Frequency-based protection schemes used to realise load management in modern substation automation systems

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BACKGROUND

Load management is an on-going challenge for electricity network operators. It requires constant monitoring and control of the load to maintain the balance between electricity generation and load demand during various network conditions. Failing to maintain the load/generation equilibrium could potentially lead to a widespread blackout.

System frequency plays an important role in indicating network overloading, as it drops when the load demand exceeds the available generation capacity. It is not a new concept for the power industry to manage their load demand using frequency based protection, but new technological developments allow for more sophisticated applications. Modern substations are equipped with intelligent devices utilising modern technologies that allow speedy and flexible load control automation to cope with the on-going network and customer demand changes.

KEY ASPECTS

Interruptible load and AUFLS

In New Zealand, load management requirements are defined under the Electricity Industry Participation Code (EIPC).

It firstly provides for interruptible loads (IL) that can be voluntarily shed when the system frequency drops to 49.2Hz. The IL refers to loads that are 'instantaneous reserve that is able to be disconnected to balance the injection supply' [1]. Vector subscribes to this by for example shedding hot water load to ease network constraints - with minimal noticeable interference to customers' electricity supply.

The EIPC further defines two blocks of mandatory Automatic Under-frequency Load Shedding (AUFLS). The first block of load (i.e. zone 1) is shed within 0.4 seconds after the system frequency drops to 47.8Hz. If the frequency persists at 47.8Hz or lower for 15 seconds, the second block of load (i.e. zone 2) shall be shed. In addition, the second block of load shall also be shed within 0.4 seconds if the system frequency drops to 47.5Hz. An AUFLS event generally occurs after a serious system fault, such as sudden loss of a large generator, and generally requires a large amount of load to be shed to maintain system stability. EIPC defines a 16% load shedding from each block giving a total of 32% of load loss in the worst case scenario. It is critical, but challenging for the network operators to implement AUFLS at the right time with the right amount of the load shedding.

Substation Automation System and IEC-61850

Modern technologies and communication facilities provide new opportunities to realise optimal operations of critical protection schemes like AUFLS or IL. This is achieved through Substation Automation Systems (SASs). SAS categorises the system into process level, bay level and station level based on their functionalities. The equipment located at process level are generally the substation primary assets (e.g. transformers and circuit breakers) providing real-time analogue (i.e. current or voltages) or digital information (e.g. circuit breaker open or close) to the bay level devices. The process level equipment is also controlled by bay level devices to maintain an optimal network performance (e.g. via circuit breaker operations or transformer tapping). Bay level devices are generally intelligent devices. They receive the real-time information from process level devices and analyse it based on their internal logic. Based on the analysis, bay level devices not only issue control signals to the process level equipment but also provide selective information to the station level. Station level equipment is equipped with facilities to receive information from the bay level to monitor and control substation activities. Refer to Figure 1.The IEC-61850 standard 'gives wings' to the Substation

Automation System. It is an international standard that defines a common language to be used to realise substation automation. According to the standard, the communication between Bay Level and Station Level can be realised using Manufacturing Message Specification (MMS). Communications within Bay Level itself can be realised using Generic Object Oriented Substation Event (GOOSE) messaging. Power Companies take the advantage of this new level of flexibility brought by IEC-61850 to create cost effective and reliable solutions to implement AUFLS, IL shedding as well as other important protection schemes.

IMPLEMENTATION

Interruptible load shedding and AUFLS could be realised using modern substation automation system as shown below.

