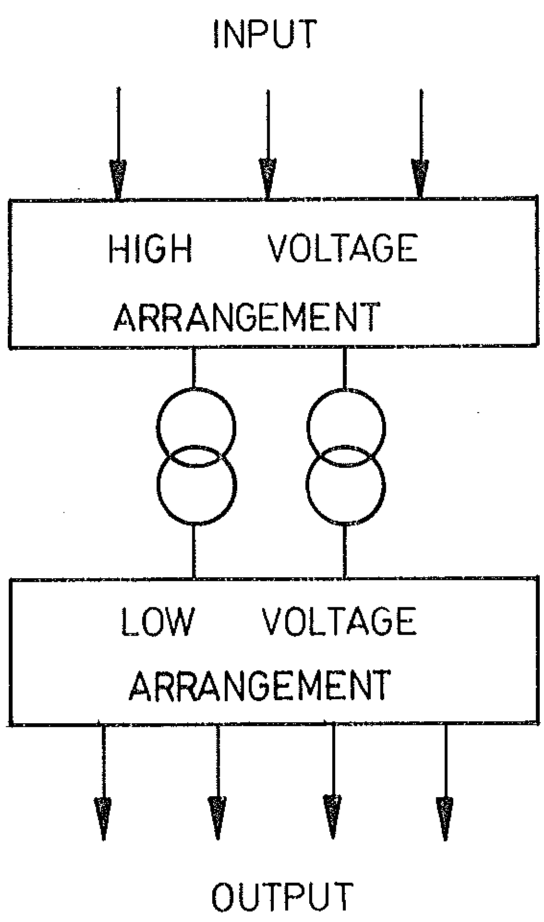

Fig. 1 Basic structure of a substation

(d) Cost. The greater the complexity of the universal network, the larger the data base, which in turn will result in a costlier system for equal performance.

In order to satisfy the expandability condition, the arrangements are divided into four sections each, and a single transformer can be associated with each pair of sections, as shown in Fig. 2. On the left-hand side of each section bus couplers are available; the ones on the extreme left can be used to couple the upper and lower bus within one section. A single section has the structure shown in Fig. 3. The elements are arranged in the form of a matrix with letters designating the rows and the columns numbered from 1 to 4, therefore such a section is called a Basic Matrix.

The choice of the Basic Matrix is a compromise between cost and flexibility. All the usual substation configurations can be realized by declaring each circuit breaker and isolator either permanently open, permanently closed, or implemented as actual device. A special schedule, shown in reduced size in Fig. 4, is used to record the configuration. But there are configurations which can not be realized with this Basic Matrix: one such is shown in Fig. 5.

