The design, manufacture and system integration of the control system for the Bu Attifel low pressure gas transmission compressors.

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Abstract
Screw compressor packages have been commissioned to pressurise gas taken from the Bu Attifel oil field in Libya prior to transmission to a natural gas liquids (NGL) plant for processing. This paper describes the design of the control systems for these highly complex variable speed compressors. The control panel design is detailed which includes an explanation on how the programmable logic controller interacts with the instrumentation on-skid; variable speed drive; stand alone machine condition monitoring system and the client’s distributed control system (DCS). The paper concludes by showing how each part of the control system is integrated during factory and site testing.

1. INTRODUCTION

Screw compressors are positive displacement rotary machines containing three main components: the casing and male and female meshing helical rotors all of which are fitted tightly together. The clearance between the meshing rotors and the rotors and the casing is extremely small with 12μm not unusual. The reason for these small clearances is to reduce internal leakages and therefore increase efficiency.

This project featured a variable speed drive which, depending on the suction pressure, varied the speed of the main drive motor, which in turn was driving a speed increasing gearbox, which was connected to the oil-free screw compressor's timing gears. These timing gears keep the rotors from rubbing against each other as they mesh together. The process gas, methane in this instance, enters the compressor through a large inlet port, into a large cavity between the rotors and then as the rotors spin the cavity moves away from the inlet port and reduces in size where at the end of the rotor the cavity is at its smallest and passes over a discharge port to allow the compressed gas to escape. The compressor produces a continuous flow of pulses of high pressure each time a high pressure cavity of gas passes over the discharge port (1). The design parameters stated we were to maintain a suction pressure with a setpoint of 274 kPa(a) using the variable speed drive and recycle valve to control the suction pressure and produce a discharge pressure of 1.273 MPa(a). The design temperature of the process gas was 45ºC with a discharge temperature of 147ºC. The package is located in the Bu Attifel oil field in the Sahara desert and has been designed to withstand the high ambient temperature of 55ºC during the day and a minimum temperature of -2ºC at night.
Figure 1, the location of the screw compressor packages in the Bu Attifel field in the Sahara desert around 1000km from Tripoli and 6 hour drive from Benghazi.

The package operation is such that it takes the low pressure well-head methane gas from storage tanks and their surrounding process after it has been dried and scrubbed and compresses it prior to transmission to a NGL plant where it is used to recover the natural gas liquids. The role of screw compressors in this type of application and gas and process industries in general has been increasing with respect to their reciprocating counterparts due to their longer service life (2).

In association with the drive train the package contains suction and discharge pipework featuring all the instrumentation used to control and monitor the pressure and temperatures of the gas within the pipework. Finally a lubrication oil system that supplies the gearbox and compressor bearings with oil and is also used as a cooling media that flows around the compressor jacket to keep the discharge temperature down was also designed and installed.

2. DOCUMENTATION

The first stage of the design process was to conduct a review of the specifications imposed by the client. In this instance this took the form of the end user’s specifications but can also be the main contractor’s own specifications or indeed a combination of both. When this happens an order of precedence is given to solve any conflict between the documents. In this instance the twenty-five specifications handed over were the end user’s site standards. After reviewing these over a period of a few days a list of technical clarifications was compiled to be answered by the client at the kick-off-meeting. Using these standards and the piping and instrumentation diagrams (P&IDs) handed over by the sales team the electrical block diagrams are drafted. P&IDs are diagrams that show the process and all the plant and instrumentation used to control the process. Block diagrams are simplified architecture diagrams that show the location of various instruments,
whether they are process transmitters or machine conditioning monitoring probes, going back to their own junction box and how these junction boxes are cabled back to the unit control panel (UCP). During the course of the specification review it became apparent that the client required separate stainless steel junction boxes for analogue and digital signals and separate junction boxes for alarm and trip signals.

Another important factor that was listed in the specifications that impacts on the block diagrams and junction box schematics is the cable colours. This simply meant that “Ex ia” instruments would be wired in blue cable whereas “Ex d” instruments would be wired in black. These ratings allow them to be used within certain “Zones”. The client had classified the area outside the compressor acoustic enclosure a Zone 2 environment and the area within the acoustic enclosure Zone 1 according to BS EN 60079-10:2003. The analogue instruments on this package was certified “Ex ia” meaning the protection is based on the restriction of electrical energy within apparatus and of interconnecting wiring exposed to the potentially explosive atmosphere to a level below that which can cause ignition by either sparking or heating effects (3). The solenoid valves were certified “Ex d” which is a type of protection in which the parts which can ignite an explosive gas atmosphere are placed in an enclosure which can withstand the pressure developed during an internal explosion of an explosive mixture and which prevents the transmission of the explosion to the explosive gas atmosphere surrounding the enclosure (4).