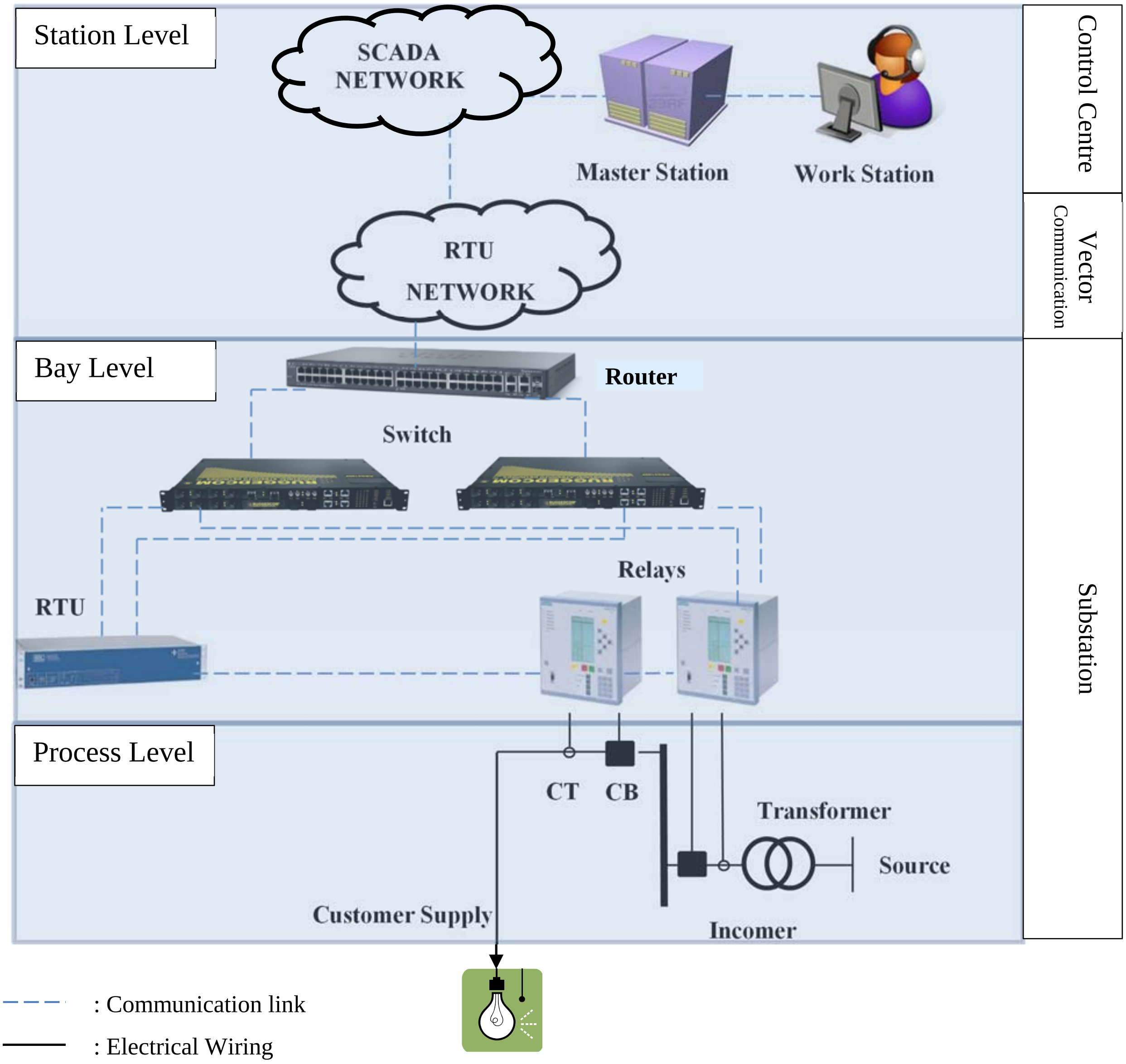

Figure 1: End-to-end load control using Substation Automation System

Customers are supplied with electricity via their local substations during normal operating conditions. The Intelligent Electronic Devices (e.g. Relays and RTU) installed in the substation are configured to monitor system conditions based on information retrieved from current and voltage transformers. Once abnormal conditions are detected, the IEDs issues signals to Circuit Breakers to shed the load. Substation activities are visible to the Control Centre via communication infrastructure inside and outside the substation using the IEC-61850 standard. Apart from monitoring, the Control Centre is also capable of controlling substation devices to carry out manual load shedding. Substation IEDs and the communication infrastructure inside and outside the substation play an important role in realising the load management automation. These are described below.

Zone Substation

Intelligent Electronic Device

IEDs are microprocessor based devices allowing speedy operation and flexible logic execution. They are multifunctional and can be configured to monitor a number of conditions associated with their targeted areas. Frequency-based protection like AUFLS is one of the protection scheme that can be implemented through these devices. In addition, the IEDs can accommodate changes with minimum interference to the existing network. This allows remote control of substation devices with few clicks of the mouse from the Control Centre.

Vector equips numerical relays and remote terminal units (RTU) in their modern substations to realise AUFLS and IL shedding. With reference to Figure 2 below, a typical zone substation comprises circuit breakers with relays to provide reliable electricity to the surrounding customers. The feeder relays are configured with a standard AUFLS scheme according to the EIPC requirements. Based on the analysis from the planning team, each feeder relay is set to operate at either zone 1, zone 2 or AUFLS disabled. The AUFLS selection is not fixed and could be altered locally or remotely via the relays.