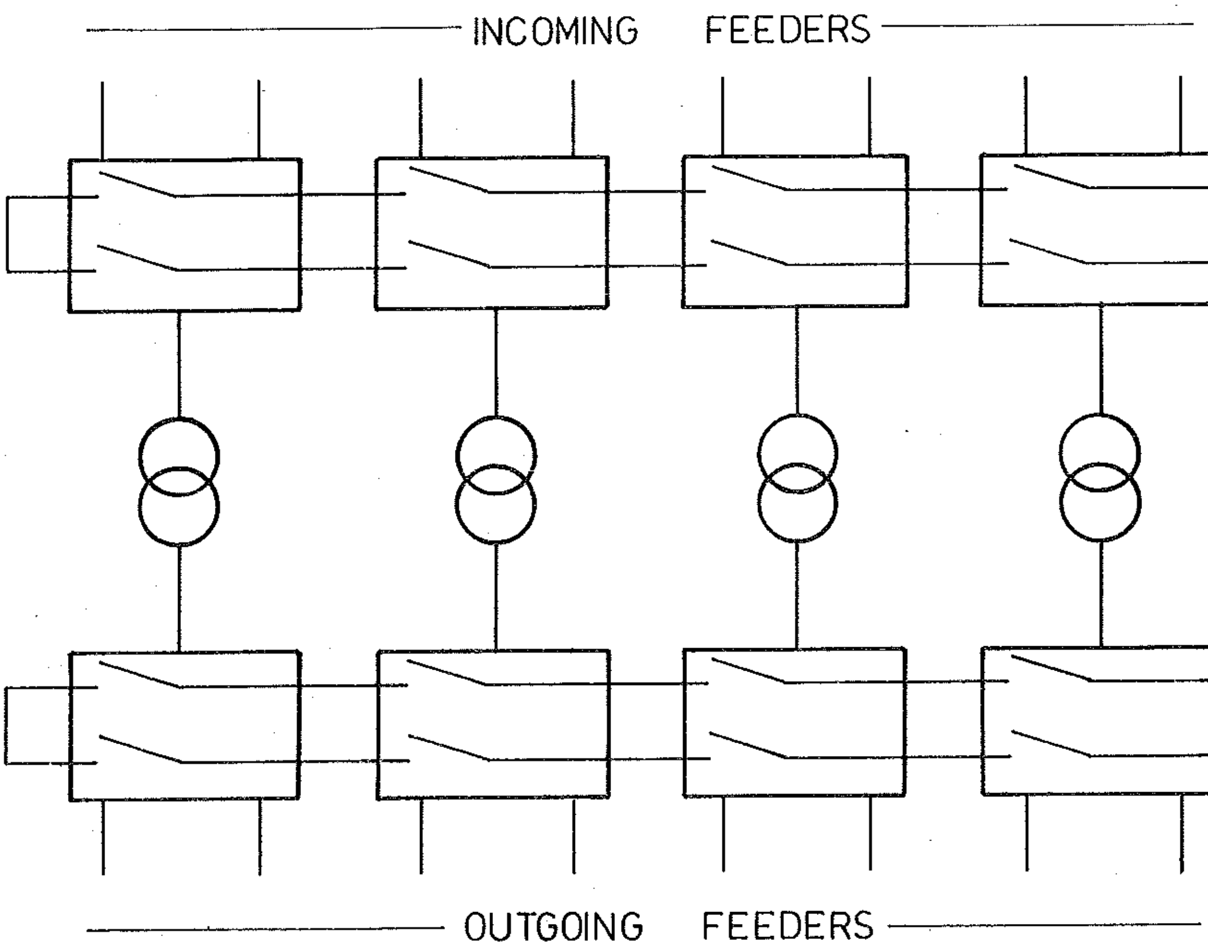

Fig. 2 A substation is divided into eight basic matrices and four transformers

4. INPUT/OUTPUT REQUIREMENTS

In order to carry out the functions listed in Sec. 2, the substation automation equipment requires a certain number of inputs and outputs. These are related to the various object types. In addition, the equipment accepts up to 256 alarm inputs from any device which the user wishes to monitor. But it is not possible to add any further inputs or outputs, or to have inputs or outputs with a different meaning or function. The I/O-structure is absolutely rigid.

The I/O-requirements for the individual object types are as follows:

Circuit breaker:

3 digital inputs (open, closed, ready)
2 digital outputs (trip, close)

Isolator:

3 digital inputs (open, closed, earthed)
2 digital outputs (open, close)(only if motorized)

