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Analysis of I^2C and Hart Protocols and Their Applications in A Nuclear Power Plant

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***Abstract*: In the given article, the intra-circuit serial communication protocols I^2C and HART will be analysed with considerations to their applications in the automated instrumentation and control system of a nuclear power plant. For this purpose, characteristics and limitations of the given communication protocols were obtained and their compatibility with the components of the I&C systems of a nuclear power plant was analysed.**

Key words: I^2C, HART, Bit rate, distance, master, slave.

INTRODUCTION:

In a Nuclear Power Plant, automated instrumentation and control systems play a very important role in monitoring and control of various important technical, physical and chemical parameters of the station and keeping them within design limits, essentially ensuring the safe and efficient operation of the nuclear power plant. To observe various parameters of the NPP, the I&C system relies on different types of sensors. The data collected from the sensors are compared with design set points and then corrective action is taken on the basis of the deviation to keep the parameters within design limits. I&C systems can be classified as digital or analog on the basis of the type of signals they work on.

The most straightforward way to describe an I&C system would be its physical layout. The layout consists of the following systems;

- Process interfaces: Sensors, transmitters/signal processing electronics, actuation devices;
- Field communication: Communication protocols through which data is transmitted from the process interfaces (sensors), e.g., HART, Digital feedbus (wired or wireless);
- Cabling, penetration and junction boxes: Physical means through which the signals are transmitted;
- Process monitoring and control systems: Data acquisition systems and control systems;
- High level communication;
- Human-system interface (HSI);
- Simulators: For training of personnel to manage emergencies.

In this article, attention will be paid to 'field communication' of the I&C system of a NPP. The field communication links the process interfaces such as the sensors and actuators with the process monitoring and control systems. The protocols define the standards based on which the data will be transmitted between these two layers and the standards are physically implemented using wires, junction boxes and interfacing ports.

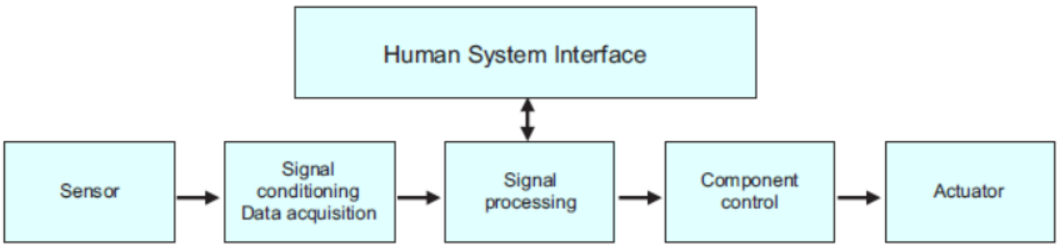

Figure 1. Functional overview of an I&C system

Field communication of the I&C system in a nuclear power plant

Field communication aspect of the instrumentation and control system of a nuclear power plant defines the protocols, i.e., the communication standards in accordance to which data is transferred in between the process interfaces i.e., the sensors and actuation devices and the process monitoring and control systems that consist of automatic control systems and data acquisition systems (DAQs). A protocol would define the contents of the data packets, the format of addressing various devices connected in the network, the number of wires that needed to be connected between the devices, the communication protocol utilized also defines a set data transfer rate.

In the I&C systems of Nuclear Power Plants, different protocols are utilized to transfer data between process interfaces and process control systems, such as:

- Analog: Even today, the most common type of field communication used in NPPs is analog communication. Generally, dc signals within the range of 4-20mA are utilized for this purpose.
- HART (Highway Addressable Remote Transducer protocol): This communication protocol is extremely popular today in various type of industries. This protocol can be defined as a hybrid of analog and digital communication. Using frequency shift keying (FSK), sine waves of two different frequencies, which define logic '0' and '1' are superimposed upon a dc signal within the range of 4-20mA. HART enables full-duplex communication, i.e., it allows simultaneous two-way communication.
- Wired Digital feedbus: While HART is commonly used for field communication due to the possibility of using it on top of the already existing analog 4-20mA communication channels, wired serial communication protocols are also being used for field communication in NPPs. Such protocols can't work on top of the already existing 4-20mA analog wiring systems, but they are much faster and can transmit more data as compared to HART. Examples of such wired digital communication protocols can be SPI, I^2C, RS-232, the Profibus and Foundation Feedbus. They have potential to simplify the construction of newer I&C systems in newer NPPs.
- Wireless digital communication protocols: Digital and wireless instrumentation and control devices use some specific and standardized communication protocols to transmit data. They are not widely used for monitoring parameters inside a Nuclear Power Plant. However, they had widespread applications outside the station premises due to them being convenient for radiation monitoring in its surroundings as well as meteorological parameters.

The layers that the field communication connects, i.e., the process interfaces and the process control systems define a master-slave architecture, with the sensors and actuators acting as slaves and the data acquisition devices and the control systems acting as masters.

Highway Addressable Remote Transducer protocol (HART)

At present, the Highway Addressable Remote Transducer protocol (HART) is one of the most popular standards for sending and receiving digital information through analog wires between smart devices (sensors/actuators) and process monitoring and control systems. This protocol finds widespread use in process industries across the world. Its usages range from simple automation applications to complex industrial applications.

The advantage of HART protocol is that it can use the already widespread presence of 4-20mA analog circuits present in various industries to send digital data, which in turn has made it one of the most popular industrial communication protocols. In the recent years, over 35 million HART devices have been installed throughout the world in various industries.

The HART is based upon the Bell 202 frequency shift keying. This technique superimposes digital signals over a 4-20mA analog one. The Bell 202 FSK calls for 2 sine waves of frequencies 1200 Hz and 2200Hz which signify logic '1' and '0' respectively. These sine waves are thereby superimposed upon the analog DC signal. In essence the analog signal is not affected since the average value of the FSK is always 0 and it also allows for simultaneous digital and analog communication. This protocol allows full-duplex communication, i.e., simultaneous bidirectional exchange of information. This protocol allows data transfer rates upto 1200 bits per second.

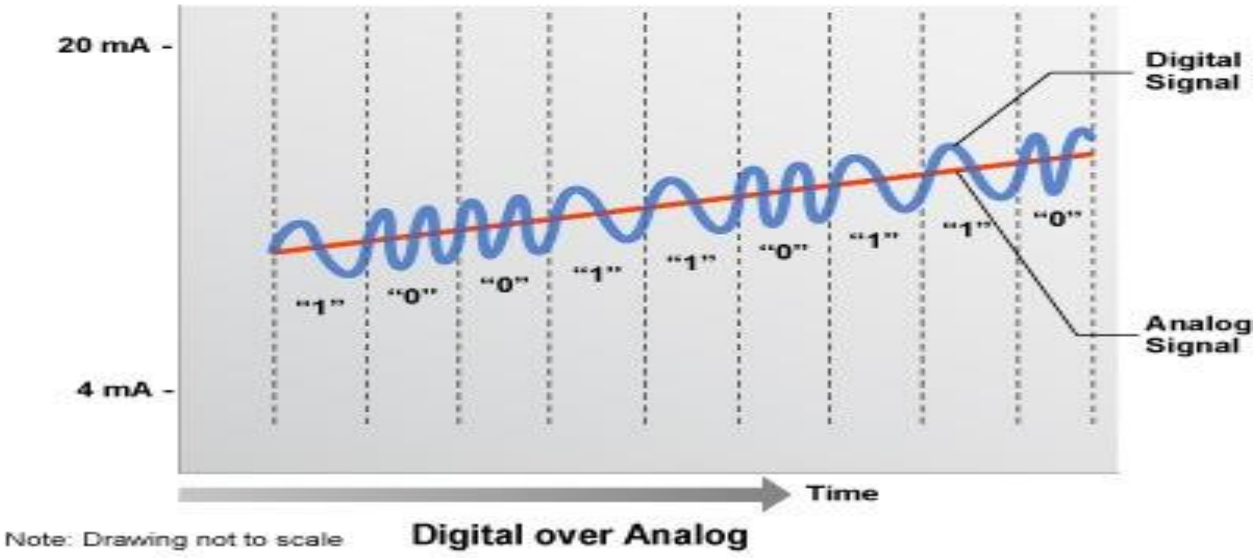

Fig 2. A HART based signal

HART-compatible devices can operate in two configurations;