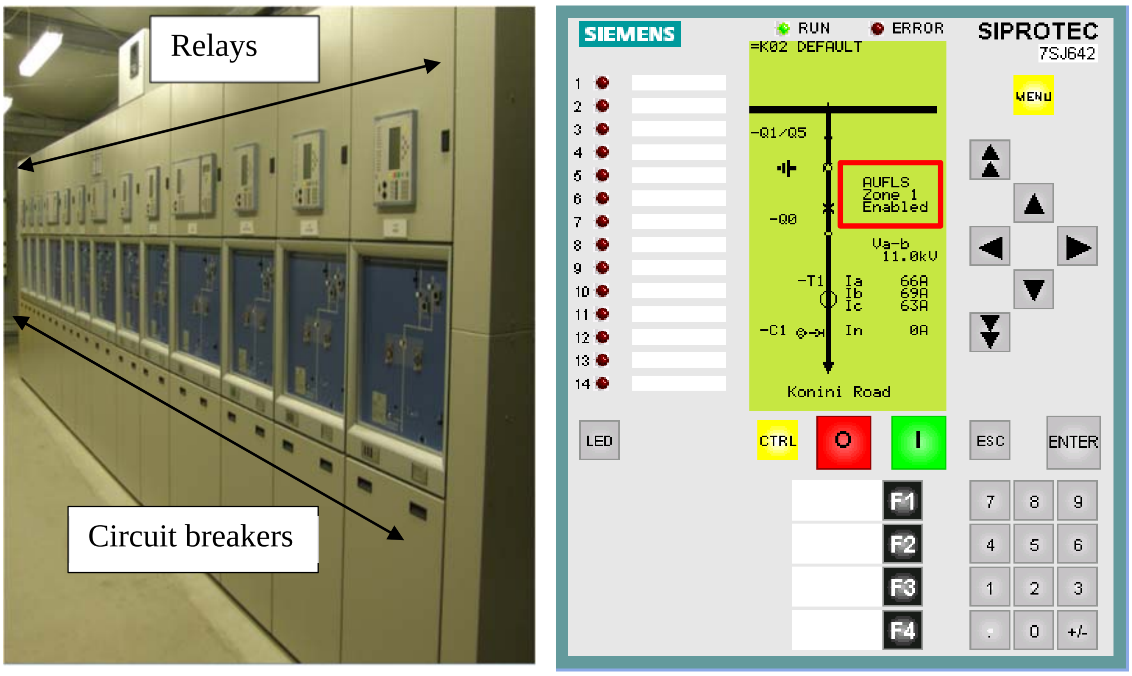

Figure 2: Switchboard and Feeder 2 relay with AUFLS zone 1 enabled, Atkinson

At Vector, the main IL shedding is from the hot water supply. At the moment, the majority of Vector's hot water supply control is carried out via a centralised under-frequency hot water radio dump system. The system is setup to detect under-frequency conditions and issues tripping signals to multiple sites via radio links. With more recent applications, the hot water control systems are being replaced by Substation Automation Systems to realise de-centralised control. These are much faster and more flexible.

As each substation is equipped with relays that sense the system frequency value. They are capable of determining if the system requires IL shedding (i.e. frequency drops to 49.2Hz). Instead of installing dedicated CT/VT and relays for controlling the hot water circuits, the information from the incomer relay can be shared with the RTU (Remote Terminal Unit) device installed in the hot water control panel.[1] In this case, the hot water circuits can be controlled by the RTU device which takes the tripping signal from the substation incomer relay and trips the hot water supply automatically. The RTU is configured to implement local/remote control of the hot water circuits. This means the operator can pick and choose the hot water circuits to be controlled automatically or manually depending on the demand and criticality of the load. Also, hot water supplies can be forced to turn on and off using the control switch inside the substation.

Substation communications

Modern substations are equipped with switches and routers to allow speedy and flexible communications. Network switches create networks (i.e. Local Area Network), routers connect to the network (i.e. Wide Area Network). The substation IEDs are connected to substation routers and network switches to realise communications among the IEDs as well as information sharing with systems outside the substation, e.g. the Control Centre.

Vector's modern substations are equipped with switches, routers and IEDs communicating via IEC-61850 to realise AUFLS and IL shedding schemes. For example, functions associated with each AUFLS zones are named according to the IEC-61850 standard. With reference to Figure 3, a tripping on AUFLS zone 1 is called PROT/PTUF1/OP which standards for Protection/Under-frequency zone 1/Operations. This meaningful function names are visible to Control Centre as 'UnderFreq Trip 81U'. The communication standard used in this application is called IEC-61850 MMS which is generally used for exchanging real-time data and supervisory control information between substation devices and the Control Centre. MMS messaging is unicast, this means information sent from the device is dedicated to one receiver from the system build behind the Control Centre (i.e. Power Automation System and Supervisory Control And Data Acquisition System). In a typical Vector substation, the IEDs are connected in a ring which then connect to two switches to have redundancies in the substation network. As a result, if the default communication path is not available, alternate paths can be used to 'deliver' the same information. The 'MMS' path shown in Figure 3 is an example.

[1] A RTU is a microprocessor-controlled device that can receive analogue or digital information as its input and then control its connected devices by switching the output contacts on and off.

