Control system concepts to improve geothermal plant availability

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Abstract
Advanced power plant controls are now commonly applied to the newest fossil, nuclear and hydro plants to achieve maximum performance and increase reliability. The expansion of integrated plant controls to geothermal plants presents equally valuable opportunities to improve energy production from this important resource. In the past, one-out-of-two systems (1oo2) have been used due to their lower installation costs but it is not clear whether during the life cycle of the plant this actually represents a saving, due to the higher risk of false alarms and increased plant shutdown when compared with the more advanced two-out-of-three (2oo3) architecture. This input will discuss the key elements of plant control-system-architecture for geothermal, highlighting the benefits that an integrated architecture can provide in relation to plant availability.

Keywords: Geothermal power plants, control systems, 2oo3, 1oo2, PFD, MTBF, Availability, Geocost, ALSPA, Reliability.

Conceptos de sistemas de control para mejorar la disponibilidad de plantas geotérmicas

Resumen
Actualmente se aplican controles avanzados en las plantas eléctricas más recientes con base en combustibles fósiles, nucleares e hidroeléctricas, a fin de lograr un desempeño máximo y aumentar su confiabilidad. La expansión de controles integrados de planta a plantas geotérmicas representa una oportunidad igualmente valiosa para mejorar la producción de energía a partir de este importante recurso. Anteriormente se había utilizado uno de dos sistemas (1oo2) debido a su menor costo de instalación, pero no es claro si esto realmente representa un ahorro a lo largo de la vida útil de la planta, al tomar en cuenta el mayor riesgo de falsas alarmas y el aumento en salidas de operación de la planta cuando se compara con una arquitectura más avanzada basada en dos de tres sistemas (2oo3). Este trabajo discute los elementos clave de la arquitectura del sistema de control de plantas geotérmicas, destacando los beneficios que proporciona una arquitectura integrada en la disponibilidad de la planta.

Palabras clave: Plantas geotermoeléctricas, sistemas de control, 2oo3, 1oo2, PFD, MTBF, disponibilidad, Geocost, ALSPA, confiabilidad.

1. Generalities concerning control system architecture

The availability of a system or power plant depends to a large on the tolerance to system failures.

1.1. Redundancy in control systems

As an example, in ALSPA® (Alstom Power Automation) control systems and for Open Loop Control/Closed Loop Control (OLC/CLC) perimeter, redundancy is implemented at the upper system level (head of cell level), with two Master Controllers operating in normal/standby configuration.

This ensures a fault tolerance of level 1: i.e., 1 failure on the active controller leads to switch over to the stand-by one, without losing the availability of the system.

However, this 1oo2 principle cannot be applied for safety related systems, as in this hot/stand-by redundancy scheme, the controllers do not monitor each other status and matching of their orders.

1.2. 1oo2 redundancy in safety systems

In a safety system based on safety 1oo2 architecture, orders of the 2 controllers shall be identical, so that the vote can accept this order. This is the compulsory condition to consider that the system is operational and safe. As a result of this condition, such systems have a fault tolerance of level 0.

Consequently, the first fault will lead to fallback to the safety state, actually to trip the system.

This 1oo2 safety architecture corresponds to 2oo2 architecture, with regard to availability: both controllers shall be working correctly, for the system to be safely operational.

This architecture is thus theoretically twice less available compared to a 1oo1 system, as there is two times more risks to have a hardware fault (in 1oo2, the number of implemented components is doubled).

1.3. 2oo3 redundancy in safety systems

When we need both safety and availability, the most common architecture is then based on 2oo3 safety vote.

Fault tolerance is equal to 1:1 failure on one of the 3 channels has no impact on the system availability, as the 2 remaining channels still ensure the safety function. Of course, a second failure on one of this 2 remaining channels will lead to a trip, as a minimum of 2 consistent orders are required by the 2oo3 voter. The 2oo3 voter compares the 3 outputs of the 3 channels, so safety is ensured by this vote and furthermore this principle allows detecting any failure of one channel, by the divergence of its order with the 2 other channels' orders.

