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Modular Web Enabled Protection, Control and Monitoring Systems for Small Distribution Substations

Dr. Alexander Apostolov
ALSTOM T&D Bitronics
Los Angeles, USA

Georgia Tech
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1. Introduction

The electric utility industry is going through significant changes caused by deregulation, distributed generation, increased competition and requirements for continuous improvement in the quality of power supplied to the users. At the same time the use of the Internet is growing and more and more utilities are using Wide Area Networks for their communications.

These are some of the reasons that utilities are looking today for new solutions based on state-of-the-art Intelligent Electronic Devices (IED) and integrated substation protection, control and monitoring systems. Such systems have to provide an economical way of delivering locally or remotely metering, monitoring, control, protection and recording functions to the different users in a utility or industrial facility.

A Web enabled protection, control, monitoring and recording (PCMR) system should be designed to provide a complete pre-engineered and cost effective solution in order to meet the needs of small industrial, municipal or rural distribution substations. The system should be based on modern off-the-shelf technology and industry standard communications and browsing tools.

The Web PCMR system should have a modular design with the basic module specified for a typical distribution substation with a single power transformer and up to four distribution feeders. The paper describes in detail the protection, monitoring and control features of the feeder and transformer IEDs.

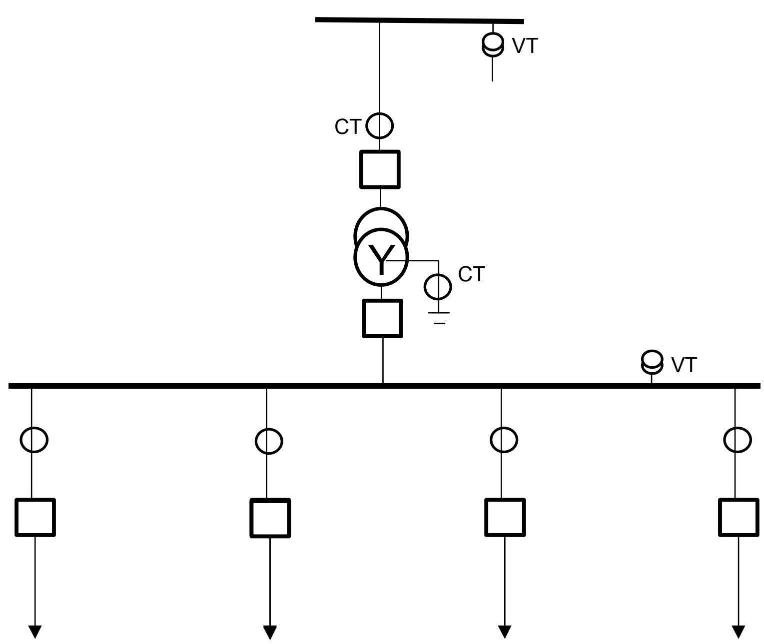

Figure 1 Typical small distribution substation

For new substations the base configuration would use microprocessor relays for feeder protection that provide a complete set of the basic protection functions implemented in existing substations with electromechanical or solid state relays, including four-shot autoreclosing.

If the utility would like to only partially upgrade the protection, monitoring and control functions and keep the existing reclosing devices, a microprocessor feeder protection relay without reclosing can be used.

The two configurations are basically identical and are offered to support both existing and new distribution substation installations. The two relay types can also be mixed in the configuration allowing migration to newer protection equipment and services.

The base protection schemes shown above can be expanded or enhanced through the selection of the Protective Intelligent Electronic Devices (PIED) used on the high side of the transformer.

Some examples of enhanced protection options are:

- Relay Tripping Redundancy
- Extended Protection
- Extended Protection with Mimic Diagram

The Web PCM can be pre-assembled for use as a turnkey solution. The basic system configuration is shown in Figure 2. Enhanced protection options can easily be added into the base system.

