Relocatable static var compensators

Four relocatable static var compensators have been installed by ABB in the 400/275-kV power transmission network of the National Grid Company (UK). The installations, which have a dynamic rating of 0–60 MVAr and are connected to the 13-kV tertiary windings of existing substation autotransformers, are designed to maintain the stability and power transmission capability of the grid under varying network conditions. Transportation on standard road vehicles as well as easy site assembly is ensured by the compact, modular design of the RSVCs.

The ongoing deregulation of the power industry seeks to meet growing market demand for competitive electric energy. For this to work in reality, technical solutions in the power transmission sector must be very flexible. At the same time, operational safety and stability must be safeguarded under changing power system conditions.

Ever since the UK electricity supply industry was privatized in 1990, the National Grid Company plc (NGC) has been responsible for operating and maintaining the 400/275-kV transmission system in England and Wales as well as forecasting demand and scheduling generation to meet it.

The need for RSVCs

The concept of relocatable static var compensators (RSVC) was developed in response to NGC's need for system security and quality standards to be maintained under changing conditions that include just 6 months notification of generating station closure. The RSVCs are connected to the 13-kV/60-MVA windings of system transformers.

Static var compensators (SVC) have been used for many years in grids to improve power transmission conditions. The SVC works by providing dynamic compensation of reactive power, ie it generates and/or absorbs reactive power in a very fast and variable way to keep the grid voltage within the required limits under varying power system conditions. In this way, voltage levels can be held steady and transient stability achieved during any dynamic events that occur in the grid. The transmission of useful active power is safeguarded as a result.

ABB relocatable static var compensators were conceived precisely for this. The controls of the RSVC are inherently robust and able to adapt automatically, ensuring an optimum response under changing network conditions. By making the SVC relocatable, dynamic voltage support can be given wherever it is needed most in the power grid. When changes in the power market create a new situation, the static var compensators can be simply moved to the required location.

The NGC specified that the design should ensure genuine relocatability as well as low operational losses and low costs for the on-site civil works. Full relocation was to be achievable within a specified time-scale of three months.

A thyristor-switched capacitor (TSC) based design comprising individually transportable modules was chosen as being the best solution. This design enables the SVC to be moved around the UK on standard road vehicles, and at the same time ensures ease of disconnection and reconnection at the respective substations.

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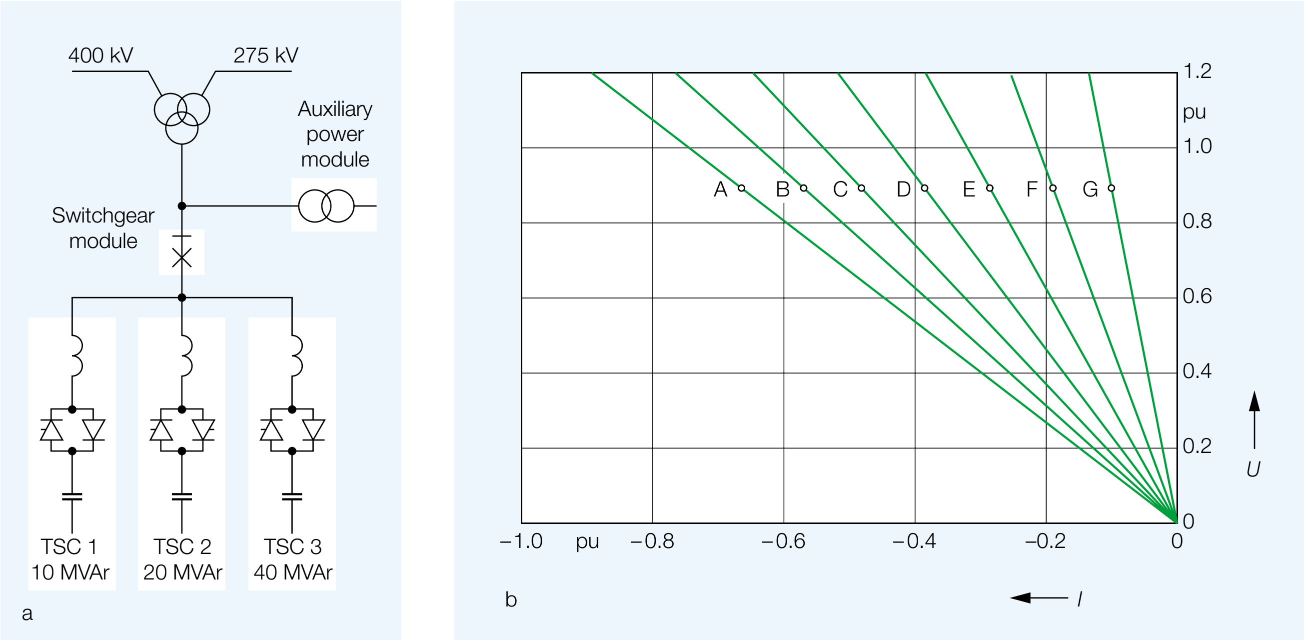
Modular design ensures true relocatability