The junction box schematics were drafted immediately after the block diagrams. One junction box drawing was produced for the valve solenoids; digital signals (valve fully open and fully closed etc); analogue signals; analogue signals (Trips), main drive motor winding temperature RTDs, gearbox machine condition monitoring instruments, compressor machine condition monitoring instruments and fire and gas instruments.

Having these documents ready and available to discuss with the client at the kick-off-meeting, along with the technical clarifications, allowed any initial design issues to be resolved and design to progress onto the UCP. Panel general arrangements (GAs) were drafted first showing the outline size of panel, location of the controls including the human machine interface (HMI) and operator push buttons. The specifications listed that the panel was located in a safe area, indoors, in an air conditioned building. This meant that the panel did not need to have “Ex p” certification which is sometimes specified for some packages and that the ingress protection rating was not excessively high. Lastly, even although the UCP was located in an air conditioned blast-proof building, a panel forced ventilation system was specified so the inlet and outlet vents also had to be shown on the GAs.

After the general arrangements were completed the panel power distribution circuits were designed. The control panel was fed by two 16Amp 230V, 50 Hz uninterruptible power supplies (UPS) from the client’s utilities distribution board to power the control system and a single 16A, 230V, 50Hz to power the panel utilities. The non-redundant supply was to power the ventilation system; heating system; laptop sockets and lighting. This meant that if the site power failed the UPS maintained power to the UCP in order to shut down the package safely but the non-critical systems were allowed to fail. After entering the panel through the main isolator, the power was reduced to 24V DC through redundant 24V DC power supply units, again if one failed the other would maintain power to the control system while signalling and alarm on the HMI. From here it was sent to the programmable logic controller (PLC) chassis; HMI; individual PLC cards, trip amplifiers, safety relays and control relays with each having their own individual protection. Having all the components protected individually not only allows for better protection as you can match the protection size closer to the full load current of the item but also allows for easy fault finding during initial power up, as each
circuit is powered individually, and also prevents one component tripping many components when it develops a fault. The machine condition monitoring system (MCM), as it was not protected by the redundant 24V DC power supply system, featured its own redundant 230V power supply module so if one of the UPS was lost, due to maintenance or broken cable, then it would also continue to operate. All of these redundant systems would prove their worth during the commissioning phase when the client’s UPS was interrupted when one of the main contractor’s personnel inadvertently switched it off.

3. CONTROL SYSTEM DESIGN

The PLC used Allen-Bradley’s ControlLogix platform however the client had specified that it must have redundant power supplies and redundant processors to control the compressor. This meant that the system had two identical chassis’ dedicated to the control of the machine. Each chassis featured: a power supply unit; ControlNet bridge module; processor module; and redundancy module. These chassis’ were in constant communication with each other via a fibre optic cable between the redundancy modules and had the master processor failed the stand-by processor would have taken control of the machine. This system also allows for a manual swap of control between the two processors so the master can be swapped on request if required using RSLinx communications software. The manual swap was demonstrated as was an unplanned swap (chassis power supply was turned off) with both swaps successful. Each chassis was set up identically having to have the same firmware version installed in the same module in their respective chassis’, with each module’s firmware version being dictated by the redundancy modules compatibility. Moreover, each of the processors had to have the same program and the ControlNet modules had to have the same node number which goes against networking convention. After the initial setting up of the PLCs redundancy system, which took two days, the copying of the program from the master processor to the stand-by processor was done automatically every time a change was downloaded into the master processor which shortened development time.

3.1 Control system communications

The PLC chassis and HMI communicated with each other using a redundant ControlNet network. Each chassis and the HMI were given individual node number, except the two processor chassis’ as explained earlier, using dials on the hardware. More communications software, RSNetworx for ControlNet was then used to configure the network to schedule the communications between each node on the network. This communications file was saved as it was required to build the PLC programme to enable the processor to communicate with the input and output (I/O) chassis and the HMI. A layout of the PLC control network is shown in Figure 2.

The I/O chassis were used to input and output analogue and digital signals to the on-skid instrumentation; variable speed drive (VSD) and Motor Control Centre (MCC). The digital on-skid signals included the signals to the solenoid valves signalling them to open or close and the signals coming back from the valves confirming if they are fully open or fully closed. The gaugeboard featured hand control stations for each of the motors allowing them to be controlled locally when the control system was put into maintenance mode which used a considerable amount of digital I/O. Digital signals were also sent from the PLC to the MCC to signal the motors and heater to start and stop with signals being returned to the PLC signalling that the motor is running, tripped or available. Lastly the same start and stop digital signals were sent between the PLC and VSD. It should also be noted that each motor had an emergency stop located next to it on-skid but this was hard-wired back to the motor starter circuit in the MCC rather than rely on the PLC tripping it and as such this did not impact on the PLC I/O count. A combination
of 24V DC and 230V AC voltages was used for the digital signals between the PLC and the surrounding plant as governed by the client’s specifications.