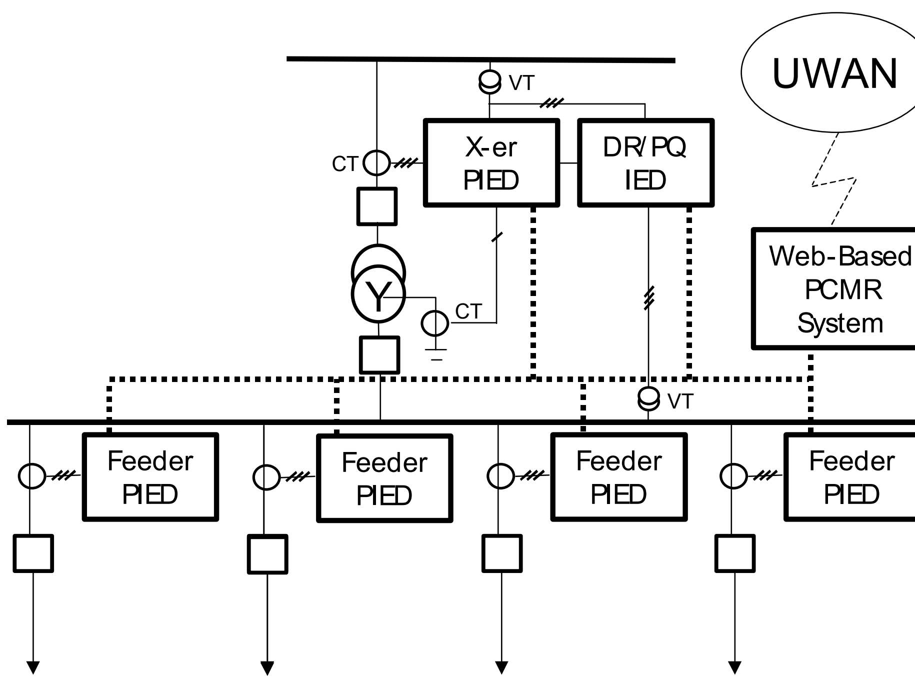

Figure 2 Simplified communications diagram

The basic system is designed to support standard industry communication protocols such as Modbus RTU or DNP 3.0. The RS-485 Modbus data communications network allows the Substation PC to poll the relays in a Client/Server manner. Data is retrieved from the relays in real-time and stored in the PCM system memory resident SCADA database.

The PCM system can be remotely accessed by either modem connection or Ethernet LAN. The PCM system can interface externally to other systems or operators through either the Modbus or DNP 3.0 protocols, ICCP (TASE.2) network, or just an Internet Explorer 4.0 or above browser. If desired, an optional Local User Display is also available. The local user display includes a 15" monitor, keyboard, and trackball.

The WebPCM system is designed for installation into a standard 19" rack. The rack can either be provided with the system or customers may already have space available in existing racks or panels. A typical WebPCM configuration is shown below in Figure 4.

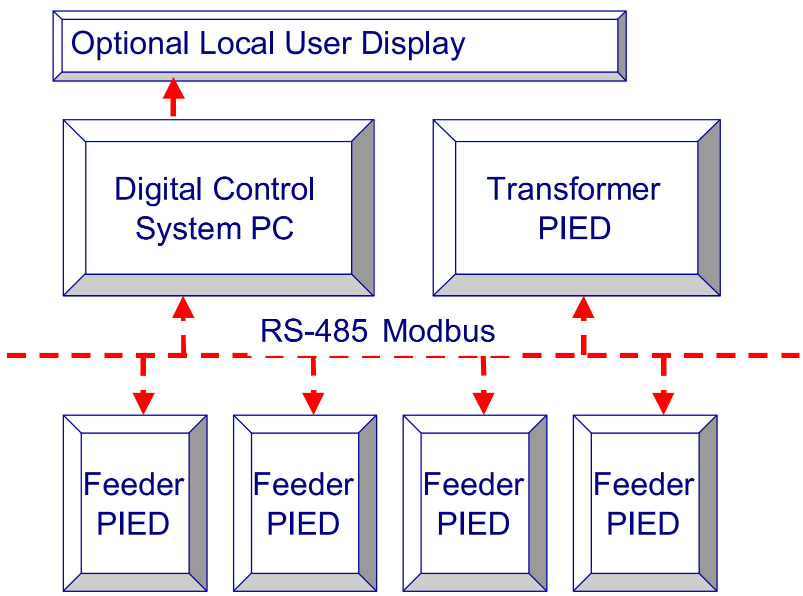

Figure 3 System Configuration

The configuration shown here can be modified to fit specific custom protection needs. The feeder protection IEDs can be with or without autoreclosing.

The IEDs installed on the high side of the transformer can be of different types, depending on the requirements of the user regarding power supply, integrated control or advanced functionality. The configurations can be tailored to meet the specific needs of the utility in a very cost-effective manner.