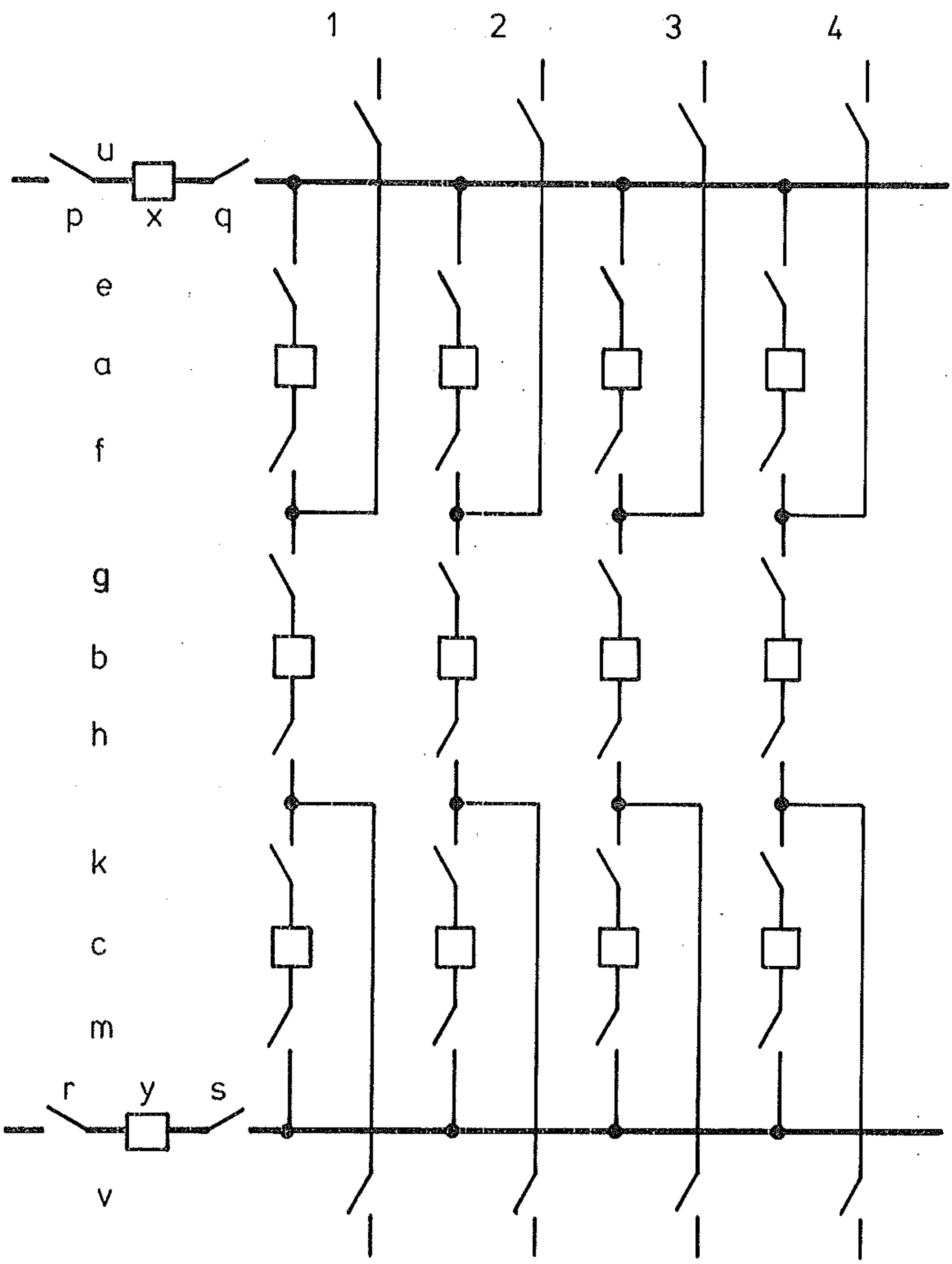

Fig. 3 Structure of a Basic Matrix

Transformer:

5 digital inputs (32 tap positions)
2 digital outputs (raise, lower)

For each Basic Matrix implemented, 32 inputs are reserved for protection signals, and the following analog inputs are available:

BBC BROWN BOVERI	BESAP Configuration Schedule Substation:	PROCONTIC DP 800

Basic Matrix No.: Date issued:

Issued by:

Circuit breakers

Pos.	0	C	I	No.
x				
a1				
a2				
a3				
a4				
b1				
b2				
b3				
b4				
c1				
c2				
c3				
c4				
y				

