

Detection and Recording of Power Quality Events in Distribution Systems

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I. INTRODUCTION

The electric power utility industry requires significant improvement in the quality of power provided to customers during faults or wide area system disturbance. This is related to the availability of tools that help energy management, planning and protection engineers to understand the processes in order to optimize the operation of the system under different abnormal conditions.

The paper describes the most typical power quality events that have the largest impact on sensitive customers.

After the characteristics of power quality events such as voltage sags, voltage swells, different kinds of voltage interruptions or voltage unbalance are well understood, it is possible to define the requirements for recording of such events.

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 use of each recording type for specific power quality events at the distribution level of the system is described.

The paper also discusses methods for detection of such events in distribution substations and how they are affected by the location of the power quality monitoring equipment and the instrument transformers.

The need for voltage transformer supervision and methods for detection of problems in the voltage circuits are presented.

II. POWER QUALITY VOLTAGE VARIATION EVENT DEFINITIONS

Power Quality for most applications can be defined as the degree to which the electric power supplied by the utility conforms to the pure sinusoidal waveform of the rated frequency and nominal voltage. Variations of these parameters can result in different kinds of problems to the utility customers and their equipment. The increase of computer controlled processes is making more and more customers to require from the utilities significant improvement in the quality of the power and at the same time a reduction of the duration of voltage sags, swells or power supply interruptions.

Most of the power quality events that result in interruption of a manufacturing or any other process are related to voltage variations of different duration and severity. Different standards exist that define the characteristics of such power quality events. They are very well summarized in Tables 1 and 2 (Tables 5.3 and 5.5 from IEEE P1159.1 Guide For Recorder and Data Acquisition Requirements For Characterization of Power Quality Events, but very similar definitions exist in other international standards) [1].

Table 1:

Short-duration variation category and typical event characteristic (IEEE P1159.1 Table 5.3)

Categories	Typical duration	Typical voltage magnitude
2.0 Short duration variations		
2.1 instantaneous		
2.1.1 Sag	0.5-30 cycles	0.1-0.9 pu
2.1.2 Swell	0.5-30 cycles	1.1-1.8 pu
2.2 Momentary		
2.2.1 Interruption	0.5 cycles-3 s	< 0.1 pu
2.2.2 Sag	30 cycles-3 s	0.1-0.9 pu
2.2.3 Swell	30 cycles-3 s	1.14-1.4 pu
2.3 Temporary		
2.3.1 Interruption	3 s-1 min	<0.1 pu
2.3.2 Sag	3 s-1 min	0.1-0.9 pu

Table 2:

Long-duration variation category and typical event characteristic (IEEE P1159.1 Table 5.5)

Categories	Typical duration	Typical voltage magnitude
3.0 Long duration Variations		
3.1 Interruption, sustained	>1 min	0.0 pu
3.2 Undervoltages	>1 min	0.8-0.9 pu
3.3 Overvoltages	>1 min	1.1-1.2 pu

Other power quality events are related to variations in frequency, unbalance or the existence of harmonics, transients, noise, poor power factor or other unacceptable values of system parameters.

In this paper we are going to concentrate on voltage variation based power quality events, their detection and recording in distribution substations.

III. VOLTAGE VARIATION DETECTION AND RECORDING IN DISTRIBUTION SUBSTATIONS

The detection and recording of voltage variation power quality events in distribution substations can be done in many different ways. It is based on the available primary and secondary equipment in the substation and the requirements of the user.

Substations of different sizes present different challenges to the detection and recording of such events. Large utility or industrial substations may have specialized power quality monitoring and recording devices installed for this purpose. However, there is still a huge number of small distribution substations with a single transformer and 2 to 4 distribution feeders that are equipped with IEDs with limited functionality or have electromechanical or solid state relays for protection. Figure 1 shows the one-line diagram of such a substation with the location of CTs, VTs and the multifunctional IEDs.

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.