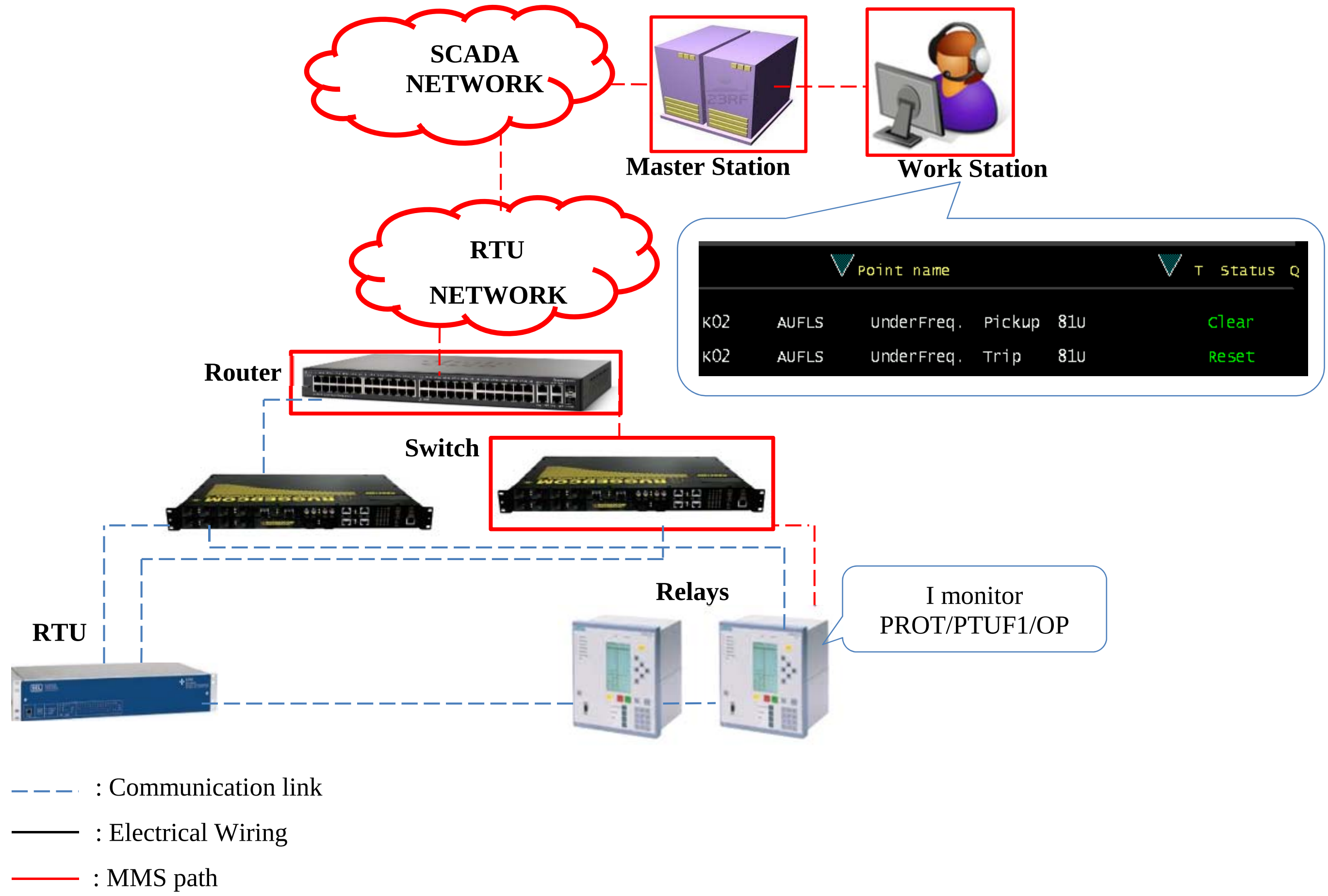

Figure 3: Communication between Relays and Control Centre using MMS

In modern substations with IEC-61850 capability, IEDs provide interesting options for IL shedding. As mentioned above, the incomer relay sends IL shedding information to the RTU installed in the hot water control panel. This communication is achieved using IEC-61850 GOOSE messaging. The incomer relay is configured to constantly monitor the frequency value for IL shedding (i.e. 49.2Hz). It is also configured to be the publisher of this information. Unlike MMS, GOOSE messaging is multi-cast. This means, the IL shedding information is available to multiple devices from the substation. It is up to the hot water panel RTU to subscribe this information and then issues the tripping signal to the hot water circuits. Referring to Figure 4, the information is published by the incomer and then subscribed by the RTU. Meanwhile, the hot water tripping information is visible as 'WH Incomer U/F Trip' at the Control Centre via IEC-61850 MMS messaging.