Isolators

Pos.	0	C	I	No.
u1				
u2				
u3				
u4				
p				
e1				
e2				
e3				
e4				
g1				
g2				
g3				
g4				
k1				
k2				
k3				
k4				
r				

Pos.	0	C	I	No.
q				
f1				
f2				
f3				
f4				
h1				
h2				
h3				
h4				
m1				
m2				
m3				
m4				
s				
v1				
v2				
v3				
v4				

BROWN BOVERI CONTROL SYSTEMS

Fig. 4 Configuration Schedule

14	Current
5	Voltage
4	Real power
4	Reactive power
4	Phase angle
1	Transformer temperature
32	

All analog inputs must be in the form of current signals within the range -20 mA to +20 mA.

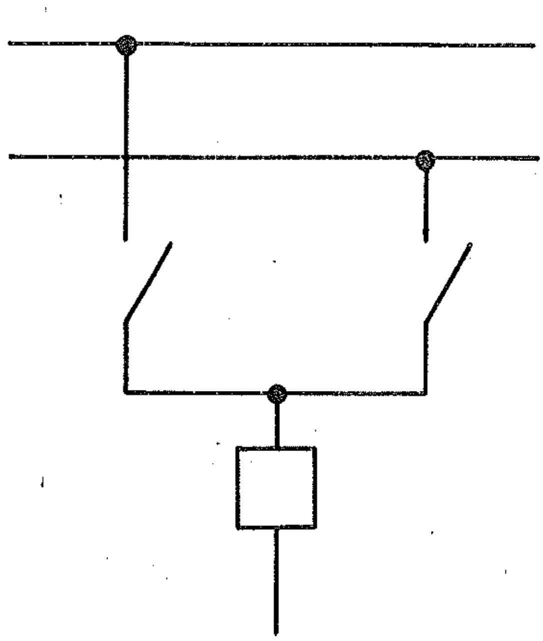

Fig. 5 Double busbar with single circuit breaker.
This configuration can not be realized
using the Basic Matrix in Fig. 3.

The input and output terminals are always ordered according to the following principle: The terminals belonging to a Basic Matrix are grouped together, and within such a group the order of objects is: Circuit breakers, isolators and transformers.

Within one type of objects the ordering is according to the objects' positions in the Basic Matrix, reading from left to right and top to bottom. The protection, alarm and transducer circuits are ordered according to the cabelling (See Sec. 6).

For the individual objects, the terminal arrangements are as follows:

Circuit breaker:

a	open	]
b	closed	] inputs
c	ready	]
d	common	]
e	trip	]
f	close	] outputs
g	common	]

Isolator:

a	open	]
b	closed	] inputs
c	earthed	]
d	common	]
e	open	]
f	close	] outputs (only
g	common	] if motorized)