- **Point to point configuration:** The primary data in this mode is communicated through the analog signal while the additional variables are transmitted over the digital signal. The host system with which all the HART enabled nodes (slaves) communicate, can have a primary and a secondary master depending on requirements.
- **Multi-point or multi-drop:** The analog signal is maintained at 4 mA and multiple field devices (slaves) are connected in parallel. In case of HART v07, it is possible to connect 64 field devices (slaves) with the transmission line. The field devices use the digital channels to transmit data and the analog channel is fixed at 4mA. The HART protocol data packet consists of the following parts:
  - Preamble: Consists of 5-20 bytes. Used for the synchronisation of the slaves with the data stream. In most cases, the preamble is made up of 5 bytes;
  - Start: After the preamble bytes, a byte containing the master number, transmitted after the preamble bytes;
  - Address: Usually has 1-5 bytes, containing the master and slave address as well as burst mode indicator, which is usually the last bit on the address bytes;
  - Expansion:0-3 bytes, contains the 5th and 6th bits of the of the start character;
  - Command: 1 byte containing the numerical value of the command issued;
  - Byte count: 1 byte containing the size of the data field;
  - Status: 2 bytes indicating communication errors, status of the received command or the receiver slave;
  - Data: 0-255 bytes;
  - Checksum: The XOR of all the previous bytes.

HART operating modes:

- **Master-slave mode:** Communication is initiated by the master (host), In this mode a primary master such as distributed control system or a PLC and a secondary master like a handheld communicator can be connected. The field devices (slaves) can be transmitters, actuators and sensors.
- **Burst mode:** This mode can only used in point-to-point configuration. Upon being commanded by the master to transmit data, the slave keeps transmitting until commanded otherwise by the master.

Advantages and disadvantages of HART:

The greatest advantage of HART is that it allows the usage of the older 4-20mA analog wiring systems to communicate digital data. 4-20mA analog wirings are already available in most of the industries as it was the older analog communication standard. Therefore, today it is possible to achieve digital communication with HART, while retaining the usage of the older 4-20mA analog communication channels hence enabling a cost-effective transition to digital data transfer.

The limitation of HART is the low speed of the digital signal transmission. The analog signal is not available in the multi-drop configuration and only a limited number of field devices can be connected to the transmission lines.

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INTER INTEGRATED CIRCUIT (I^2C)

The inter integrated circuit (I^2C) is a packet switched, serial communication protocol that is used for usually short distance communication between multiple devices (usually integrated circuits) based on a master-slave architecture. This protocol is based on communication using two bi-directional lines designated as "SCL" and "SDA". All the devices connected to a I^2C enabled loop are only connected to these two lines. This protocol and its compatible bus were invented in 1982 by Phillips Semiconductors (today NXP Semiconductors).

I^2C has become increasingly popular in the electronics and processing industries due to its simplicity, availability of multiple master capability, ability to support large number of devices and connect them with the usage of simple start and stop bits.