The design chosen for ABB Power Systems' RSVC allows the complete relocation of an installation from one place in the grid to another in just a few weeks, depending on local conditions. Because it is modular, the RSVC can be transported on normal roads using standard vehicles.

The overall dynamic range of the RSVC of 0–60 MVAr is provided by three TSC branches, one each rated 10 MVAr, 20 MVAr and 40 MVAr, in a binary arrangement **1a**. Although the TSCs generate no harmonics themselves, detuning reactors have been installed to prevent the amplification of existing harmonics at the sites where the RSVCs are installed in the system.

The compact design of the RSVC is achieved with seven preassembled and transportable modules **2**, **4**:

- One switchgear module, mounted on an open steel frame. This module



Single-line diagram and U/I characteristic of the relocatable static var compensator for the National Grid Company, UK **1**

a *Single-line diagram* b *U/I characteristic (base: 100 MVA)* A–G *Operating points*

TSC1, 2, 3 *Thyristor-switched capacitor modules*

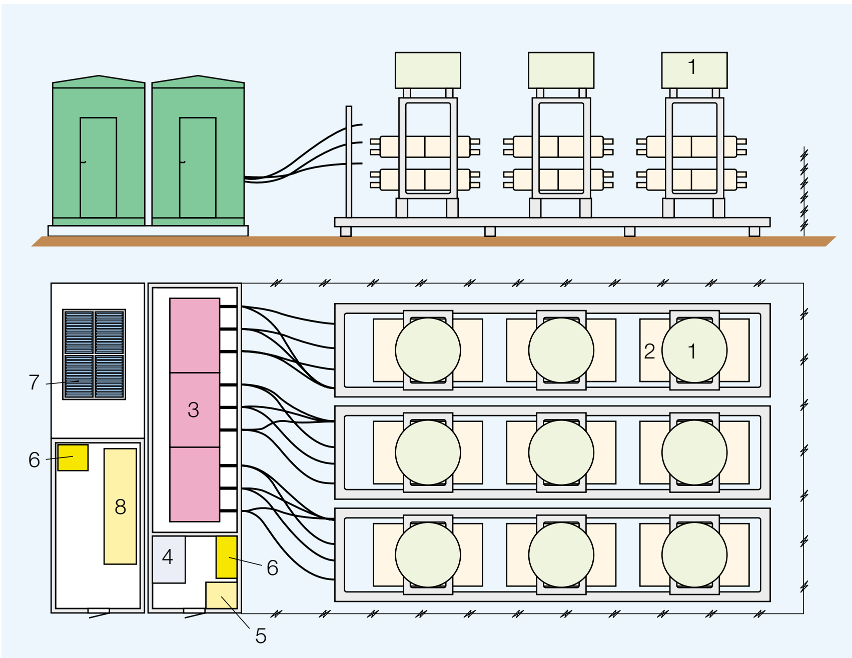
contains the 13-kV circuit-breaker and disconnector as well as measuring transformers and surge arresters.

- Three TSC modules, each mounted on open steel frames. These modules contain the capacitor banks and damping reactors.
- One thyristor valve module, housed in a prefabricated enclosure. This module contains the thyristor valves, valve base electronics and valve cooling equipment.
- One control module, housed in a prefabricated enclosure. This module contains the control, protection and DC distribution equipment.
- One auxiliary power module, housed in a prefabricated enclosure. This module consists of an auxiliary power transformer and the AC distribution equipment.