Transformers:

```
a   LSB       ]
b             ]
c             ] tap position,
d             ] 5-bit input
e   MSB       ]
f   common    ]

g   raise     ]
h   lower     ] outputs
i   common    ]

j ]
k ] status signals
l ]
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All current loops:

a current in (+)
b current out (-)

Protection and alarm inputs:

Normally in groups of six inputs, with one common terminal per group, but otherwise according to the cabling.

5. MANUAL BACK-UP

If for any reason, such as testing, carrying out service work or extending the installation, the substation automation equipment is taken out of operation, there must exist some means of controlling the substation manually. Because this manual control facility is intended only as a back-up in those rare instances when the automation equipment is down, speed and convenience of operation is not important. The switching operations will be carried out according to a written schedule and/or might be individually authorized by telephone from a control centre. Consequently, the manual controls will be designed to be as simple as possible, with direct, immediate action, and without any hard-wired interlocking circuits.

Furthermore, the closer the manual control facilities (e.g., push-buttons, rotary switches) are to the devices being controlled, the better the back-up, in the sense that the automatic and back-up equipment have less circuits in common. From this point of view it is best to mount the manual control facilities directly on the devices, such as circuit breakers and tap changers. However, some users find it unsafe or impractical for the operator to stand next to a device when it operates, and prefer a central manual control facility. In this case a very elegant and cost-effective solution is to place an extra cubicle next to the automation equipment and looping the cabling from the I/O-modules to the terminals through the manual control devices, which are accessible from the front of the cubicle, and mounting the terminals in this cubicle. How this is done in the case of a circuit breaker control circuit is shown in Fig. 6.

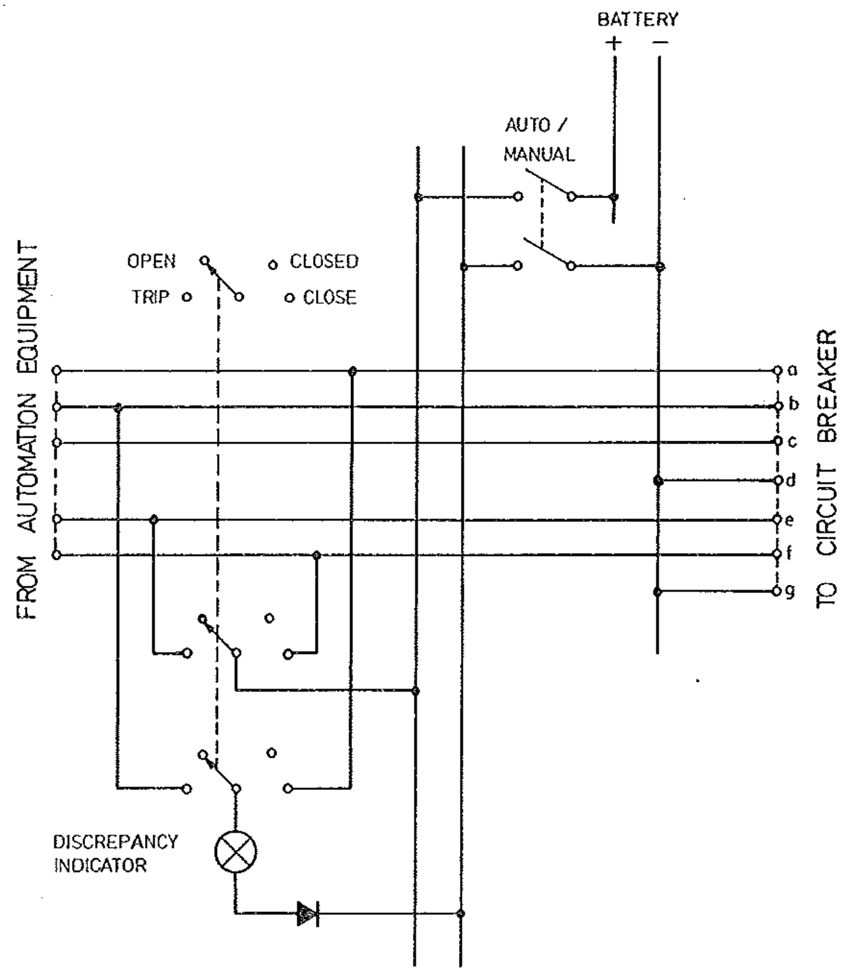

Fig. 6 Manual control of a circuit breaker using a discrepancy switch

6. CABLING

The simplification of the control cabling is an essential feature of substation automation. The savings realized by eliminating all the hardwired interlock and control circuits equals a significant part of the cost of the automation equipment. It includes not only the cost of the cable, but the cost of laying and terminating it, as well as the cost of producing the documentation for installation and maintenance.

Between the control equipment and a circuit breaker only 7 cores are required, and it is anticipated that these would constitute a separate cable, 7 x 1.0 mm^2. The same size cable would be appropriate for motorized isolators with earthing switches; in the case of manually operated isolators two could share one cable.

The control of a transformer tap changer requires a total of 9 cores. In addition, three status signals (e.g. ready, in progress, fuse blown) may be taken back to the control equipment, so that a 12-core cable, 12 x 1.0 mm^2, would be used.

The idea is now to use only these two cable types, as far as possible. Current signals from transducers and alarm or status signals from relays, limit switches etc. are brought back to the control equipment using a small marshelling box with 13 terminals. Various connection diagrams are shown in Fig. 7. This provides a very clear and systematic layout of the