Figure 2, showing the redundant ControlNet network topography showing the HMI, processor chassis linked together and the two I/O chassis.

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As both the UCP, housing the PLC, and the VSD were located in safe areas then these analogue signals did not require any hazardous area protection unlike the on-skid analogue instrumentation. As all the on-skid transmitters were classed "Ex ia", and hence limit the amount of energy being delivered to the package preventing sparks in the event of a fault, each of the signals were passed through a galvanic isolator. On-skid analogue instrumentation included pressure transmitters to measure lube oil pressure and the suction and discharge gas pressure. Differential pressure transmitters were used to measure the differential pressure across the filter where a high reading would indicate a blocked filter and initiate an alarm while an additional differential pressure transmitter was used to measure the pressure across the suction isolation valve used to prevent fluid hammer. Temperature transmitters were also installed in the lube oil pipework and the gas pipework to measure the temperature in their respective media. The transmitters were specified to have smart HART communications (Highway Addressable Remote Transducer) which allows additional benefits such as remote setup (6). Separate pressure and temperature transmitters were installed for each alarm and trip condition should one fail the other would alert the operator to the abnormal process condition. Each of the transmitter values was displayed on the HMI so the operator could monitor the package from the UCP.

### 3.2 MCM system

The MCM temperature instrumentation measured the main drive motor windings, the various gearbox bearing temperatures and the compressor bearing temperatures. The MCM vibration measured the gearbox high speed shaft axial displacement; gearbox shafts speed; gearbox shafts radial vibration; gearbox casing vibration; compressor casing vibration and rotor axial displacement. Each of these transmitters was wired back to a Bently Nevada 3500 system located in the UCP. Each of the instruments, except the keyphasors, were given alarm and trip setpoints to monitor the status of the machine. Voting was carried out within the system to activate alarm and trip relays that will first alert the operator to any abnormal process conditions. The alarm relays are cabled directly back to the PLC which allows the HMI to display the alarm. The trip relays are wired back to a high-integrity safety relay, which in turn trips the main drive motor, before replicating the trip signal to the PLC so it too can be displayed on the HMI.

The PLC was also able to read the MCM instrument readings via a serial communications link. The MCM was equipped with a Modbus communications module allowing it to pass values to third party equipment and each of the PLC I/O chassis was equipped with a Prosoft Modbus module to allow it to communicate with the MCM and DCS. This meant the HMI was able to display the instantaneous MCM values. It should also be noted that the serial link between the PLC and MCM was a redundant link which allowed communications to continue even if one of the PLC Modbus modules failed. Each PLC Modbus module was fitted with two ports which were setup independently allowing one port to communicate with the MCM.
system and the other port was setup to communicate with the DCS. This also allowed redundant communication with the DCS which is a necessity when the process is deemed critical (7).

Figure 3, the gearbox and compressor outfitted with MCM instrumentation located within an acoustic enclosure.

A Modbus address register was built for the PLC Modbus module within the PLC programme with all the transmitter values, MCM instrument values, valve status values, motor status values and alarms status values copied into the register allowing the DCS to read them. This enabled the operators to monitor the process remotely from the DCS control room. The DCS also passed values into the register which allowed a remote start and stopping facility. For example: if a ‘1’ was passed into the remote start address register the PLC program would read this and providing process conditions were conducive the package would start.

4. MANUFACTURING RESTRICTIONS

Many restrictions were placed on the manufacture of the package due to its hazardous location such as the instrumentation and power cabling all had to be protected by steel wire armour and have flame retardant insulation. The instrumentation and power cabling had to be run in a separate cable tray with at least ten per cent spare capacity should additional cables be run in the future which meant over-sizing the cable tray and over-sizing the cable tray run to fit two different cable trays. In addition to this the cable tray was fitted with covers to stop the ingress of flora and fauna and protect the cables from direct sunlight which over the twenty-year design life could make the insulation brittle. The cable tray covers also afforded the cable some protection from the sandstorms which trouble the region. The “Ex ia” instrumentation was cabled using cable with a blue outer sheath while the remaining instrumentation and power cables were cabled using cable with black outer sheaths. The cables were terminated using nickel plated flameproof
glands as specified by the client. The client’s electrical specification also specified that cables were only to be gabled into the bottom of junction boxes to prevent the ingress of water, bearing in mind the final location is the Sahara desert, this meant over-sizing the junction boxes so all the cables could be terminated on the bottom gland plate rather than using a combination of bottom and side plates. The junction boxes themselves were manufactured from stainless steel and all individually certified “Ex e” which is protection applied to electrical apparatus in which additional measures are applied so as to give increased security against the possibility of excessive temperatures and of the occurrence of arcs and sparks in normal service or under specified abnormal conditions (8).