3 shows a TSC module ready for transport. The RSVC installed at the Penn substation is shown in **4**.

Modular layout of RSVC (excluding switchgear and auxiliary power modules) **2**

1 *Damping reactor*
2 *Capacitor bank*
3 *Thyristor valves*
4 *Thyristor cooling plant*
5 *Valve base electronics*
6 *Forced ventilation*
7 *Cooling towers*
8 *Control and protection*



RSVC TSC module ready for transport **3**

RSVC at the NGC's Penn substation **4**

Easy erection and commissioning

The modular structure of the RSVC greatly facilitates erection and commissioning work on site. The modular design also means that testing of a large part of the equipment and of the system as a whole can be carried out in the workshop, thereby minimizing the testing necessary on site.

The civil works is reduced to the concrete sleepers (or foundation slabs) on which the equipment is placed. Only the switchgear module requires the use of anchor bolts.

Low environmental impact

The technical solutions utilized in the RSVC guarantee low acoustic noise as well as low magnetic interference, thereby limiting the environmental impact. Since there are no TCRs (thyristor-controlled reactors) in the RSVC the stray magnetic flux close to the installation is low.

Similarly, since only damping reactors are used and no harmonic currents are generated by the RSVC, its noise contribution is also low.

Control functions

V/I characteristic

The RSVC capacity rating of 60 MVAr is defined at 0.9 pu tertiary voltage. When all TSC modules are switched on, the short-time overload capability of the RSVC is 70 MVAr, being limited by the capability of the tertiary winding of the supergrid transformer.

The RSVC is designed for continuous operation at any tertiary voltage between 0.8 and 1.2 pu. Operating points in the V/I characteristic **1b** are defined as follows: A 60 MVAr, B 51.5 MVAr, C 42.9 MVAr, D 34.3 MVAr, E 25.7 MVAr, F 17.2 MVAr, G 8.6 MVAr. The design of the tertiary winding limits the RSVC continuous output to 0.6 pu current. A limiting function (transformer winding temperature limitation) is built into the RSVC control system.

Operating modes

The SVC has two main operating modes, 'Automatic' and 'Manual'. In Manual mode, the susceptance of the SVC is controlled manually by the operator. In Automatic mode, the SVC susceptance is controlled by the automatic voltage regulator.

The Automatic mode is a closed-loop control mode. It can only be operated in connection with an HV bus voltage response.

Smooth transition between the two regulator modes is ensured.

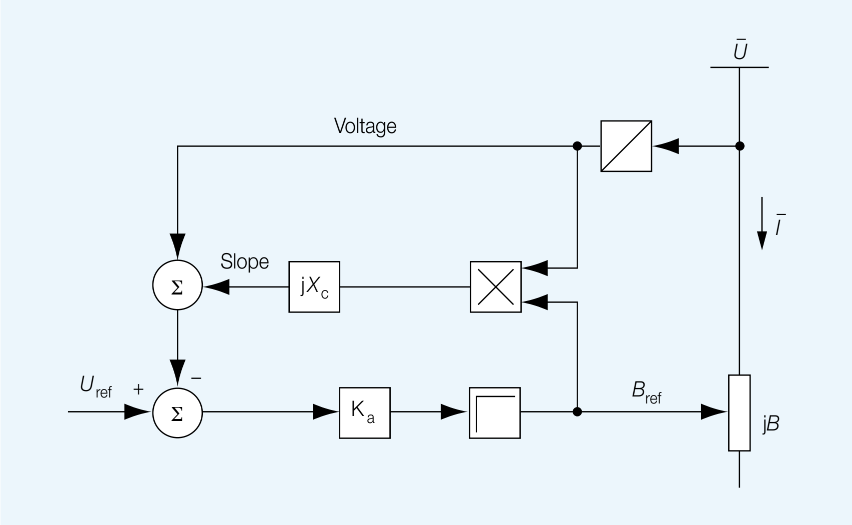
Voltage regulation

A three-phase symmetrical closed-loop controller is used to regulate the voltage **5**. The reference for this control is obtained by converting the voltage reference signal received from the man-machine interface (MMI). Parameters limit the reference signal range, which is shown to the operator on the MMI.