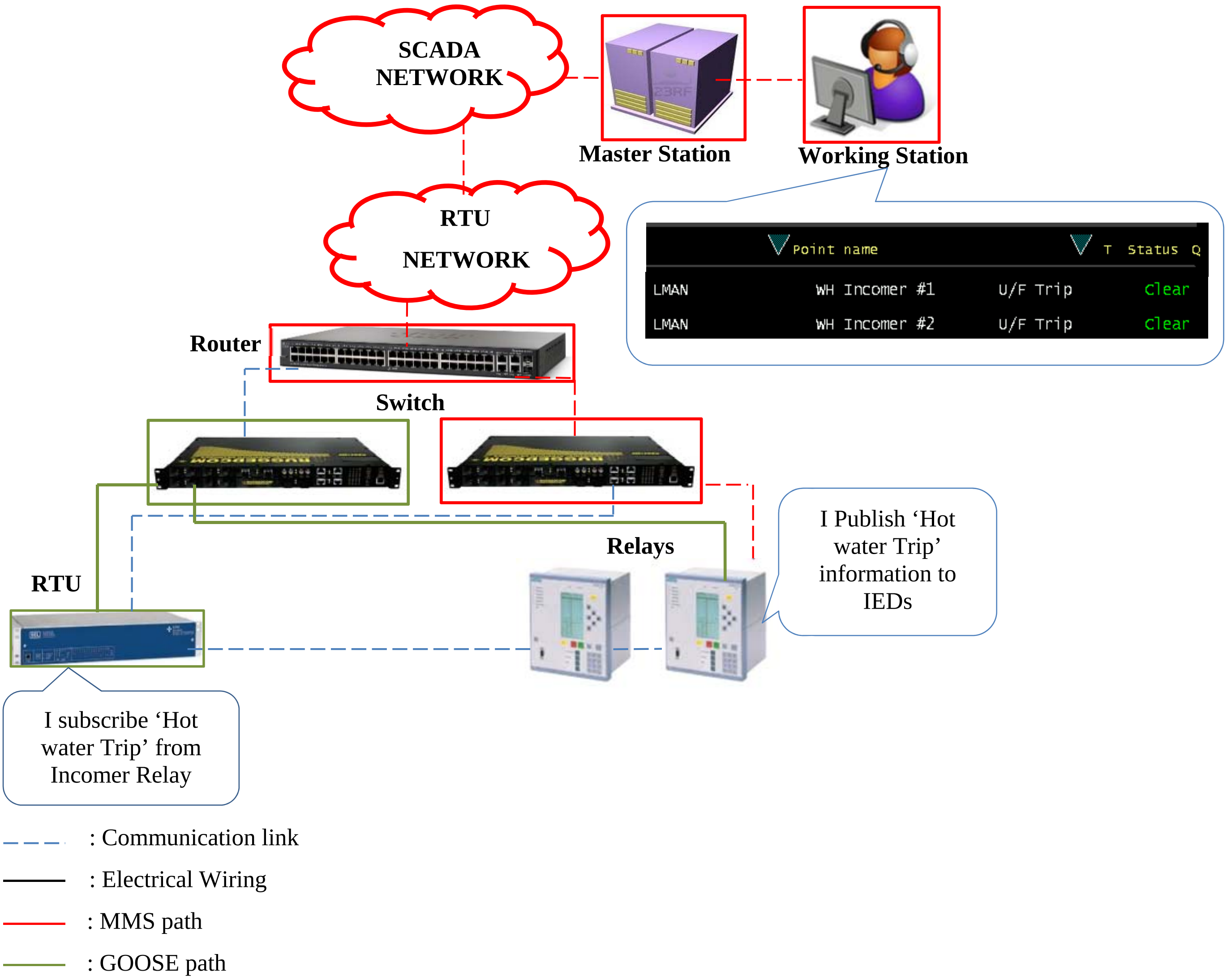

Figure 4: Example showing the communication between RTU, relays and Control Centre using GOOSE messaging and MMS

Communication Infrastructure

From substation to Control Centre

A Local Area Network (LAN) is a network that connects devices within a limited area. The substation devices connected to switches are therefore part of the substation LAN which allows communications between the devices within the same substation. It can also be configured into multiple Virtual LANs (VLANs) to provide segregations of substation devices of different purposes. A RTU Network is a secured Wide Area Network (WAN) that is managed by Vector Communications. Once the information is ready to be sent out from the local substation, it 'travels' through the substation LAN to the RTU network and then received by Control Centre via Vector's Supervisory Control And Data Acquisition (SCADA) network. Refer to Figure 5.