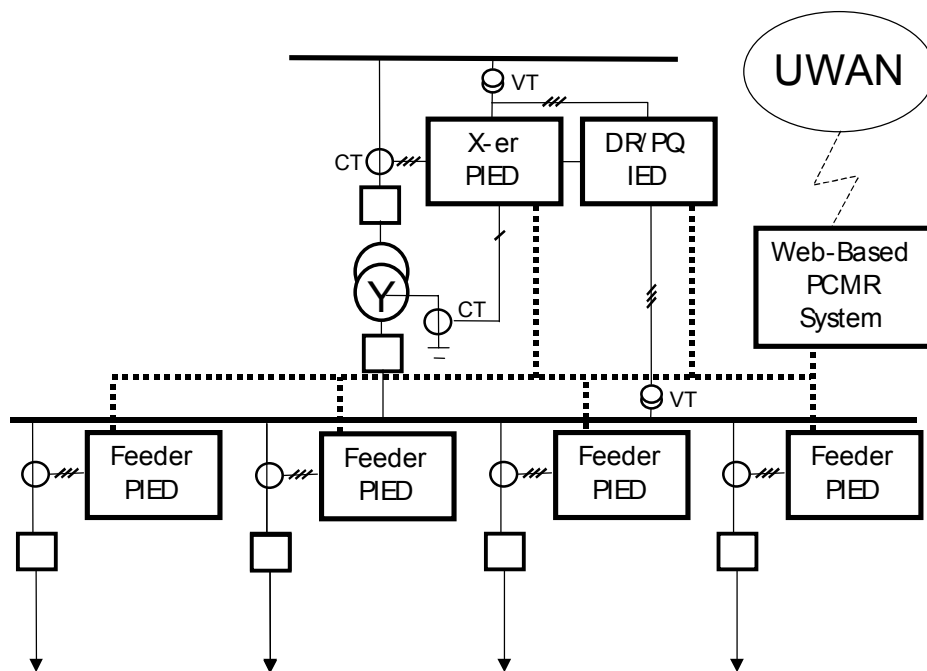


Fig. 1 Simplified one-line diagram of a small distribution substation

An important fact to consider when designing the voltage variation power quality event detection and recording system is the availability and location of voltage transformers in the substation. Fig. 1 shows a typical case when the voltage transformer is located on the distribution bus. In this case, even if all distribution feeder relays have voltage monitoring functions, they are all going to be connected to the same voltage source.

A. FEEDER RELAY FUNCTIONS THAT CAN BE USED FOR POWER QUALITY EVENT DETECTION

Modern microprocessor based distribution feeder protection relays have multiple overcurrent protection elements that perform their primary function – distribution feeder protection. These relays also have many additional functions that provide protection for different abnormal system conditions, as well as advanced monitoring features that allow the user to switch from scheduled to “event” driven maintenance.

We are going to concentrate only on the elements that allow modern distribution feeder relays to become power quality event detection devices.

1. PROTECTION FUNCTIONS IN DISTRIBUTION FEEDER RELAYS AND THEIR APPLICATION FOR POWER QUALITY EVENT DETECTION

Undervoltage protection: Voltage sags or interruptions are detected in distribution feeder relays by appropriately set instantaneous or time delayed undervoltage elements. They can be used in combination with other timers in order to build a logic scheme to detect voltage sags and power interruptions. However, some low end distribution feeder relays do not have voltage inputs and thus can not be used for voltage sag detection.

Overvoltage protection: Voltage swell in distribution feeder relays is detected by appropriately set instantaneous or time delayed overvoltage elements. They can be used in combination with other timers in order to build a logic scheme to detect such voltage variations.

Programmable Scheme Logic: The purpose of the programmable scheme logic (PSL) in multifunctional relays is to allow the user to configure an individual protection, control or alarm scheme in order to suit their own particular application. This is achieved through the use of programmable logic gates and delay timers.

The input to the PSL is any combination of the status of the digital input signals from the optoisolators on the input board, the outputs of the protection elements, e.g. protection starts and trips, and the outputs of the fixed protection scheme logic. The fixed scheme logic provides the relay’s standard protection schemes. The PSL itself consists of software logic gates and timers. The logic gates can be programmed to perform a range of different logic functions and can accept any number of inputs. The timers are used either to create a programmable delay, and/or to condition the logic outputs, e.g. to create a pulse of fixed duration on the output regardless of the length of the pulse on the input. The outputs of the PSL are the LEDs on the front panel of the relay and the output contacts at the rear.

The execution of the PSL logic is event driven; the logic is processed whenever any of its inputs change, for example as a result of a change in one of the digital input signals or a trip output from a protection element. Also, only the part of the PSL logic that is affected by the particular input change that has occurred is processed. This reduces the amount of processing time that is used by the PSL. The protection and control software updates the logic delay timers and checks for a change in the PSL input signals every time it runs.

This system provides flexibility for the user to create their own scheme logic design. It can be used in combination with the described above protection functions in order to detect and alarm for power quality voltage variation events. An example of a voltage sag detection scheme is given in Fig. 2.