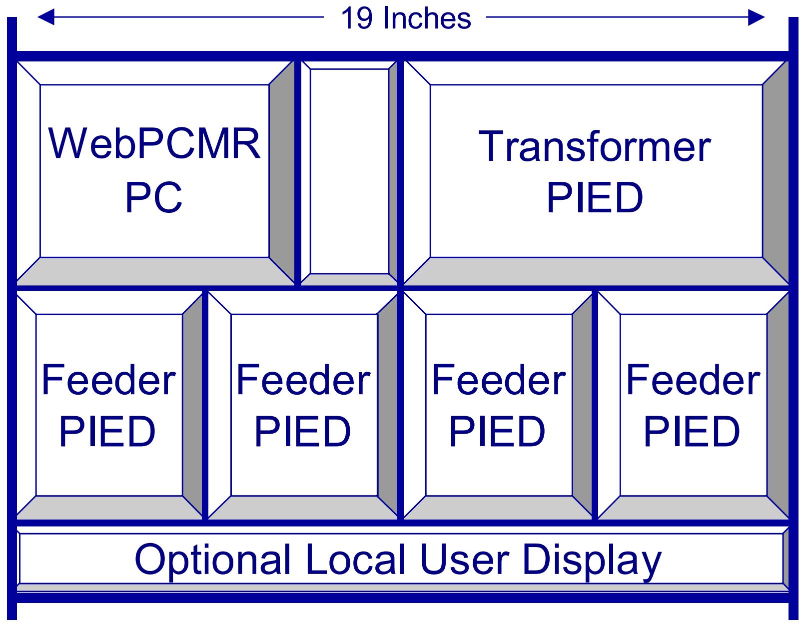

Figure 4 Example of 19 inch rack configuration

2. Substation Protection, Control, Monitoring and Recording

The distribution of protection, control, monitoring and recording functions between the different IEDs used in the integrated system is very important in order to ensure the most cost effective and at the same time complete solution.

Since protection and monitoring/recording devices are designed with different primary functionality, they should be selected in such a way, that the requirements for primary and backup devices for each function are available.

Obviously, the primary protection functions will be performed by the protection IEDs on the transformer and the distribution feeders.

Backup protection for the transformer should be provided by a backup protection IED or by backup protection functions in a monitoring/recording IED.

The backup protection for the distribution feeders should be provided by using advanced protection functions and logic schemes implemented in the transformer relays and based on status, alarm or control signals from the feeder relays.

The main monitoring and recording functions for the substation transformer and distribution bus should be provided by a specialized power quality monitoring and recording device. Backup monitoring and recording should be provided by the transformer protection IED.

The main recording and monitoring function for feeder faults or other abnormal power system conditions should be performed by the feeder protection IEDs. Since the faulted feeder and the transformer are in series, backup recording for feeder faults can be provided by the monitoring recording device on the transformer and the transformer protection IED.

Figure 5 shows the IEDs for one possible configuration of an integrated PCMR system that meets the above requirements.