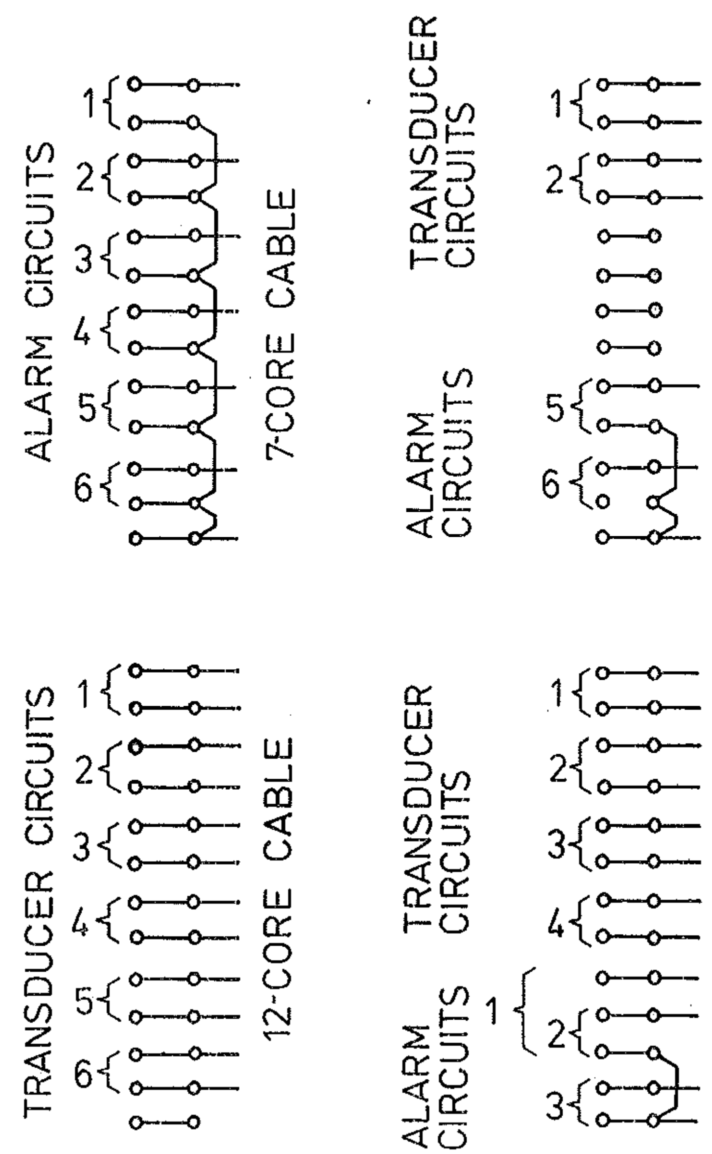

Fig. 7 Some typical marshalling arrangements, using the two standard cable sizes

control cabling, and the terminal assignments follow a set pattern. It also simplifies the documentation of all the cabeling and termination schedules; indeed, a large part of this documentation can be produced automatically by the same computer which assembles the software.

7. MAN-MACHINE INTERFACE

Although substations are unmanned, the requirements placed on the man-machine interface are, as far as data volume and manual interaction features are concerned, essentially the same as for a manned station, e.g., a small control centre. But the design of the interface is governed by some facts peculiar to substations.

- The interface is not used very often or for extended periods of time. On the one hand this means that operator fatigue is not an important problem; on the other hand it cannot be expected that the operator will remember anything but the simplest operating procedure from one time to the next.

- The operator will not be skilled in the operation of EDP equipment, he will normally be an electrician or a linesman.

- Changes in the software due to changes in the substation configuration are generated in another facility and loaded into the automation equipment in the form of firmware (see Sec. 8). No provisions for on-line modifications are necessary.

As all the acquired data is available within the processor, it is most efficient to use a VDU as the means of displaying it, selecting whatever section of the data is of interest at any particular time. All other forms of displays, such as lamps and instruments, are dispensed with.

Commands are given to the system by means of a very simple keyboard, as shown in Fig. 8. The five buttons on the right constitute a cursor control; depressing a key marked with an arrow makes the cursor step in that direction. At first slowly, and then faster, so as to allow a convenient and accurate positioning of the cursor. The centre key, HOME, just places the cursor in the upper left-hand corner of the screen.

The data is displayed in so-called "pictures". This may be an actual picture, such as a single-line diagram, or a table. The content of each picture will consist of two types of information, a fixed part which reflects the substation configuration, and a dynamic part which shows the present state or value of a set of variables. A picture is selected by means of a menu by typing in the number of the picture as given in the menu, followed by ENTER. Pressing the RETURN key will always make the Main Menu appear. The contents of the Main Menu will, to some extent, depend on what functional modules are implemented, but the following items are always present:

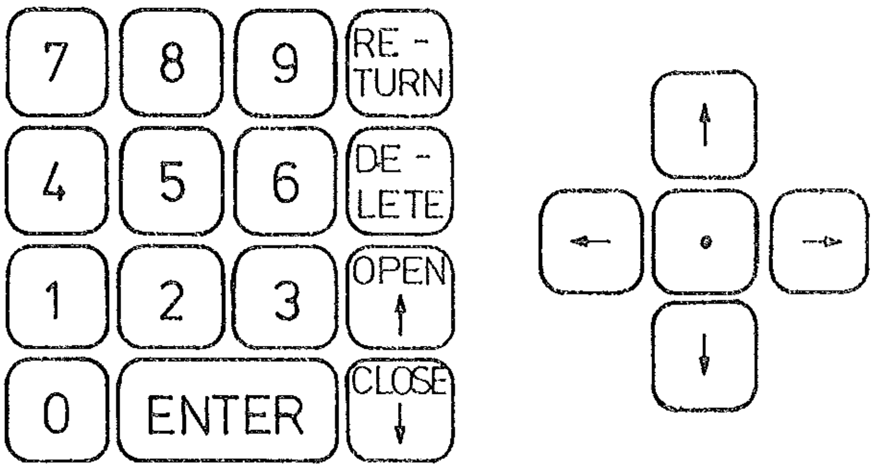

Fig. 8 Keyboard with cursor control

1. System Configuration
2. System Status
3. HV arrangement
4. LV arrangement

The System Configuration picture contains such information as the date on which the program was assembled, the number of Basic Matrices installed, and the number of the various objects implemented in each Basic Matrix. It also lists the functional modules installed.