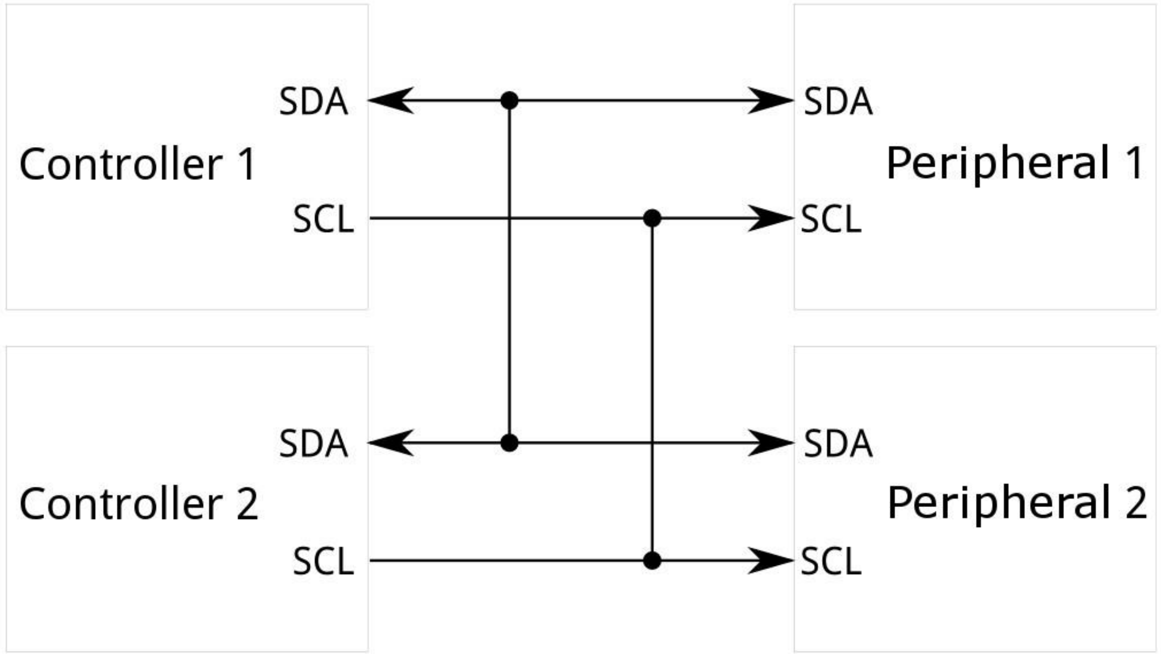

Fig 3. An I^2C block diagram

Unlike HART, I2C is a purely digital communication protocol where voltage levels of +5 or +3.3 V designate logic '1' and 0V designates logic '0'. This protocol provides half-duplex communication, i.e., bidirectional communication between master and slave nodes are possible but not simultaneously. I2C supports multiple masters and slaves.

The I2C protocol can utilize either 7-bit or 10-bit addressing systems and can easily use multiple master devices. There are four modes of operation in I2C communication on the basis of the bit rates.

- Standard mode: 100 kbps;
- Fast mode: 400 kbps;
- Fast mode plus: 1 Mbps;
- High-speed mode: 1.7 Mbps – 3.4 Mbps;
- Ultra-fast mode: 5 Mbps.

In an I2C compatible network, any number of master devices and upto 1008 slave devices can be connected.

As mentioned earlier, data in an I^2C compatible network is transmitted over the SDA (serial data) line of the two I^2C cables, the other being the serial clock (SCL), which is used to keep the flow of the data synchronised and can only be controlled by a master device. The SDA line can be manipulated by the slave devices as well as the master(s). The data packet of I^2C contains the following information;

- Start bit: This bit indicates the initiation of communication over an I^2C network. Initiation can only be done by the master by pulling the SDA line low, while the SCL remains high. From the next bit, the SCL begins functioning as the serial synchronising clock transmitting high and low (logic 1 and logic 0) in the pattern similar to a square wave until the operation is stopped by the master.