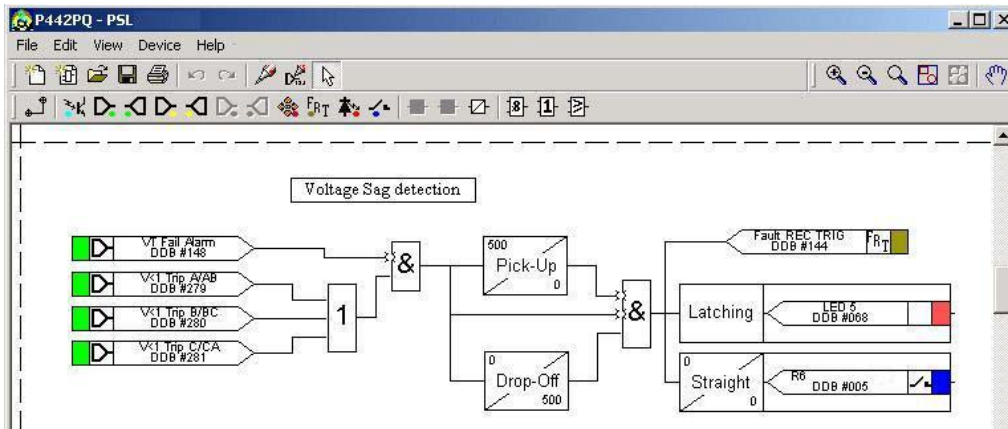


Fig. 2 Programmable Scheme Logic based Voltage Sag Detector

The voltage sag is detected by phase A, B or C undervoltage elements, while at the same time there is no Voltage Transformer Supervision alarm. The output of the AND gate starts two timers in order to define a voltage sag window of 8ms to 2 sec. These time settings can be different and are determined by the user's definition for a voltage sag. The output of the second AND gate will operate a relay output, an LED on the front panel of the relay and will trigger the Disturbance Recorder in order to capture the voltage sag waveforms.

The relay output and the LED are latched to ensure that the indication of the event is not lost. However, the relay output can be unlatched if the signal is going to SCADA in order to remove the alarm signal as soon as the undervoltage condition ends. It will still be time-stamped and logged and the latched LED will have to be reset from the front panel of the relay after reviewing the event information.

Similar schemes shall be used for the detection of the other power quality monitoring functions in the protective relay.

2. MONITORING FUNCTIONS IN MULTIFUNCTIONAL DISTRIBUTION FEEDER RELAYS AND THEIR APPLICATION TO POWER QUALITY MONITORING

The operation of a multifunctional distribution feeder relay is affected by different factors, such as the current and voltage circuits or the breaker status. Voltage transformer supervision logic is used to avoid misoperation of the relay in the case of failure in the analog circuit, while the breaker status can be used in breaker failure or reclosing schemes.

These features are also very useful in power quality event detection schemes. For example, a fuse failure in the voltage circuit will be seen by the IED as a loss of voltage in one or more phases. This will be detected as a voltage interruption, while in reality such event did not occur. That is why a voltage transformer supervision element can be used to block the detection of voltage sag or interruption events.

A simplified logic diagram for a voltage transformer supervision scheme is shown in Fig. 3. Different logic is used to detect single- or two-phase voltage circuit failure and three-phase voltage failure during operation or line energization conditions. When a voltage circuit failure is detected, the relay will send an alarm, log the event and block all voltage related functions, in our case the voltage sag or interruption event detection.

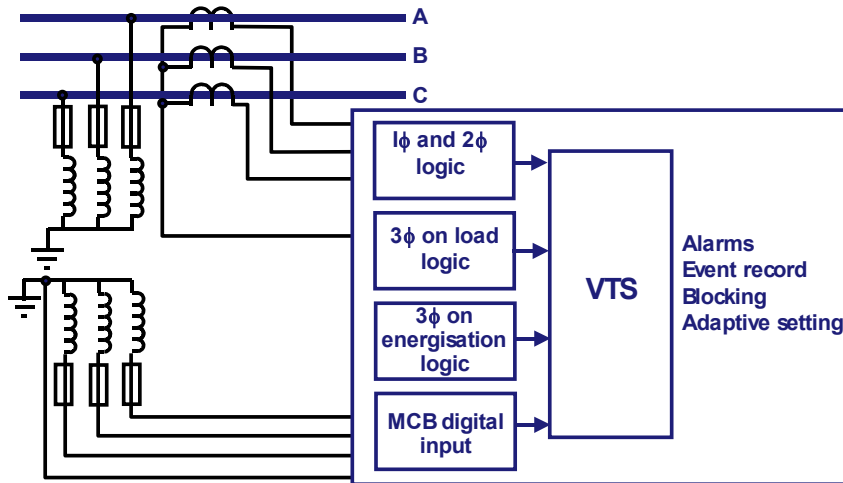


Fig. 3 Voltage transformer supervision in distribution feeder relay

A voltage interruption is typically detected by power quality monitoring devices when the measured voltage goes below a set level – for example 0.01 V_{nom} . However, the detection of such condition is affected by the location of the voltage transformers. In many cases the voltage transformers are located at the distribution bus. As a result of that, after a fault and the opening of the faulted line breaker the bus voltage will go back to normal and no voltage interruption will be detected.