On ALSPA 2oo3 protections channels for example, several faults can be tolerated, if they concern independent parts of the safety system. Example: we can tolerate a digital input failure on one channel and an analogue input failure on another channel, if these 2 inputs are not used in the same safety function. This still improves the availability of the system, while keeping the required safety level.

According to IEC61511 standard (IEC, 2003), a single channel component can only reach a SIL2 level (Safety Integrity Level 2). If used in 2oo3 configuration with voter, it is then possible to reach a SIL3 level for the association of these 3 components. The IEC 61508 standard (IEC, 2010) focuses on safety, but doesn't consider the availability aspect.

The risk for the safety function not to ensure the protection is measured by the PFD or PFH value, depending on the way the safety system operates. PFD (Percentage of Failure on Demand) is the criteria used for a system that realizes very seldom safety actions. PFH (Percentage of Failure per Hour) is used for a system that regularly generates safety orders. Steam turbine safety systems are considered as of the PFD type.

By computing the PFD value for a 1oo2 safety system and for a 2oo3 safety system, it can be noted that the 1oo2 performs better in some areas (e.g. less risk of failure as only 2 sets of components instead of 3 sets). The 2oo3 PFD value however is generally still compatible with IEC61508 SIL level up to 3, and its availability is far better, which leads to use it as the best compromise for a SIL3 safety system or high availability protection system.

The huge availability of 2oo3 systems comes from their ability to be repaired without stopping the machine (hot swap maintenance operations while safety is still ensured).

This is why most of the SIL3 systems or high reliability protection systems we implement are based on 2oo3 architecture. This is notably the case for the over-speed protection relay and for condenser protection (3 independent channels, SIL3 systems).

1.4. 2oo3 redundancy in non-critical protection systems

The choice of 2oo3 architecture for non-critical protections depends on the type of the machine and associated sensors. 2oo3 allows hot-swap maintenance while the machine is in operation and is well suited if a majority of sensors are triplicated (Fig. 1).

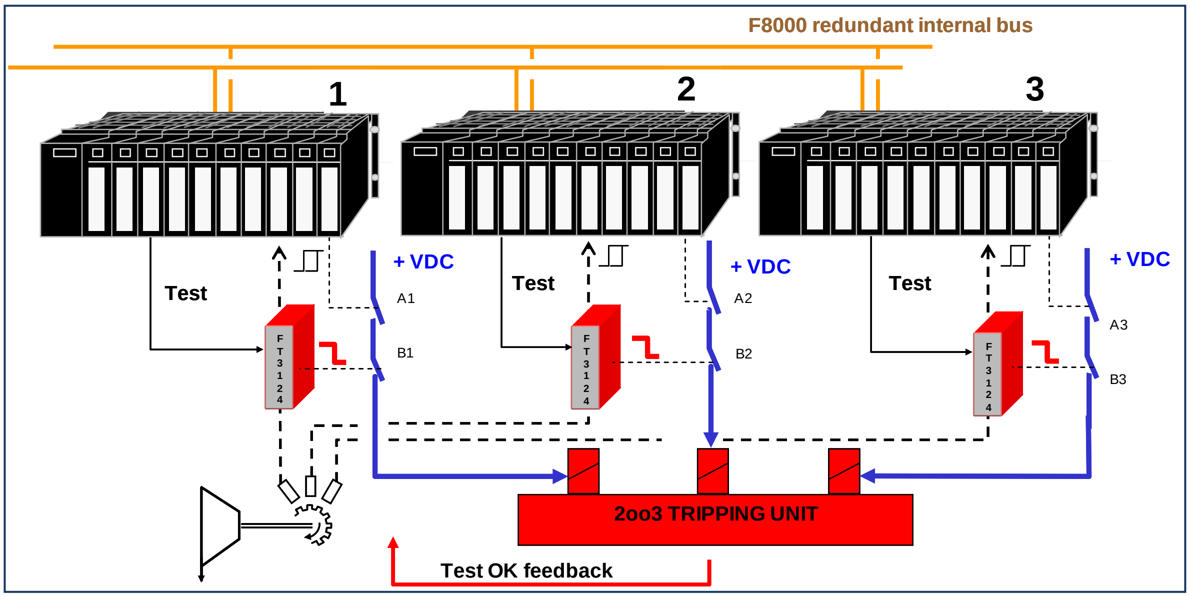


Fig. 1. 2oo3 Control System Architecture.