The feedback for the voltage control is the primary voltage, which is taken from one phase of the HV bus. The voltage regulator receives the voltage response as input. The regulator, which is of the integrating type, operates with a deadband on the input that corresponds to the step changes in the controlled voltage resulting from the step-wise control of the main circuit.

The regulator output is multiplied by the voltage response to obtain a signal which is proportional to the SVC current. This signal, multiplied by the slope setting, is added to the voltage response to obtain the correct slope in the compensator characteristic.

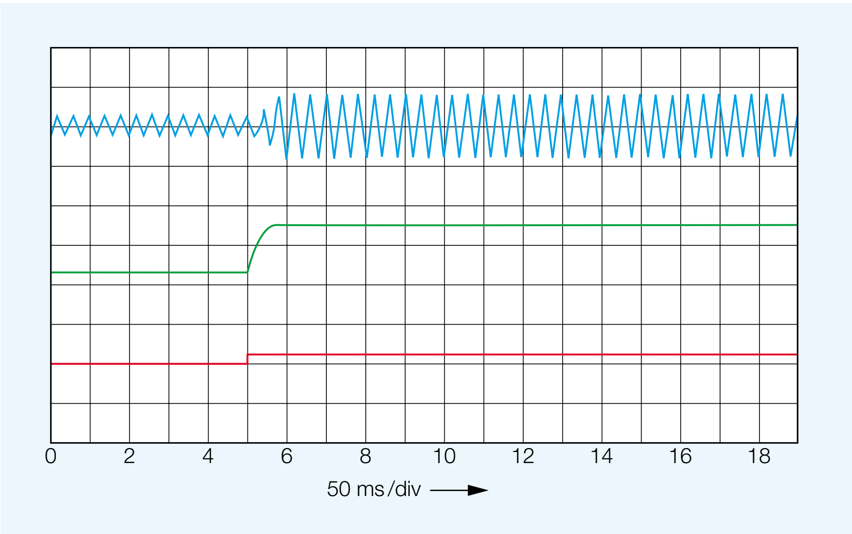
The slope can be set between 2 and 10 %, according to the needs of the ac-