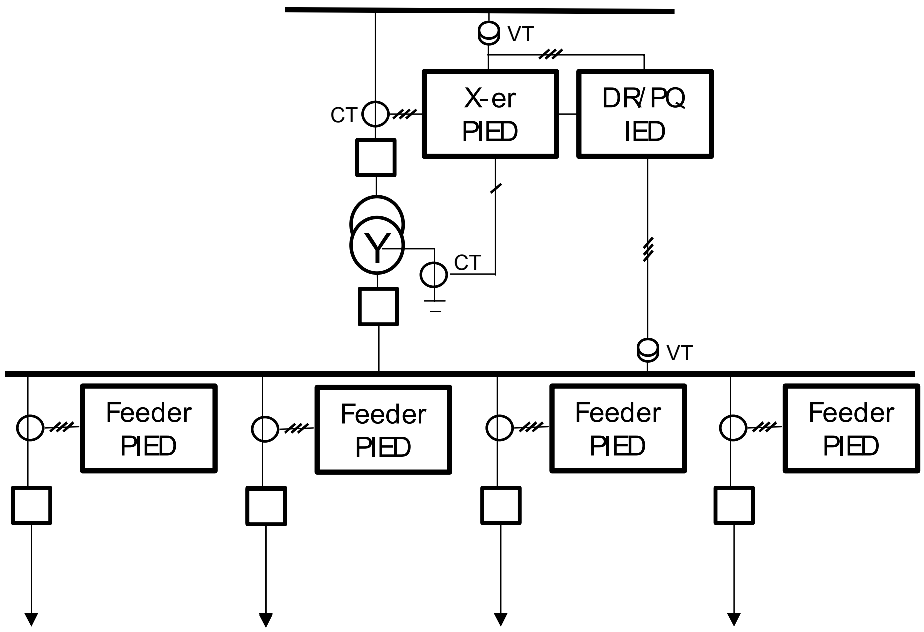

Fig. 5 Protection and monitoring/recording IEDs in a PCMR system

3. PCM System Substation Computer

3.1 Computer Processor

The PCM requires a standard Windows based PC. An example is a substation computer with Intel 266 MHz processor integrated into a PC104 form factor subsystem. The processor is equipped with 128 MB of memory and has 4 Gigabytes of disk. The unit is equipped with an RS-485 serial port, two Ethernet ports, and a PCMCIA modem for external communications. The computer is driven from DC and can be run off station batteries. The PCM system susbstation computer runs Microsoft's Windows 2000 operating system. The processor is equipped with connections for an optional external monitor, keyboard, and trackball.

3.2 System Architecture

Figure 6 below depicts an example WebPCM system PC104 system configuration and shows the communications available. All IEDs are connected through an RS-485 shielded twisted pair network that can run up to 1000 meters. The PCM system processor executes a RTU MODBUS master station implementation of this industry standard protocol. This allows interfacing of up to

31 devices to a single MODBUS master station. This MODBUS master may be connected via RS485, RS232 or fiber optic. Optional devices include a 56 Kbps modem, local user display, or UCA 2.0 devices.

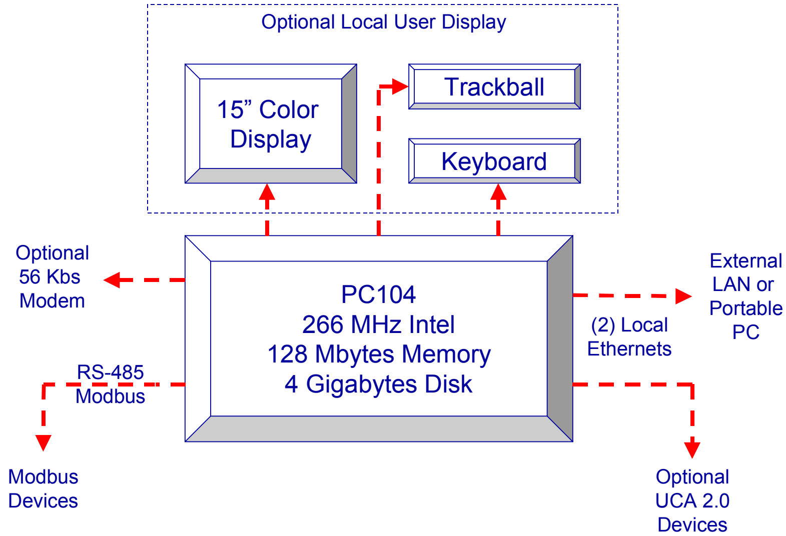

Figure 6 Simplified substation PC architecture

3.3 SCADA Functionality

The PCM system requires a memory resident SCADA software package with a wide range of SCADA features including:

- Real-time Data Viewing
- Event and Alarm Logging
- Real-time Trending
- Historical Data (periodic or by exception)
- Abnormal and Not In Service Summaries
- ASCII Import/Export of Data
- Flexible Calculator Package
- Multiple Limit Checking
- Audible Annunciation

When the PCM SYSTEM is integrated into a mail service, the alarms may also be issued using common e-mail services to other mail address, pagers, or even cell phones.

3.4 Human Machine Interface

One of the main problems with any integration system is the development of the Human Machine Interface. The concept of the modular Web enabled system described in the paper is to have a pre-engineered solution. This is achievable for the small distribution substations under consideration, because they have a pretty much standard configuration. Still, the user may have requirements for customization in order to develop a "utility standard" HMI. This requires the availability of engineering tools such as a display builder. That allows cutomization of displays and graphical representation of data and alarms. The displays may be interconnected through hot links for navigation between views.

These tools have to be user friendly and should support a drag and drop display to database linkage tool which allows easy connection of icons to database values such as status, analogs, and counters.