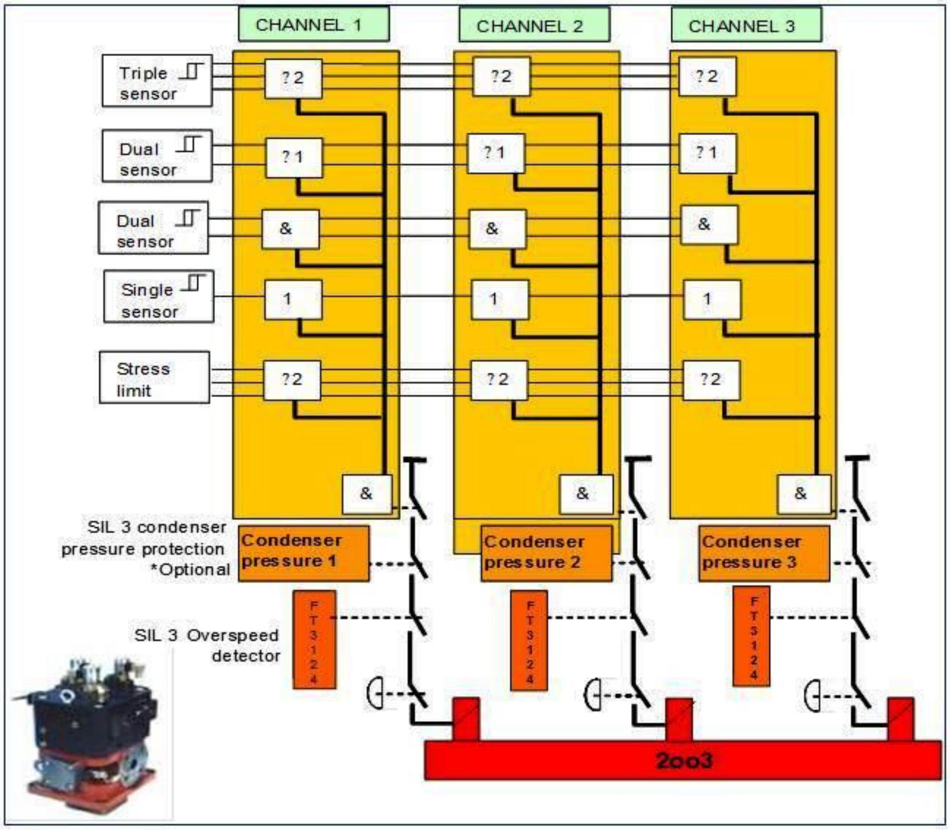
However, for simplex or doubled sensors, the ALSPA 2oo3, dispatched by redundant protection concept, links the single or doubled information to all 3 channels, in order to apply the 2oo3 vote concept as early as possible in the system, even for non-triplicate sensors. This way, sensor information is fully distributed through the internal bus and available for other channels that need it. Figure 2 outlines the system.

2. Case Studies

2.1. MTBF Example

Physical systems are often subject to unexpected changes such as component failures and variations in operating conditions that tend to degrade the overall system performance and availability. Such changes are commonly referred as “failures”, although they may not represent the physical failure of a component.

In order to maintain a high level of availability of the system, we can either make sure that failures are promptly detected and identified so that appropriate remedies can be applied, or use redundancy so failures can be processed and/or discarded depending on the control algorithm. In this case, to evaluate the availability of a system, we can use once again the concept of the Probability of Failure on Detection (PFD) given by the IEC61508 standard for a MooN architecture. This can be expressed as a general formula that expresses the time before failure of a system as a ratio of the basic configuration (1oo1).