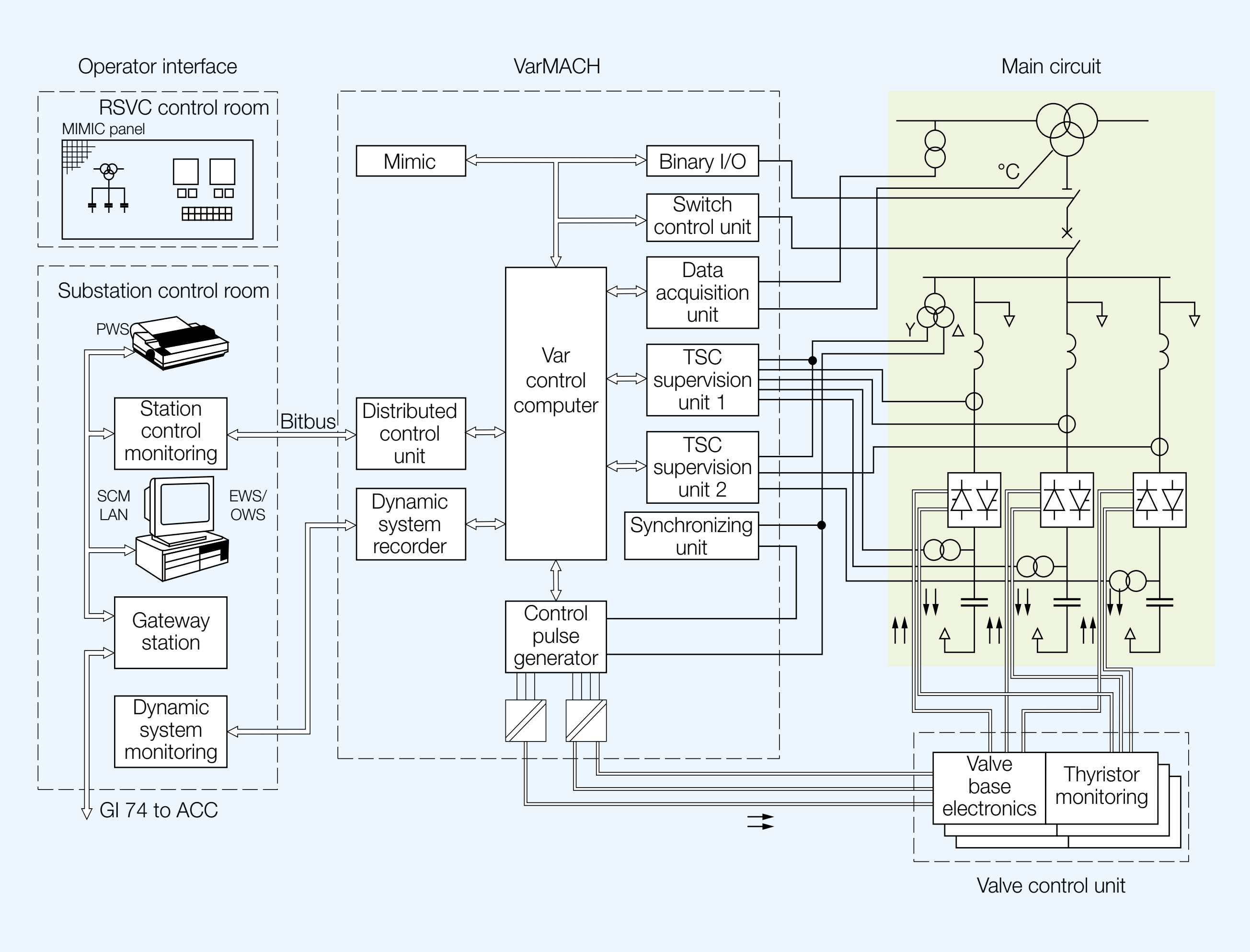


Basic circuit of the voltage regulator for the RSVC **5**

Dynamic response of RSVC (gain = 3) **6**

Blue *SVC current (2,500 A/div)*
Green *Regulator output (B_{ref})*
Red *Voltage step*





VarMACH control and protection system **7**

ACC *Area Control Center*
GI 74 *Proprietary protocol of NGC*
EWS/OWS *Engineering/operator workstation*
PWS *Printer workstation*

tual network. The limits of the voltage regulator are automatically adjusted to the relevant SVC range.

Performance check: dynamic response of the RSVC

During commissioning, the voltage regulator was tested under realistic network conditions with different gain settings. The final setting resulted in a regulator response of 25 ms (without overshoot). The recording in **6** shows, as an example, how a step in the voltage reference affects the regulator output (B_{ref}) and the SVC current.

Gain supervisor

Major changes in the network impedance can cause the reactive power output of the SVC to begin oscillating. The control system (VarMACH) of the RSVC therefore includes a function for supervision of the MVAr output. This is known as the 'gain supervisor'.

Oscillations in the system are detected by periodic changes in the susceptance reference B_{ref}, and cause the gain supervisor to automatically reduce the gain of the voltage regulator until the SVC output becomes stable again. An alarm is given in such cases, and the operator can reset the gain to its normal value.

Gain optimizer

The gain optimizer works together with the gain supervisor. The task of the optimizer is to adapt the relative gain factor to the short-circuit level of the network by trying to keep the voltage regulator deadband 30 percent larger than the widest voltage range that is possible as a result of switching within the SVC reactive power range.

The optimizer generates step disturbances to initiate switching of the smallest TSC bank. It is switched in or out for three to four cycles. This causes approximately 10 MVAr step changes in the SVC output. The response to the disturbance is detected via the voltage response on the HV side of the transformer.

Protective functions

The RSVC is designed to meet all operational requirements of the network. A number of protective functions are provided which increase the reliability of normal operation and avoid operation of the RSVC outside of its design limits. Some of these functions are given in the following.

Transformer winding temperature limitation

The VarMACH control system receives two signals related to the transformer winding temperature. One signal immediately blocks the thyristors and trips the SVC circuit-breaker. The other signal blocks the three highest SVC output levels. These levels become available again after a time delay of 10 minutes. An alarm is sent to the station control and monitoring system (SCM) whenever this function is activated.