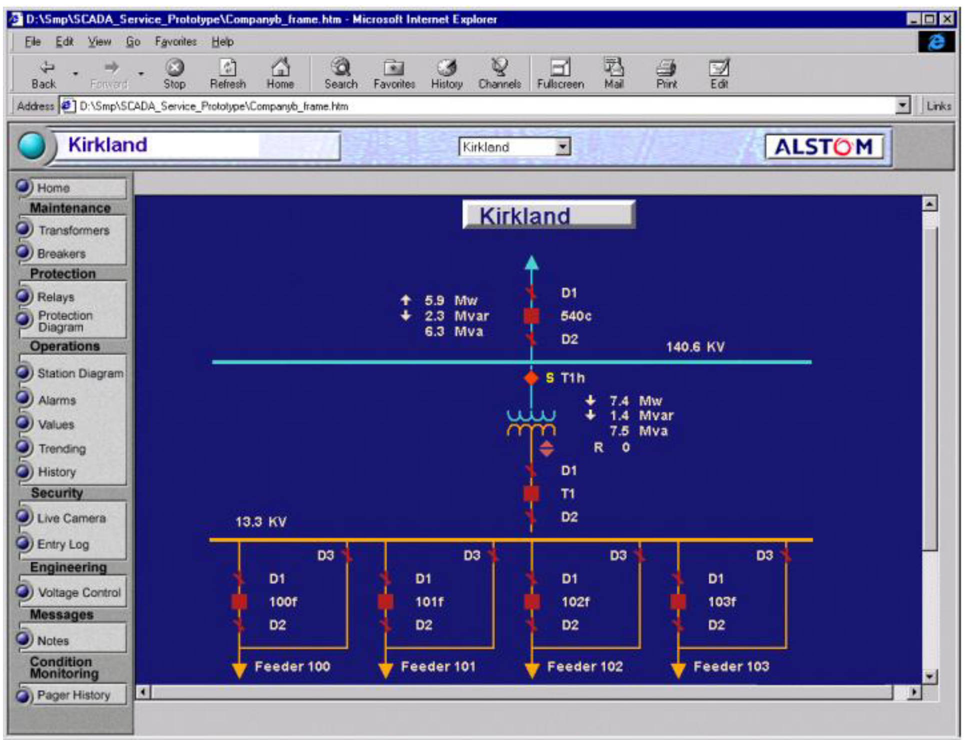

Fig. 7 Substation one-line diagram in a Web browser window

3.5 External Web Browser Interface

The PCM system is also equipped with a display builder that is quite unique. When a display is built and linked to the database, two viewable images are automatically generated. One of the images can be locally displayed on an optional user display unit and does not require a browser to be viewed. The second image is created using HTTP, which means that the display may be viewed with Microsoft's Internet Explorer from a remotely connected PC. These displays may be viewed locally on one of the two Ethernet connections or remotely using the optional 56 Kbps Modem for external access via phone line.

Fig. 7 shows the substation one-line diagram from the Web browser interface. Fig. 8 shows a page with a view of the yard from a substation camera in the center. On the left side of the page are the controls that allow the user to select other screens such as the substation one-line diagram, load profiles, the communications architecture, alarm and event logs, etc.

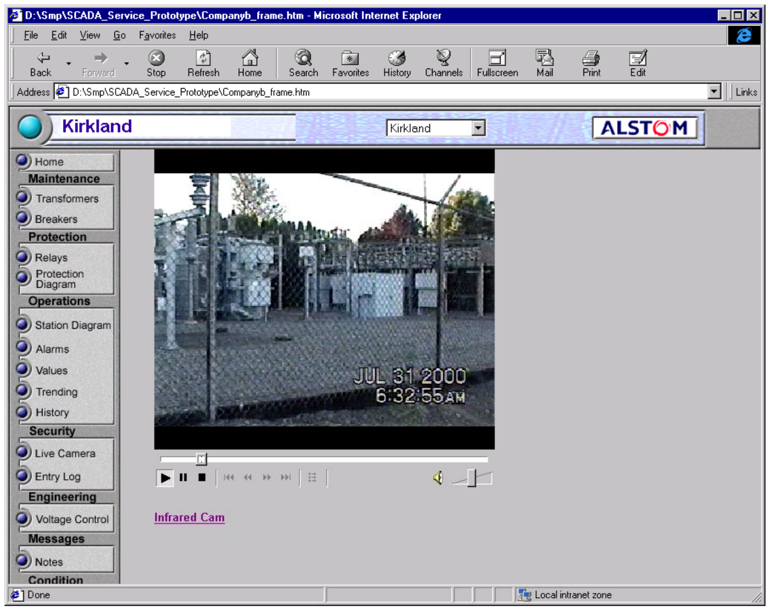

Fig. 8 Example from the Web browser interface

4. Feeder Protection, Control, Monitoring and Recording

4.1 Protection

The protection IEDs included in the Web PCM system should support the following protection functionality for each of the distribution feeders:

- Multiple phase overcurrent stages (instantaneous and time-delayed)
- Multiple ground overcurrent stages (instantaneous and time-delayed)
- Tripping curves type IEC (short time inverse, standard inverse, very inverse, extremely inverse, long time inverse) and IEEE/ANSI (short time inverse, moderately inverse, inverse, very inverse, extremely inverse)
- Negative sequence overcurrent
- Undercurrent
- Thermal overload

- Output relay latching
- Broken conductor detection
- Circuit breaker failure detection
- Circuit breaker monitoring
- Trip circuit supervision
- Four shot autoreclosing (only for new substations or complete upgrade of existing substations)

4.2 Measurements and Recording

The PIEDs should provide complete measurements and recording functions including:

- True RMS values available on the front panel LCD or remotely
- Event recorder with multiple events, 1ms time-tagged.
- Fault recorder with the last several faults
- Disturbance recorder with storage of multiple records

5. Transformer Protection

Main transformer protection may be enhanced by implementation of any of three options described below as a function of the availability of voltage transformers in the substation, as well as the requirements for mimic diagram and breaker control from the relay panel.

5.1 Main Transformer Relay Tripping Redundancy (Option 1)

If only a single battery is available in the substation (the typical case for small distribution substations), the main transformer protection is provided by a dual powered relay. It is recommended in order to provide transformer protection and ensure the tripping of the transformer high side breaker even in case of loss of DC in the substation. The functionality of the relay is identical to the feeder protection IEDs.

Considering the importance of the power transformer, a second protection IED with limited functionality (three-phase and ground overcurrent protection only) is used as a backup protection.

Both relays also provide backup protection in case of failure of any of the feeder relays. They can also be used in a blocking scheme to provide distribution bus protection.

5.2 Main Transformer Enhanced Protection (Option 2)

If voltage transformers are available in the substation, the main transformer protection is provided by an IED with voltage inputs and extended protection, monitoring and control functionality. This is described in detail below.

An optional dual-powered relay is recommended in order to provide backup transformer protection and ensure the tripping of the transformer high side breaker even in case of loss of DC in the substation.

The extensive functionality provided by the advanced protection IED replaces many discrete protection, control and measuring elements, thus allowing reduced costs due to fewer components, less wiring and less panel space. The built-in supervision of the measuring circuits and interfaces to external devices guarantees secure operation.

In addition, the relays offer the following benefits:

- Selectable protection functions cover multiple applications
- User customizable LEDs and text messages
- Keypad and multiple communication ports allow convenient access to settings and records

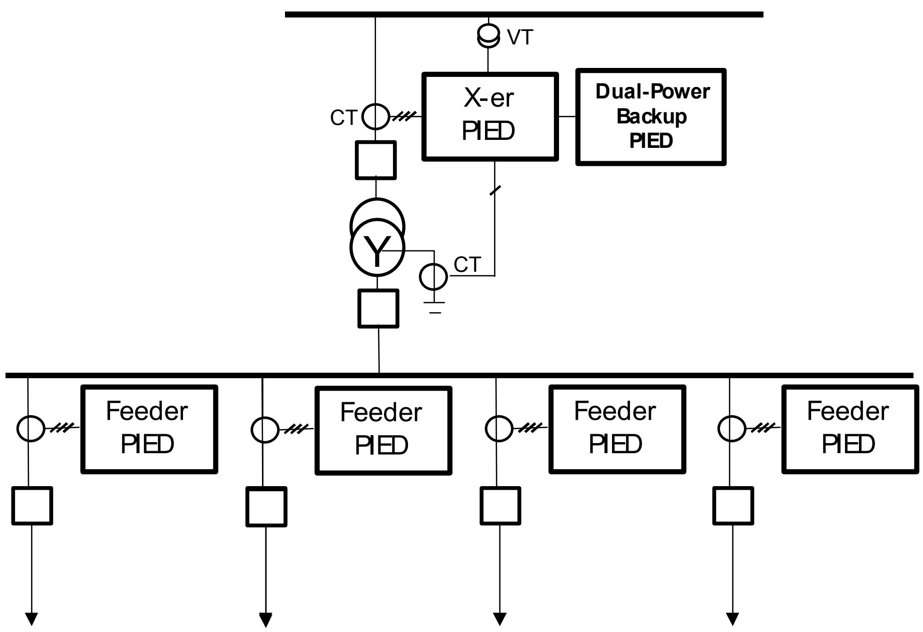

Fig. 9 Transformer protection with advanced main protection and simple backup

5.2.1 Protection

Advanced protection IEDs provide a wide range of protection functions in order to ensure fast and sensitive protection for short circuit or other abnormal system conditions. Different functions can be combined or supervised using programmable scheme logic in order to meet specific application requirements.