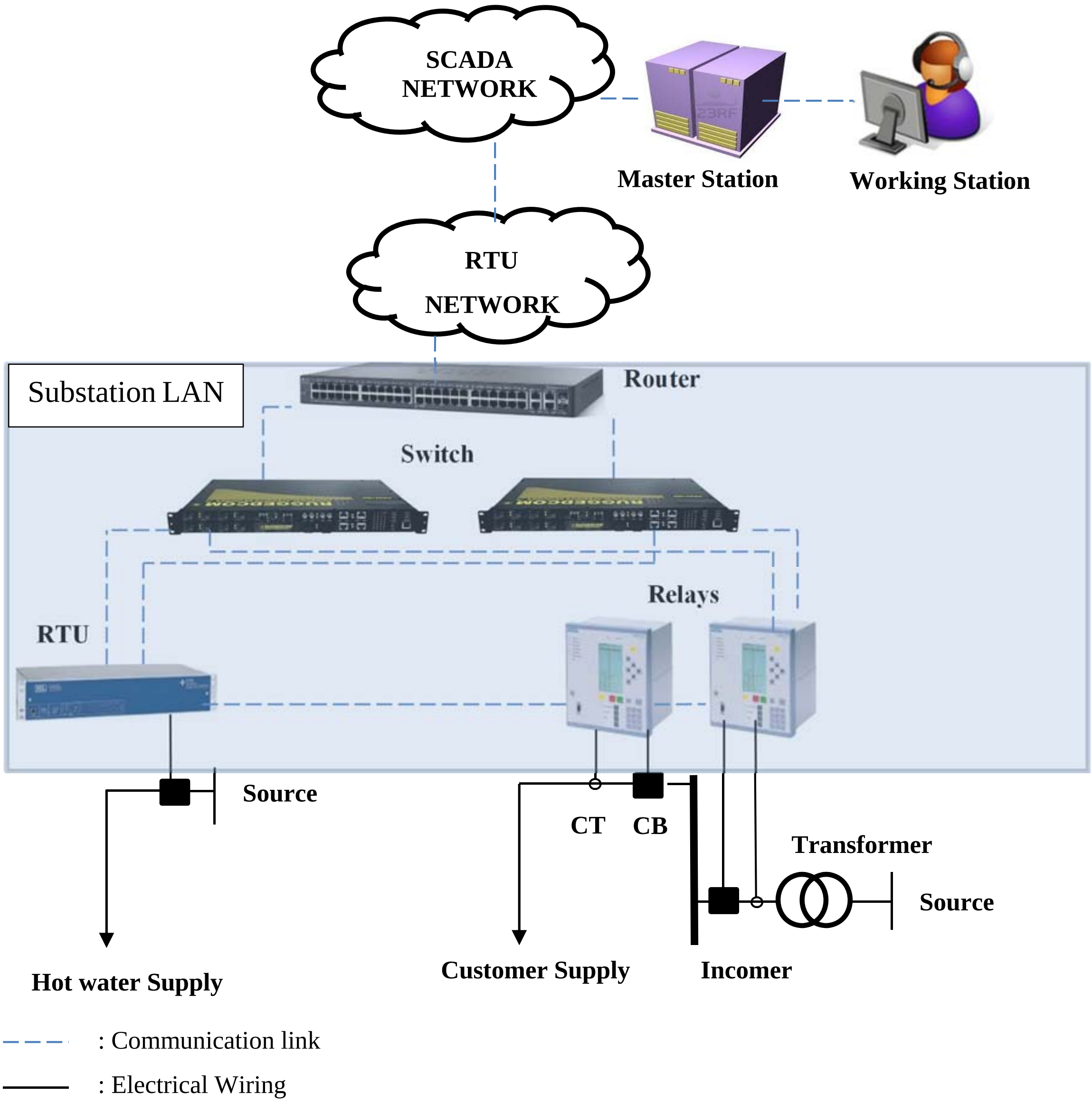

Figure 5: Substation LAN and its relation to the Substation Automation System

Control Centre

As mentioned previously, the Control Centre has the ability to monitor the ongoing status of AUFLS and IL shedding along with other substation information. Refer to Figure 6, the example shows feeder 4 and feeder 10 are operated with AUFLS zone 1 enabled with the rest of the feeders operating with AUFLS disabled.

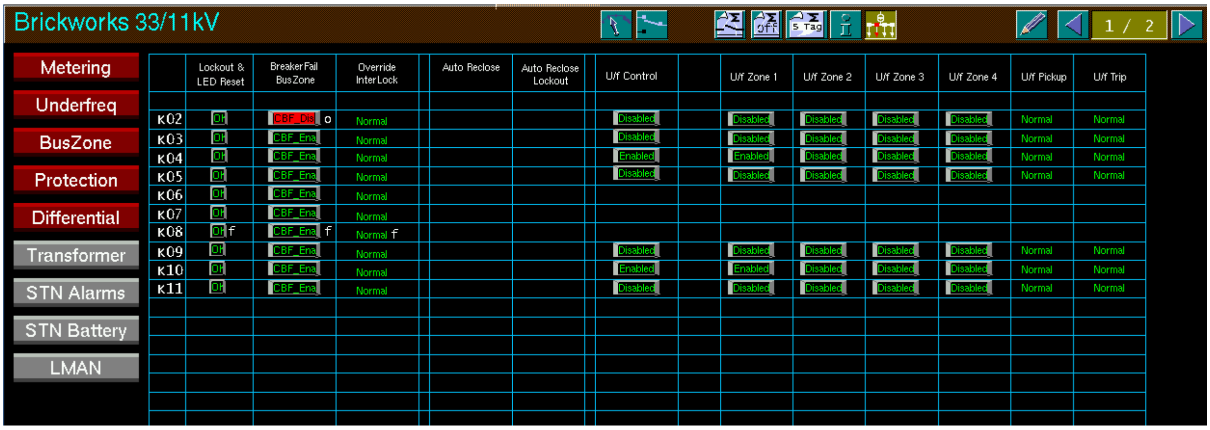

Figure 6: Control Centre screenshot showing AUFLS status, Brickworks

Similarly, the IL shedding status can be seen by the Control Centre as shown below. In this particular example, all three hot water circuits (A, B and C) are disabled from automatic under-frequency IL shedding. This means the hot water supply cannot be cut off when an under-frequency condition (i.e. 49.2Hz) is detected by the incomer relay.

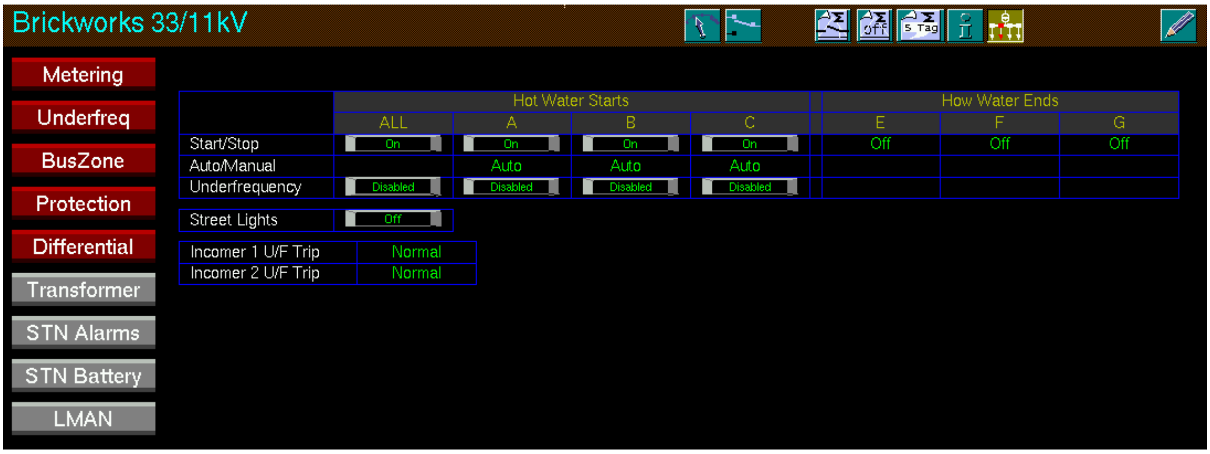

Figure 7: Control Centre screenshot showing Hot water control status, Brickworks

Controllers are able to operate the buttons from the screenshots above and alter the AUFLS zone selection, enable/disable the automatic hot water control or to carry out manual load shedding.