TSC overcurrent protection

The overcurrent protection prevents the thyristors blocking after a very high surge current, for example due to false firing of the thyristors.

The current is measured phase-by-phase in the branches of the delta-connected capacitor bank by means of current transformers.

The current response is fed via intermediate current transformers and voltage dividers to the control system.

If it should exceed a preset level in the delta capacitor branch, the current protection will generate an order for continuous firing pulses to be sent to the TSC as well as an order to trip the main circuit-breaker.

TSC overvoltage protection

This protection avoids overvoltage of the TSC bank due to excessive charging. The voltage of each capacitor phase is monitored; if the capacitor voltage exceeds a certain level the protection prevents blocking of the thyristor firing pulses as long as the overvoltage remains.

Voltage strategy

Undervoltage

If the tertiary voltage (three-phase average) drops below 0.8 pu all of the control pulses are blocked after 1.5 s. Below 0.4 pu, blocking takes place immediately and the SVC is tripped after one hour.

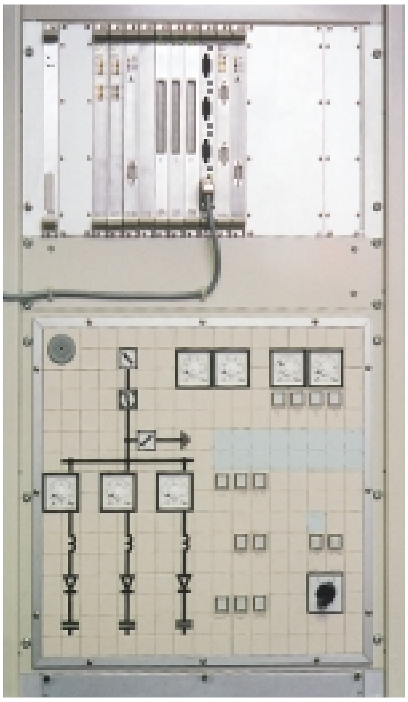
If the synchronizing unit detects an undervoltage the control pulses are blocked after 500 ms.

Overvoltage

The SVC control system features an MVAr output limitation function that prevents SVC voltages above 1.2 pu, and thus keeps the voltage generally below the design range of the equipment. If the tertiary voltage (three-phase average) rises above 1.2 pu, all control pulses are blocked immediately. Above 1.3 pu the SVC is tripped after 500 ms.

Blocking and tripping are reported to the SCM system.

VarMACH control and mimic panel **8**



VarMACH control system of the RSVC

The MACH control system is a powerful microprocessor-based ABB hardware platform for different systems applications, such as SVC, series compensation (SC) and high-voltage direct current (HVDC) transmission. VarMACH is an adapted version of the proven MACH control system with additional capability for operating and controlling RSVC installations. **7** gives an overview of the different units making up the control system, how they are connected internally and to the Area Control Center (ACC), and how the control system interfaces with the main circuit of the RSVC. The VarMACH control and mimic panel – the operator interface – is shown in **8**.

The control system processes the input signals, calculates the on/off orders to the TSC units, and converts them to control pulses for the TSC thyristor valves. These pulses are transmitted over fiber-optic links to the valve base electronics (VBE).

The VarMACH control system is based on Multibus II units (IEEE1296). On the basis of this standard bus, ABB Power Systems has designed several general-purpose computer boards, a high-speed digital signal processor (DSP) board, a bitbus communication board and a control pulse generator. Some of the main functional elements are given in the following.

DCU – distributed control unit for SCM

The unit for system control and monitoring is a general single-board computer which acts both as a collecting unit and a process interface to the SCM system. All events and alarms sent from the Var-

MACH control system to the SCM system, and also the orders given by the SCM system, are executed via this board.

The DCU clocks all events and alarms and stores them in internal queues until the central SCM collects them. In this way, up to 1,000 events can be stored internally. The queues work as backup memory to the memory on the central SCM computer. If a fault should occur in this computer, it is possible to download the events as soon as the SCM computer is back in service again.

Integration of the DCU in the control system significantly reduces the internal and external wiring of the cubicles. The reliability of the operator interface is therefore increased, since only very few parallel hardware I/Os are needed for control and monitoring.