Some of the functions required for the protection of the transformer included in the IED are as follows:

- Multi-stage directional/non-directional phase and ground overcurrent
- Sensitive directional/non-directional ground fault
- Restricted ground fault transformer differential protection
- Voltage controlled overcurrent
- Directional/non-directional negative sequence overcurrent
- Thermal overload
- Under/overvoltage
- Residual overvoltage
- Negative sequence overvoltage
- Under / overfrequency
- Circuit breaker failure

The correct operation of the protection functions requires monitoring of the analog input circuits and the trip circuits to and from the relay. Supervision functions required include:

- Voltage transformer supervision
- Current transformer supervision
- Trip circuit supervision
- Extensive self-monitoring and system supervision

If there are any specific requirements for the protection and control logic, a powerful and easily implemented scheme logic with a large choice of gates and timers is needed to make the relay completely customizable.

5.2.2 Measurements and Recording

The transformer PIEDs should provide complete measurements and recording functions including:

- True RMS values available on the front panel LCD or remotely
- Event recorder with multiple events, 1ms time-fagged.
- Fault recorder with the last several faults

5.3 Main Transformer Enhanced Protection with Mimic (Option 3)

If voltage transformers are available in the substation, and there is a requirement to provide a substation Mimic Diagram and control of all breakers from the front panel of the relay, the main transformer protection is provided by a protection IED with enhanced control capabilities and built-in control functions (One Box Solution). This relay provides extensive protection, metering, monitoring and control functions, as described in detail above. The main difference is that it has a large LCD display (Fig. 11) that allows the user to visually monitor the status of up to six breakers or switches and to select and Trip or Close each one of them from the front panel of the relay. This eliminates the need for panel mimic diagram and breaker control buttons or switches.

An optional dual-powered relay is recommended in order to provide backup transformer protection and ensure the tripping of the transformer high side breaker even in case of loss of DC in the substation. Figure 10 below shows the solutions configuration.

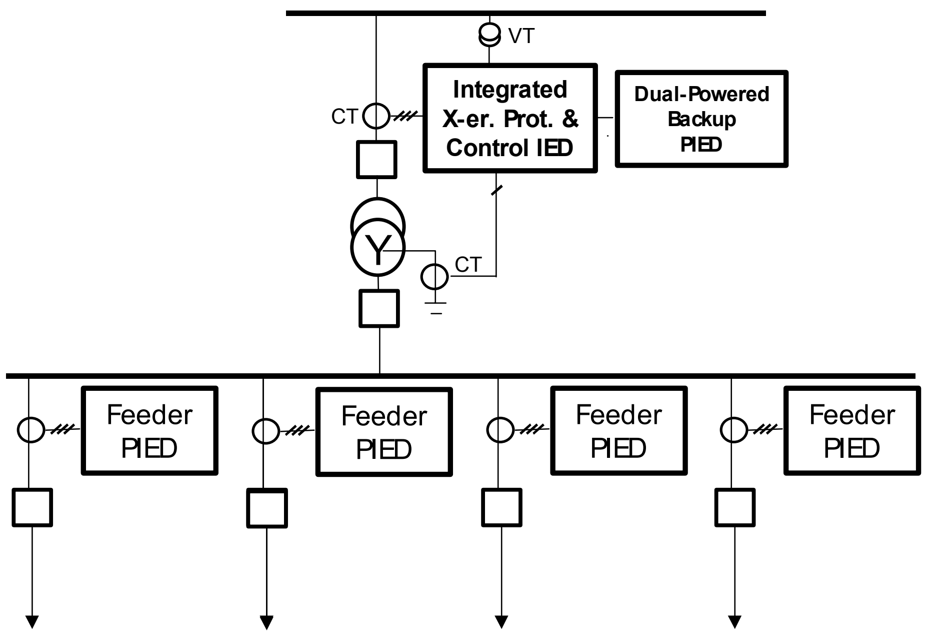

Fig. 10 Transformer protection with integrated protection and control IED and simple backup