The System Status picture displays that general information which is available through the Substation Management Program. this includes a list of all currently active alarms (only semi-dynamic, shows status at the time the picture was selected), a number which shows how many times the man-machine interface has been activated, and any error messages (e.g. input discrepancy).

The HV Arrangement picture displays a single-line diagram of the HV arrangement, showing the status of all circuit breakers and isolators in this arrangement. The dynamic information is updated on the average once a second, and by means of the cursor the objects in this picture can be controlled manually. To operate a circuit breaker, one guides the cursor onto the breaker symbol and presses ENTER. The symbol will then blink slowly,showing that the system is ready to accept a command, and if one then presses OPEN or CLOSE, the symbol will blink rapidly (indicating discrepancy) until a message is received that the operation has been carried out,at which time the symbol changes to its new state. The picture may also contain names or labels for feeders and circuit breakers,as well as a short message for the operator, but it can not contain any further dynamic information. Measured values are displayed in separate pictures (if this function is implemented).

The LV arrangement picture is functionally equivalent to the HV arrangement picture. In both cases it may be that the size of the arrangement exceeds that which can conveniently be displayed in a single picture. Then two or more pictures are used, and one moves from one picture to the next by positioning the cursor in the lower right-hand corner and pressing ENTER, and one can page backward by positioning the cursor in the lower left-hand corner and pressing ENTER.

Most of the functional modules have pictures associated with them, and in some cases one can change parameter values. An example is the tap-changer control function, where one can change the nominal voltage, dead-band limits, etc. This is done by positioning the cursor on the line in which the parameter occurs, keying in the desired parameter value and pressing ENTER. The keyboard does not contain a decimal point, so all parameter values have been scaled such that whole numbers can be used.

8. SOFTWARE GENERATION

In any process control application, the cost of the software constitutes a very considerable part of the total project cost. It is clear that substation automation, in the form described, will be cost-effective only if the amount of software which has to be written specifically for each installation is reduced to an absolute minimum. To achieve this result, a large part of the software has been written in the form of standard modules. For any particular installation the appropriate modules are selected and parametrized as and where required, and then linked together to form a complete program. However, there will always remain quite a bit of software which can not be prepackaged in this manner, for example most of the pictures. For this part of the software the aim must be to generate it in a largely automatic fashion, or,in other words, to develop some tool that will allow one to produce the software much more efficiently than coding by hand. As already mentioned, the key to this procedure lies in the fixed structure of the substation, which allows all the information about an installation to be expressed in tabular form.