Var control computer

The main control functions, ie the voltage regulator function, gain supervisor and gain optimizer, are implemented in the var control computer (VCC). This computer is the system host and is responsible for the higher-level control of the RSVC.

The main processor is an Intel 486DX2 with 66-MHz clock. It has a 1-Mbyte flash PROM as program memory and a fast 1-Mbyte data memory (SRAM). Remote I/Os are connected via a CAN (controller area network) bus interface.

A front panel connector (RS232) allows a PC or terminal to be connected for program loading and debugging facilities.

Station control and monitoring system

The PC-based SCM system is used for local and remote control and monitoring of the RSVC. The system is built around three main elements:

- Process interface
- Central SCM
- Man-machine interface (MMI)

The process interface is made up of the distributed control units (DCU). The two other elements are described briefly in the following.

Central SCM

The central SCM system is responsible for all collected and stored data in the system. Live databases and alarm queues are constantly updated via the integrated front-end system (DCUs). The central SCM also continuously handles all trends, reports and user-defined calculations. A sequence of events recorder (SER) is included in the SCM system.

Man-machine interface (MMI)

The man-machine communication is handled by different workstations, for example the operator workstation OWS, engineering workstation EWS and printer workstation PWS. Standard industrial hardware and software products are used for the MMI. Its open system approach is very important in this application as it greatly simplifies future extension or upgrading of the system.

Programming methods

Most of the application functions are produced using ABB's proprietary Windows-based full graphic code generating tool HIDRAW. It can be run on any industrial standard IBM-compatible PC, either stationary or laptop 9. HIDRAW is very easy to use as it is based on the simple pick, drag and place method. If functions are required which are not available in the comprehensive library, new blocks can be easily designed manually and linked to the software diagrams using a simple name reference.

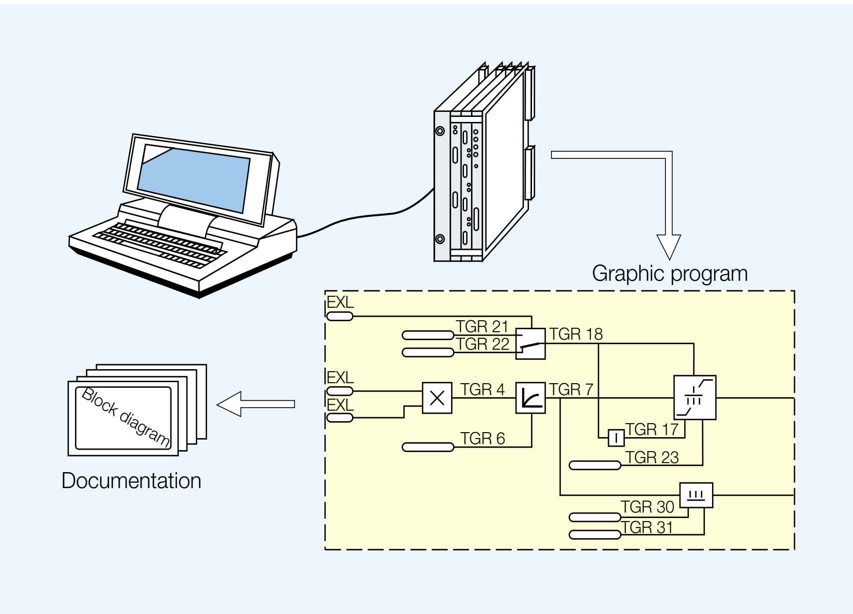
Depending on the type of application to be programmed, HIDRAW can be set up to produce either Intel's high-level language code PL/M or Motorola's ASM5600.