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- Address bits: Following the start bit, on the SDA line, come the address bits, which signify the address of the slave devices with which the communication is being carried out. The address can be of 7-bits or 10-bits depending on the addressing system being utilized.
- Read/Write: A single bit of information that signifies whether the operation is to read data from a slave or to write data (or give a command) to it. This bit follows the address bits on the SDA line. If it is low (logic 0) then the operation is a write operation and if it is high (logic 1) then the operation is to read data from the slave.
- Acknowledgement bit (ACK): It is a bit transmitted by the slave device to let the master know that it has received the data transmitted or has transmitted the required data. At the end of each byte of data on the I^2C line, the master signifies the completion of transmission of a byte by pulling the SCL low. Subsequently, the slave must pull the SDA low in order to acknowledge the transmission. If in case, SDA is not pulled low by the slave, the such a condition is considered to be a NCK (no acknowledgement).
- Data bits: Contains 8 bits of information. In case of a read operation, the salve transmits these 8 bits on the SDA line following the acknowledgement bit. In case of write operation, the 8 bits of data follow the acknowledgement from the master and is written onto the slave.
- Stop condition: At the end of a transmission, the master must execute a ‘STOP’ condition by first pulling the SCL high (0->1) and then the SDA high, while keeping the SCL at logic 1. In order to avoid false stop conditions during normal data writing operations the value of SDA should only change when the SCL is low.

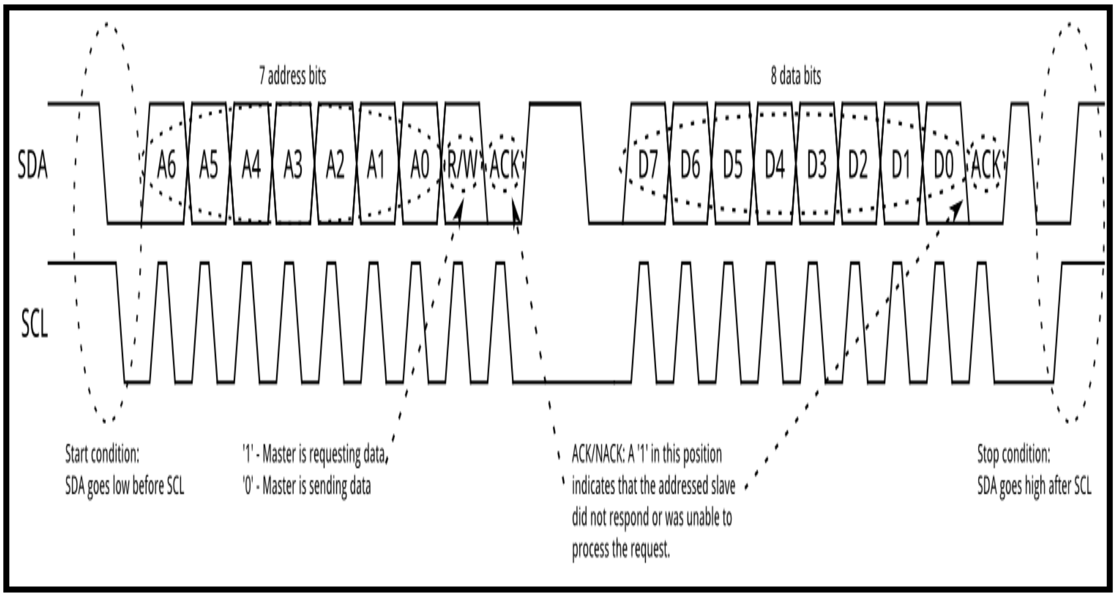

Fig 4. I^2C data frame with 7-bit addressing system

Comparison between HART and I^2C

Although both HART and I^2C are two very serial communication protocols that are used to connect electronic devices with each other in a master-slave architecture and achieve the same purpose of exchanging information between the devices connected in the network, they have significant differences between. In the following table, a comparison of the major characteristics of both communication protocols is given.

Inter Integrated Circuit (I^2C)	*Highway Addressable Remote Transducer protocol (HART)*
In an I^2C compatible network, information is transmitted in the form of digital binary signals. `	In a HART compatible network, information is transmitted through both analog and digital signals.
An I2C network is a 2-wire network, through which digital signals with logic levels of +5V/+3.3V and 0V are transmitted.	A HART compatible network can work on top of existing analog communication lines of 4-20mA.
Supports 7-bit and 10-bit addressing system. • The address frame contains the slave address and the read/write bit.	The addressing system can have from 1 to 5 bytes. • The address frame contains the addresses of master, slave and a burst mode indicator
In different operating modes, the transmission speeds range from 100 kbps to 5 Mbps.	Data is transmitted at a rate of 1200 bits per second (bps).
Provides half duplex communication in the network.	Provides full-duplex communication in the network.
Can support multiple masters and slave devices. The maximum number of slaves is 1008.	Supports 2 masters and multiple slaves. The maximum number of slaves is 64.
I2C compatible wired networks can have lengths up to 10 meters only.	The wiring in a HART compatible network can extend up to 3000 meters.