Within the framework of substation automation, the design of a substation would proceed as follows: From considerations of predicted load, existing and planned network configurations, availability, etc., the design engineer will decide layout (e.g. double or single busbar), capacity (number and rating of transformers) and the number of feeders. It is important to give due thought to any expected expansions, because if these are highly probable and in a not too distant future, it is much more economical to implement the corresponding parts of the control system in the first stage rather than adding them on later. This information, together with information on number and location of transducers,alarm devices and protection inputs, is transferred into tables, an example of which was shown in Fig. 4. These tables completely define the substation as far as the substation automation is concerned, and they provide the interface between the design engineer and the software generation. The data is entered directly from the tables into a host computer, usually a PDP 11 with the RSX 11 operating system, where an interactive program carries out the following tasks:

(i) Generates the single-line diagrams
(ii) Prints a schedule of all external cables
(iii) Prints a table of all terminals
(iv) Generates the internal wiring schedules and a corresponding list of the required hardware modules
(v) Prints a map of the data base

This documentation is normally reviewed by the design engineer, and names or labels and a certain amount of text may be added. The first stage of the software generation is completed.

To proceed further, one must specify which functional modules are to be implemented. The corresponding software modules, which are stored in the PDP 11 in assembly language, are linked with the Substation Management Program, and the result is transformed into microprocessor machine language (or object code) by a cross-assembler. The object code is finally burned into PROMs or EPROMs, and these are loaded into the automation equipment. The final documentation, consisting of memory maps, flow diagrams and assembly language listings are also produced on the PDP 11, but only after the acceptance test has been carried out.

If, at a later date, it is decided to add a functional module, only step two has to be repeated. But if new, unforeseen objects are added to the substation, the whole generation process has to be repeated. However, due to the partitioning into Basic Matrices, the existing cabling and terminal arrangements will not be changed.

9. CONCLUSION

The substation automation system described provides a cost-effective alternative to present hard-wired systems under the assumption of an average substation complexity and that all the functions are realised within the integrated system. The latter requirement places certain limitations on the substation design, but it also offers all the advantages of standardisation, such as better documentation, higher transparency, reduced requirements on maintenance and operating personnel, and interchangeability of components between substations. From articles that have appeared in the technical literature in the last few years as well as from the extensive contacts we have had with electricity supply authorities on this subject,it seems absolutely clear that the development will go in the direction of an integrated, processor-based system, and we believe that the time has come to take a decisive step in this direction.