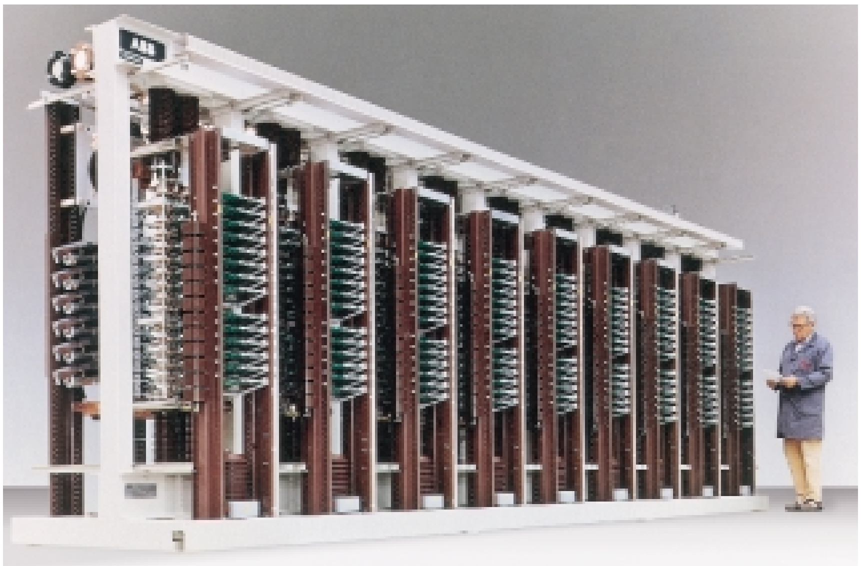
The program first runs an on-screen reasonability check of the software diagram, followed by cycle time and priority assignments and automatic cross-reference generation. Finally, it produces a 'make' file, which is then run on the same PC. The resulting file is ready to be downloaded via a serial link from the PC to the target system, ie the var control computer.

Thyristor valves

As already mentioned, the thyristor valves for the three TSC branches in the

HIDRAW programming of RSVC applications 9





Thyristor valves for RSVCs are of a more compact design than standard thyristor valves. Shields inserted between the phases ensure the required insulation class. **10**

RSVCs of NGC are mounted in a common steel structure. Since each thyristor valve is designed for three phases, a total of nine valve phases are housed in the same frame. These valves are of a more compact design than standard thyristor valves to enable them to be installed in the limited space in the relocatable module **10**. Insulation class LIWL 125 kV is ensured by shields which are inserted between the phases to compensate for the reduced flashover distances that result from the compact design.

The valve currents vary from 350 A to 1400 A on account of the binary set-up of TSC branches with power ratings of 10 MVAr, 20 MVAr and 40 MVAr. Thyristors with 2-inch active silicon wafers are used in the 10-MVAr and 20-MVAr branches, while the thyristors in the 40-MVAr branch have 3-inch wafers. The SVC voltage is determined by the connection to the tertiary winding of the existing supergrid transformers (13 kV). Use of thyristors rated at 6.5 kV results in a total of 13 thyristors being connected in series, including one redundant unit.

The valves are cooled by a liquid-to-air system with redundant pumps. The cooling liquid, a mixture of deionized water and ethylene glycol, meets the requirement for operation at a minimum ambient temperature of –25 °C.

The thyristor valves can be controlled either manually or automatically via the RSVC control equipment. Firing orders are sent to a valve control cubicle in which the valve base electronics are located. This forwards a corresponding pulse telegram to the thyristor electronic boards in the valves. Electric signals are used for the gate pulses sent from the thyristor electronics to the thyristor gates.

Each anti-parallel thyristor pair is monitored by the VBE. A printer keeps the operator informed about the thyristor valve status.

Flexible reactive power management

The described RSVC enables transmission system operators to take full advantage of power market deregulation by offering them a flexible and highly reliable tool for reactive power management. Flexibility is provided in both the hardware and the software areas. Whenever there is a change in demand for compensation, the RSVC can be quickly relocated to the required site. This ensures an optimum return on investment.

Use of the VarMACH and PC-based station control and monitoring (SCM) system allows local control – from the RSVC control room (bottom left enclosure in **2**) or the adjacent substation control room – as well as remote control in the network control center.

There are practically no limits to the control range of an RSVC, although higher reactive power outputs obviously require a larger number of transportable modules, which increases in steps accordingly. The optimum RSVC configuration for relocation purposes is the TSC combination described. It is, however, possible to design any SVC configuration as an RSVC. While the NGC RSVCs are designed to be connected to the tertiary winding of existing supergrid transformers, ABB can also supply RSVCs with a transformer designed for relocation.

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