The last major implication of the client’s specification regarding the selection and erection of the junction boxes was the requirement to provide at least twenty per cent spare terminals within the enclosure for future use if required. The junction boxes were located at the package edge, below the gaugeboard, to enable ease of connection to the client’s cable at site. The indicators showing the process conditions, as depicted on the project P&IDs, were also located on the gaugeboard at the front of the package to allow the operators to monitor the package locally. The gaugeboard itself was designed and supplied so that only connection to the client’s wiring circuits, via the junction boxes below was required at site (9). In total the operators are able to monitor the package in three different locations: locally at the package; at the UCP and finally in the DCS control room.

5. CONTROL SYSTEM TESTING

System testing was carried out in two phases: factory testing in Renfrew and site testing at the package final location in the Sahara desert.

5.1 Factory acceptance test
Prior to shipping the package to site the client demanded a witness test of the entire package. This required the building of the 6kV/690V transformer that fed the VSD and connecting it to the factory medium voltage (MV) switchgear and the VSD. The VSD was then cabled to the motor. In order to understand the size of the package the compressor itself was an H5204 oil free machine, a relatively small machine by Howden standards, but due to the ambient temperature of the local environment, the main drive motor was actually an 800kW motor de-rated to 523kW to cope with the ambient temperature. Indeed trying to test the lubrication oil temperature control system proved problematic as the system was designed for the high ambient temperatures of the Sahara desert and not the mid-winter temperatures on the shores of the Clyde.

To test the package the junction boxes were temporarily cabled back to the UCP, the VSD controls were cabled back to the UCP and the Howden test MCC was used to supply the auxiliary motors (lubrication oil pumps, oil cooler fan motors and acoustic hood vent fans motors) with the control of the MCC done from the UCP. Once the temporary cabling was complete the UCP could be powered up, the test program loaded, and functional loop checks of all instruments could commence. After a week testing the system, both in manual and automatic control modes, where the solenoid and control valves were stroked to ensure correct operation and feedback from the limit switches. The auxiliary motors were first run in manual then the automatic sequence was run up to the point of starting the main drive motor (MDM) then stopped. During this run the sequencing of the valves and the starting and stopping of the auxiliary motors and heaters were checked for correct automatic operation. The medium voltage was then energised and the sequence run again this time the MDM was spun for a short period and the stop sequence was checked. The MDM to gearbox coupling was still not fitted at this point to
protect the gearbox and compressor should something fail but as the system had been performing well the couplings were fitted and a short machine run on air commenced.

Figure 4, showing the factory test setup. In it the transformer, VSD, control panel, oil cooling fans and compressor package can be seen.

Over the period of the next week the machine runs became increasing longer eventually running for over four hours at a time simulating an entire witness test. During the test runs the compressor axial probes were setup to their running float position but after the witness test were backed-off to prevent wiping them during transit. Due to the amount of test runs completed in the week leading up to witness test, the test was successfully completed without any unexpected events. The test cabling was promptly disconnected and the package and peripheral components were crated for shipping.

5.2 Site acceptance test
After the client had transported the package to site an urgent request from the main contractor was received for Howden personnel to attend site to commission the package. Upon arrival the installation was found to be half completed and nowhere near ready for commissioning. The partially completed cabling was loop checked while the remaining cabling was installed. After all cabling was installed and loop checked the instruments were powered and the same process of checking the valves and auxiliary motors that took place prior to the factory tests were completed but this time included the valves on the client’s pipework that were being controlled from the PLC.

Communication tests between the client’s DCS and the PLC were completed on-site but after the successful DCS test at the DCS manufacturer’s facility in Italy the previous year this passed without incident. An ABB service engineer was requested on-site to verify the transformer, VSD and motor setup prior to spinning the motor and test the sequence. As with the factory test, once the manual and automatic operation had been verified the couplings were inserted and the machine was run on gas for the first time.

After a series of these runs, where the process parameters were constantly checked and verified against the design parameters, the machine was handed over to the client. During particular test runs the discharge temperature had been breeching the high alarm limit of 155ºC when the package had been recycling for long periods of time. This is because the process gas, which is heated by the compressor every
time it passes through it, once discharged is routed back to the suction pipework to be sent to the compressor again. By increasing the flow rate through the compressor during recycle mode the process gas was not allowed time to heat up as rapidly thus lowering the discharge temperature and preventing the high temperature alarm activating.

REFERENCE LIST