CASE STUDY

AUFLS event

An AUFLS event occurred on the 12 November 2013 due to an HVDC commissioning test failure. As a result, the power flow from South Island was cut off leaving a generation deficit in the North Island. Block 1 AUFLS event was initiated as the grid frequency dropped to 47.8Hz, with Vector shedding 7.5% (or 90.5MW) of its load against the AUFLS requirements of 16% [2].

The under-frequency event that occurred is quite unique in terms of its duration and frequency variations, in that the system frequency dropped to 47.785Hz for 250 milliseconds which is only 0.015Hz below the zone 1 frequency threshold. The accuracy tolerance of modern IEDs varies from manufacturer to manufacturer. In general, the frequency tolerance is around 0.005 ~ 0.010Hz with a pickup time of approximately 80 milliseconds and a delay tolerance time of 3% of the setting value or 10 milliseconds to guaranteed trip initiation [3]. Vector relays are set to operate AUFLS zone 1 with 120 milliseconds delay. Based on the relay tolerances, under a worst case scenario, relay requires an under-frequency duration > 200ms. This particular event occurred at the boundary of the frequency and duration threshold, if the under-frequency event have been sustained for longer, 18.1% of Vector's load could have tripped, which is well above the required percentage.

The event record of Atkinson Substation Feeder 2 has been retrieved as an example, see Figure 8 below. AUFLS zone 1 (i.e. 81-1) is picked up for 120ms followed by a 'Relay TRIP' assertion. The circuit breaker takes approximately 50ms to open after receiving the tripping command.

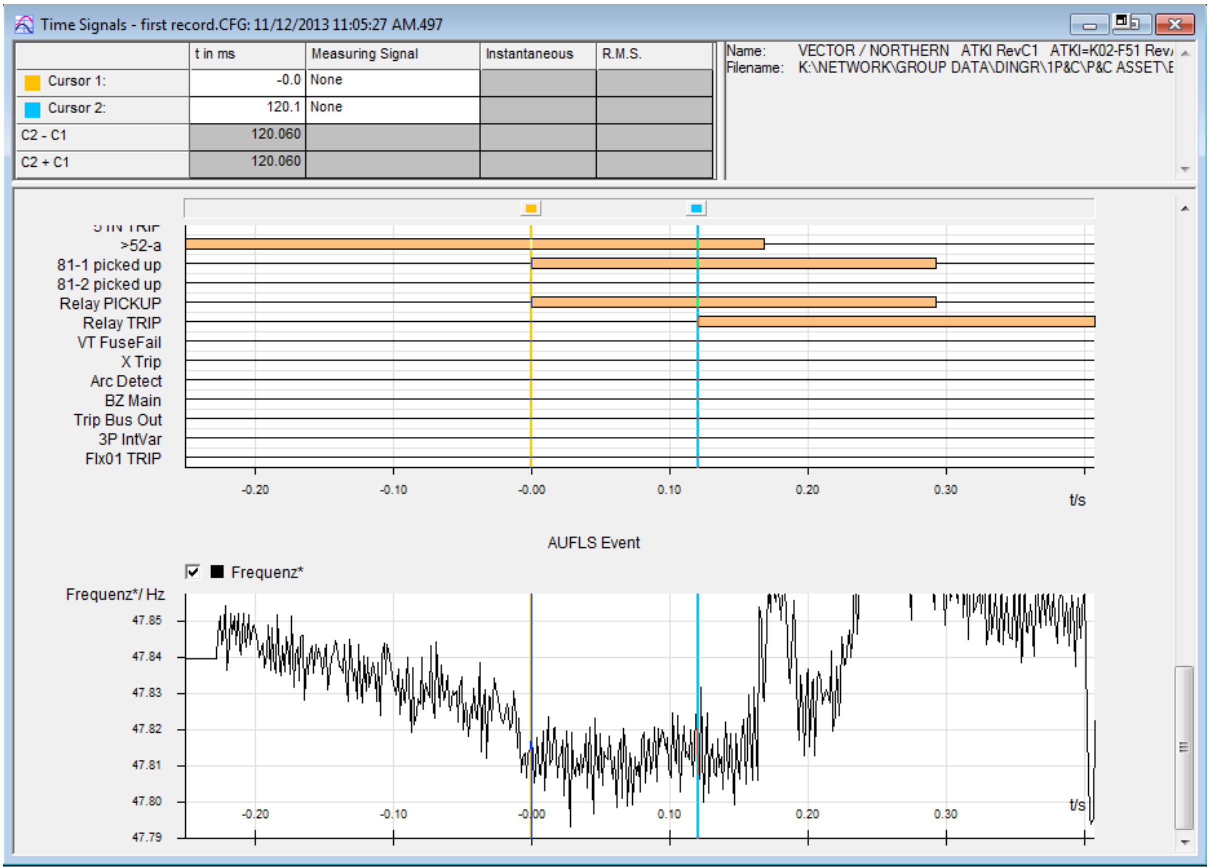

Figure 8: Feeder 2 response to AUFLS event from November 2013, Atkinson

The event was also recorded at the Vector Control Centre as shown below.