Table 1. Comparison of characteristics of HART and I^2C serial communication protocols

From the above comparison, it is clear that each of the two protocols in discussion have their own advantages and disadvantages.

- The address frames and data frames of a HART data packet are considerably larger than that of a I^2C address or data frame.
- Data transmission rates in an I^2C network are significantly higher than that in a HART network.
- The maximum possible wiring range in a HART network is significantly larger than that in an I2C based network.
- The maximum possible number of slaves and masters is higher for I^2C based networks.
- HART enables full-duplex, i.e., simultaneous bidirectional exchange of information in the network, while I^2C only allows half-duplex communication.

With the above differences taken into consideration, it is easy to understand that these two serial communication protocols are used for very different sets of applications, despite them both being serial communication protocols.

I2C is primarily used for exchange of information between integrated circuits, over very short distances. Whereas HART is today a very popular protocol for exchange of information between devices in various process industries, which is used to connect process interfaces such as sensors and actuators with control systems. I2C protocols can also be used for the same purpose (i.e., connecting sensors and actuators with control systems) but over smaller distances.

Applications of digital communication protocols in the nuclear industry

As discussed earlier, the nuclear industry has been quite slow in adapting the latest development in electronics and automation due to the larger amount of safety standards the latest technologies must satisfy in order to be adopted into the infrastructure of the nuclear industry. However, at the same time the nuclear industry is also one of those which require automation more than any other industry due to the involvement of radioactive materials and different types of radiation that are involved in various parts of the industry, from mining and enrichment of nuclear fuel to power production using a controlled fission chain reaction to nuclear waste management, at all stages and parts of the nuclear industry, radioactive materials and radiation is always involved and hence the requirement of automation is urgent.

However, according to a report published by the International Atomic Energy Agency (IAEA) [1], the automation in nuclear power plants around the world still relies on 4-20mA analog technology of the 1960s, but slowly various digital communication standards and protocols including analog-digital hybrids like HART and purely digital ones are being adapted by the nuclear industry to improvise its automation systems.

As the nuclear power plants already possess the infrastructure of 4-20mA analog communication technology, it is easy to implement HART compatible networks on top of this existing infrastructure. However, HART still has the obvious disadvantage of significantly lower data transmission rates as compared to purely digital transmission protocols such as I2C and SPI, especially over lower distances.

Therefore, it will be more optimal to utilize digital inter circuit communication protocols such as I2C for information exchange between devices placed at shorter distances to each other. However, to transmit data over an I2C enabled network, the data collected by sensors must be converted from analog to digital, using analog to digital convertors (ADCs).

CONCLUSION

Considering the characteristics, advantages and disadvantages of both HART and I^2C communication protocols, a conclusion can be made that both of these protocols can be useful in replacing the older analog field communication systems in place in the nuclear power plants and modernizing the automation technologies there. I^2C, being able to support faster data transmission rates over shorter distances can be utilized to transmit information between process interfaces such as sensors and actuators and data acquisition systems placed over shorter distances. This would require the use of analog to digital converters to convert the analog data collected by the sensors (any of them such as pressure, temperature, neutron flux sensors etc) into digital and then transmit it over to the data acquisition systems. Whereas for communication over longer distances up to 3000 meters, HART protocol should be utilized since it can function over the already in place 4-20mA DC analog wiring systems and hence from an economic point of view, such an arrangement would be beneficial since it won’t require installation of new infrastructure to support the usage of digital electronics instead of analog. And for a more modernized automation in the nuclear industry, the field communication aspect of the instrumentation and control systems of the NPPs can adapt these digital serial communication protocols to replace the existing analog field communication systems.

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