Sensor redundancy principle:

a) Single sensor (non critical):
Signal is acquired by one channel and threshold is distributed over the internal F8000 bus to other channels.

b) Dual sensor:
Channel 1 and Channel 2 implement their threshold detection which is distributed over the internal bus to other channels. Then a "and" or "or" gate is applied on each channel internal bus.

c) Triple sensor:
Each channel implements threshold detection which is distributed over the internal bus to other channels. Each channel performs a 2oo3 selection.

Fig. 2. ALSPA 2oo3 protection concept.

For a system with an architecture based on a 1oo2 redundancy, the time before failure can be expressed as:

1oo2 system = 4/3 (1oo1 System)

And for architecture based on a 2oo3 redundancy the time before failure can be expressed as:

2oo3 system = 4 (1oo1 System)

The above formulas show the 2oo3 redundancy based system ratio of availability is 3 times higher than the 1oo2 redundancy based system. Moreover, this shows that the architecture based on a 2oo3 redundancy would have a MTBF before failure that is higher than a 1oo2 architecture based system. Therefore there is a possibility that the initial investment in a 2oo3 redundancy system could be paid back due to the higher availability over time.

If we consider the example of the 2oo3 safety over-speed protection relay, the value we obtain for the Mean Time Before Failure (MTBF), according to a Mean Time To Replace (MTTR) of 3 hours, which assumes that the spare is available on site, is very large, as shown in Table 1.

	Overspeed protection (EPRO)
AVAILABILITY	99,9999%
RELIABILITY (Hrs)	2595039
RELIABILITY (Years)	296,24
MAINTAINABILITY (Hrs)	3

Table 1. Safety Over-speed Protection Relay.

2.2. Cost considerations for geothermal

Of course, the cost of a 2oo3 system will be higher, as it requires more components, but it also handles more sensors if they are triplicate. The cost of instrumentation will also increase, but this will also lead to a higher availability for the perimeter of sensors and actuators. These above mentioned costs are one-time initial costs.

However the difference of cost with a 1oo2 system could be negligible, if we compare it to a loss of production, which can be a repetitive cost over the life cycle of the installation.

To demonstrate this assertion, a simple cost analysis examines the effect of adding a 2oo3 control system concept to a geothermal power plant. The tool used for the analysis was *Geocost*, a whole project cost and development model developed by the US Department of Energy (DOE) and adapted by Hiriart (2005), and the aim was to determine a basic cost-benefit of the approach given a reasonable set of starting assumptions.

Project name:	**Base Case**	
Power Plant Capacity	[MW]	100
Specific Steam Consumption	[Ton/h*MW]	7.5
Power Plant Cost	**[US$/kW]**	**1,500**
O&M Plant (Permanent Cost)	[US$/MWyear]	45,000
O&M Plant (Variable Cost)	[US$/MWh]	30
Discount Rate	[1]	10.0%
Lifetime Project	[year]	25
Plant Capacity Factor	**(% per annum)**	**90**
Gross Power Generated	GWh per annum	790
Levelized Cost of Electricity	**¢$US/kWh**	**8.62**

Table 2. Base case scenario for power plant cost of production.

The analysis assumes a cost of the power plant installation and considers that the steam delivery was not subject to reduction, alteration or interruption for the lifetime of the plant. This is in order to isolate the power plant availability from that of the steam field, where separate O&M approaches and availability calculations apply. The two variables thus in the analysis are simply: i) the installed cost of the power plant, and ii) the project capacity factor achieved as result. The output is thus the effect on the levelized cost of production.

For the base case analysis, Table 2 highlights the cost assumptions and shows the levelized cost of electricity production which results for the base case scenario.