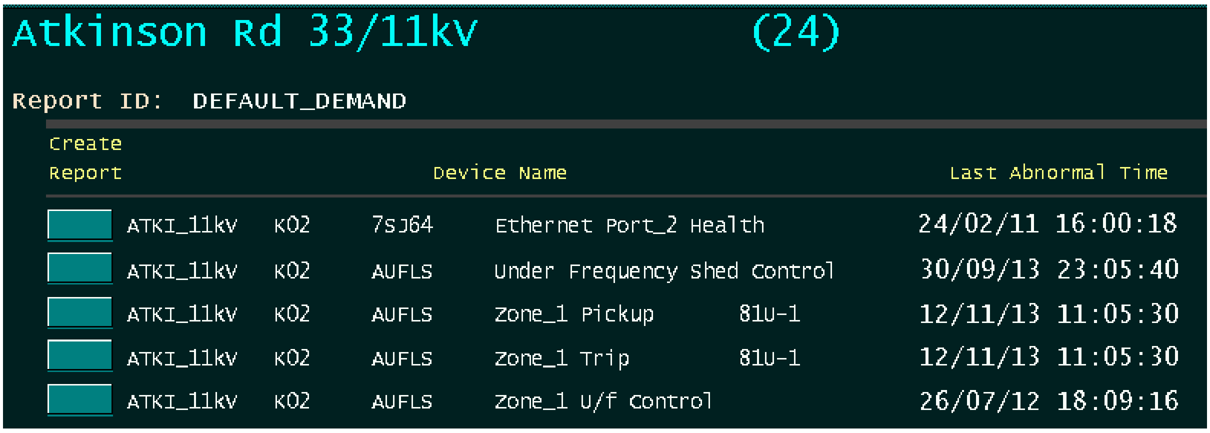

Figure 9: Control Centre display showing feeder 2 (Atkinson substation), AUFLS operation

Utilisation of the IEDs gave useful information for engineers to analyse the event that occurred and the subsequent relay operations. The remote control capabilities were effectively used to achieve remote feeder restoration after the AUFLS event using our modern communication infrastructures and the IEC-61850 communication standard. It is however noted that no matter how sophisticated the relays are, they all have an accuracy tolerance margin. Given the closeness of the event parameters to the operating margins, various devices reacted differently to the same AUFLS event. In addition, as each AUFLS event is unique, it can be a challenge to prove that the network company has in fact met its AUFLS obligations.

IL Event

At Brickworks substation, the original hot water supply was controlled by the centralised radio dump system at Sunset Road substation. As part of Brickwork's protection upgrade, a RTU with IEC-61850 capability was installed in the hot water control panel. This RTU is connected to the substation switches along with other substation IEDs. As mentioned previously, information from the hot water panel RTU can be shared with Control Centre using IEC-61850 MMS. The under-frequency condition is retrieved by the RTU from the incomer panel relay using IEC-61850 GOOSE messaging.

The implementation of IL shedding using SAS and IEC-61850 greatly reduces the large amount of control and signalling hard-wiring otherwise required to a few fibre connections. It also reduces the hot water tripping speed from 6 seconds to less than 200 milliseconds. The GOOSE message is also available for monitoring purposes. Last but not least, with modern substation automation systems, applications like hot water load shedding can be easily set up using the existing modern substation IEDs, this means large amount of work can be carried out in the office with no/minor physical changes at the substations.

NEAR FUTURE

Modern Substation Automation Systems can effectively be adapted for future changes. This could include adding more AUFLS zones, or to implementing centralised AUFLS control via Transmission System Operators (i.e. Transpower).

At the moment, AUFLS events are determined using frequency value. To justify if sufficient load is shed by electricity distribution companies like Vector, a percentage value is used as the benchmark. However, it is difficult to determine if the selected feeders will be able to make 16% of the overall load available for shedding when the AUFLS event occur. Accordingly, to avoid breaching our obligations, a higher quantity of load is programmed to be shed. This situation can be improved by for example EIPC increasing the number of AUFLS zones or implementing rate-of-change in frequency standards to determine load shedding conditions. Such changes will require modifications to relay settings, and SCADA mapping at the Control Centre needs to be modified to cope with the requirements – this can be easily accommodated with the new IEC 61850-equipped devices. No physical changes would be required at the substations.

A bit further down the track, AUFLS could also likely be implemented using centralised control signals from Transmission System Operators. Once again, the infrastructure installed in modern substations would be capable of receiving and responding to the control commands using the IEC-61850 communication standard. Again, no physical changes would be required to substation devices.

ACKNOWLEDGEMENTS

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REFERENCES:

[1] Electricity Industry Participation Code 2010

[2] Under-frequency event – 12 November 2013 – technical report, Vector

[3] Siemens relay manual