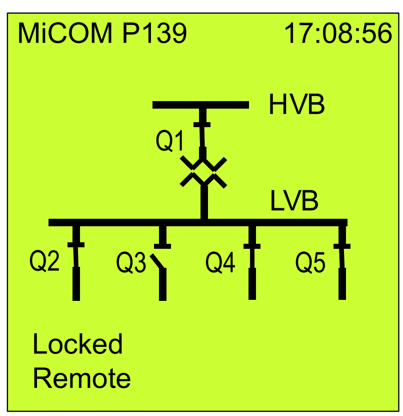

Fig. 11 Front panel display of substation one-line diagram in a protection and control IED

5. Power Quality Monitoring

Power quality affects not only different devices and industrial processes, it may affect the performance of protective relays as well. On the other hand, the behavior of protection and control devices at different distribution or transmission levels of the electric power system will to a great extent determine the duration of time with abnormal system parameters. That is why utilities and industry are paying more attention to power quality monitoring.

Power quality monitoring requires from the IED high sampling rate for the detection of harmonic content, as well as the implementation of algorithms for the detection of power quality events such as voltage sags and swells, power supply interruptions or flicker.

Microprocessor based relays are not designed to perform such functions. Due to the typically lower sampling rate they can not detect high order harmonics. They can perform some basic event detection based on under and over voltage elements being used in a specifically designed for such application programmable scheme logic. Still, these features are not as advanced as in specialized power quality monitoring devices. That is why they can be used as backup monitoring devices.

A power quality monitoring device can be installed at the substation transformer (Fig. 5). Voltage transformers on the high and the low side of the transformer and current transformer connections on the low side allow the device to detect high order harmonics and to measure and calculate any power system parameter. The device in this case will also monitor power quality events.

Multifunctional power quality monitoring IEDs sample the current and voltage inputs with a high sampling rate (for example 128 samples/cycle) and based on these samples and after FFT calculate hundreds of different measurements that can be used to detect power quality events or to trigger their recording for further analysis of such events by the available tools at the substation computer. Following is a list of some measurements available in modern power quality monitoring devices:

- Current, Voltage, Frequency measurements
- Power measurements
- Demand measurements
- Symmetrical Components measurements
- Harmonics
- THD

6. Recording

The requirements for the recording of normal and abnormal conditions in transmission or distribution/industrial systems can vary significantly and cover a wide range from more than a hundred samples per cycle, to more than a minute between samples.

The analysis of all these different types of events in some cases require sampling of the waveform, while in other they need a periodic log of the RMS value of the monitored parameter.

Microprocessor based relays can be used to provide the waveform capture recording for faults on all distribution feeders. However, they do not provide advanced recording features that are required for system level disturbance recording and for load-profile recording at the substation level.

That is why a state-of-the-art multifunctional IEDs with power quality monitoring and recording capabilities that has multiple recording types should be used at the transformer.

Four different types of records with appropriate sampling rate ranges and record length are identified:

- Load profiles
- Low-speed abnormal system conditions
- High-speed abnormal system conditions
- Waveform capture

The combination of waveform capture and high- or low-speed disturbance recording triggered by the same system condition allows the recording of long events, while at the same time the details of the transitions from one state to another are recorded in the waveform capture.

In order to allow the user to "zoom-in", all recording types should run in parallel, as required by the application, power system condition and triggering criteria specified by the user. This is possible, since the same triggers can be used for the different types of recording and also because all records have accurate time stamps based on the time-synchronization feature in the IEDs.

The different records can be extracted from the IED automatically when the substation client recognizes the availability of disturbance records based on a status bit change.

The availability of a built-in FTP server in the monitoring and recording device offers increased reliability, because it allows the extraction of records from the device even when the substation computer is out of service.

7. Conclusions

The new utility environment requires availability of state-of-the-art protection, control, monitoring and recording systems. These systems must require minimum engineering from the user, be easy to install and maintain, and take advantage of the advanced functionality of multifunctional protection and monitoring/recording IEDs with communication capabilities and support for industry standard communication protocols.

At the same time, the availability of utility communication networks and the use of off-the-shelf Web technology makes the data and information from the IEDs easily available to different utility clients using standard Web browsers.

The paper described in detail different protection, control and monitoring system architectures for small distribution substations that provide a modular, inexpensive, and very effective solution for existing or new distribution substations.

Power quality monitoring and disturbance recording requirements are also considered to define the need for specialized devices and their integration into a complete solution that meets all the needs of utility or industrial installations.