Project name:	**Increased availability**	
Power Plant Capacity	[MW]	100
Specific Steam Consumption	[Ton/h*MW]	7.5
Power Plant Cost	**[US$/kW]**	**1,500**
O&M Plant (Permanent Cost)	[US$/MWyear]	45,000
O&M Plant (Variable Cost)	[US$/MWh]	30
Discount Rate	[1]	10.0%
Lifetime Project	[year]	25
Plant Capacity Factor	**(% per annum)**	**95**
Gross Power Generated	GWh per annum	834
Levelized Cost of Electricity	**¢$US/kWh**	**8.32**

Table 3. Reduction in levelized cost of electricity for availability increase of 5%.

Table 3 considers the scenario where there is an increase in plant availability, such that could occur from use of an upgraded control system, where a value of 95% plant availability was modeled initially. It is expected a higher availability as result of a decrease in the levelized cost of electricity of approximately 0.3 cents/kWh as shown below, with a further 44 GWh of additional electricity production available per annum.

Table 4 shows the possible increase in power plant capital cost that could be justified (at 95% availability), to return the levelized cost of generation to that of the base case scenario.

As shown in the Table 4, for a power plant of 100 MW, a capital cost increase of $US 206 per kW would be acceptable, maintaining the levelized cost of generation at the initial condition of 8.62 cents of $US per kWh.

This represents an increase of some 13-14% of the total cost of the power plant over the base case scenario ($US 1500/kW).

Project name:	Increased cost and availability	
Power Plant Capacity	[MW]	100
Specific Steam Consumption	[Ton/h*MW]	7.5
Power Plant Cost	**[US$/kW]**	**1,670**
O&M Plant (Permanent Cost)	[US$/MWyear]	45,000
O&M Plant (Variable Cost)	[US$/MWh]	30
Discount Rate	[1]	10.0%
Lifetime Project	[year]	25
Plant Capacity Factor	**(% per annum)**	**95**
Gross Power Generated	GWh per annum	834
Levelized Cost of Electricity	**¢$US/kWh**	**8.62**

Table 4. Increase in power plant cost achievable for no net change in levelized cost of production, for a plant availability increase of 5%.

This can also be expressed in terms of the capital costs of adding 1% more availability to the plant, all other things being equal. For the 100 MW plant, this computes to a value of 4,100,000 $US per percentage point increase ($US 41/kW).

As it turns out (Table 5), this value is not sensitive to variations in O&M cost for the same initial conditions (allowing for rounding errors), nor is it sensitive to the total availability increase achieved, assuming there is no change to the number of wells drilled.

When we factor this back to the initial cost of a plant control system, we can see then that it would be economic to spend on the control system up to the amount of $US 41/kW per % point increase in availability that is achieved. In such a scenario, the levelized cost of production would remain equal or less than the initial condition.

		Total Plant Availability Increase (%)					
		1	2	3	4	5	Average cost per % increase of availability
O&M Cost USD/kWh	0.01	$ 41	$ 82	$ 124	$ 165	$ 206	$ 41
	0.02	$ 41	$ 82	$ 124	$ 165	$ 206	$ 41
	0.03	$ 41	$ 82	$ 124	$ 165	$ 206	$ 41
	0.04	$ 41	$ 82	$ 124	$ 165	$ 206	$ 41
	0.05	$ 41	$ 82	$ 124	$ 165	$ 206	$ 41

Table 5. Cost matrix showing total capital cost increases (per kW) across a range of O&M costs and availability gains.

Thus in the plant modeled, for a 2oo3 control system to be economically justified over a 1oo2 system, either it should: i) cost the same or less as the 1oo2 system, or ii) demonstrate that each percentage point of increased plant availability comes at a capital cost which is less than $US 41/kW. Hence for a 5% increase in plant availability (considered achievable in swapping from 1oo2 to 2oo3) the additional costs of the 2oo3 control system over the equivalent 1oo2 system could be up to $US 206/kW greater and still be justifiable in the project lifecycle economic analysis.

If it is considered that a typical range of installed costs for geothermal plant control systems can be estimated at between USD 75 and $US 225 per kW, the conclusion overall is that there would seem to be quite good scope to consider an increase in capital costs for this type of equipment, especially where the 2oo3 system can directly show an increase in plant availability.

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