That is why it is recommended to detect voltage interruption based on voltage measurements or breaker status criteria. Since the breaker status is provided by auxiliary contacts of the breaker, improved reliability of this scheme can be achieved by monitoring both the normally open or normally closed auxiliary contacts of the breaker.

In the cases when the distribution feeder relays are current only based, obviously they can't be used to detect voltage variations such as voltage sags. However, they can still be used to detect voltage interruptions based on their breaker status monitoring elements.

3. RECORDING FUNCTIONS IN DISTRIBUTION FEEDER RELAYS

The distribution feeder relay records and time tags hundreds of events and stores them in non-volatile (battery backed up) memory. This enables the system operator to establish the sequence of events that occurred within the relay following a particular power system condition, switching sequence etc. When the available memory is filled-up, the oldest event is automatically overwritten by the new one.

The real time clock within the relay provides the time tag to each event, to a resolution of 1ms. IRIG-B input to the relays should be used for time synchronization in order to ensure accurate time-stamping for further analysis of the records from multiple IEDs in a distributed analysis architecture.

An event may be a change of state of a control input or output relay, an alarm condition, setting change etc. They can be protection element starts and trips or the operation of a power quality monitoring scheme. Any event is logged as an event record, consisting of a text string indicating the operated element and an event value. This value is intended for use by the event extraction software.

Power quality voltage variation events will be logged in this case as operations of undervoltage or overvoltage elements with different settings, or as the operation of the distribution feeder breakers. If the relay has only current inputs, voltage interruptions will be logged based only on the detected change of breaker status. When the relay has operated and cleared a short circuit fault, this event log can be used as an indirect indication that there has been a voltage sag or swell at the same time, however the distribution feeder relay can not provide any information on the level of the voltage during the fault.

Voltage level information can be provided by the addition of a specialized power quality monitoring and recording device that measures the voltages on the transmission and distribution levels of the substation. This is also valid for the cases when the transformer and distribution feeder protection in the substation is provided by electromechanical or solid state relays.

Disturbance Recorder: The integral disturbance recorder in the relays is a waveform recorder that has an area of memory specifically set aside for record storage. The number of records that may be stored is dependent upon the selected recording duration but some relays have the capability of storing a minimum of 20 records, each of 10.5 second duration. This is very important in the case of power quality monitoring functions, since it allows a longer pre-and post-trigger record that will provide a better understanding of the system behavior during the event. Waveform samples continue to be recorded until the available memory is exhausted, at which time the oldest record(s) are overwritten to make space for the newest one.

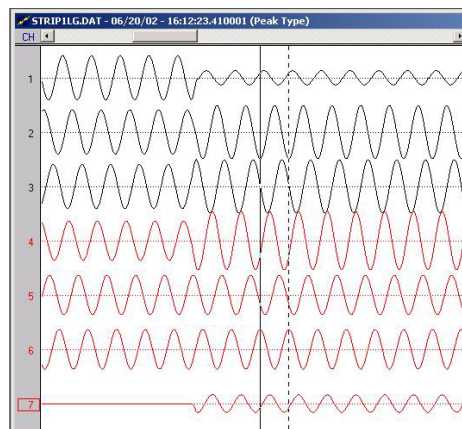


Fig. 4 Waveform record showing voltage sag and swell during a phase to ground fault

The recorder stores actual pre-filtered samples which are taken at a different rate as a function of the hardware and software of the IED. Some typical sampling rates are 4, 8, 12, 16, 20, 24, 32 or higher samples per cycle.

If a further trigger occurs whilst a recording is taking place, the recorder will ignore the trigger if the "Trigger Mode" has been set to "Single". However, if this has been set to "Extended", the post trigger timer will be reset to zero, thereby extending the recording time.

Fig. 4 shows a waveform record from a distribution feeder relay that can be used to analyze the voltage sag and swell during a single-phase-to-ground fault. Since these are defined based on the rms value of the voltage, an analysis tool that calculates these values from the recorded waveform should be used.

B. USE OF SPECIALIZED POWER QUALITY MONITORING AND RECORDING DEVICES

It is clear from the previous sections of the paper that modern microprocessor based distribution feeder protection relays can be used successfully for the detection of voltage variation and interruption events. At the same time it is obvious that they have some limitations in their detection and recording capabilities. This is especially true in the cases when protection of the distribution feeders and the transformer in the substation is provided by electromechanical or solid-state relays (see Fig. 5).

Specialized power quality monitoring devices have built-in functions designed specifically to detect and classify such events. Advanced recording devices also have many features that make them suitable for detecting and recording voltage variations in the distribution system.

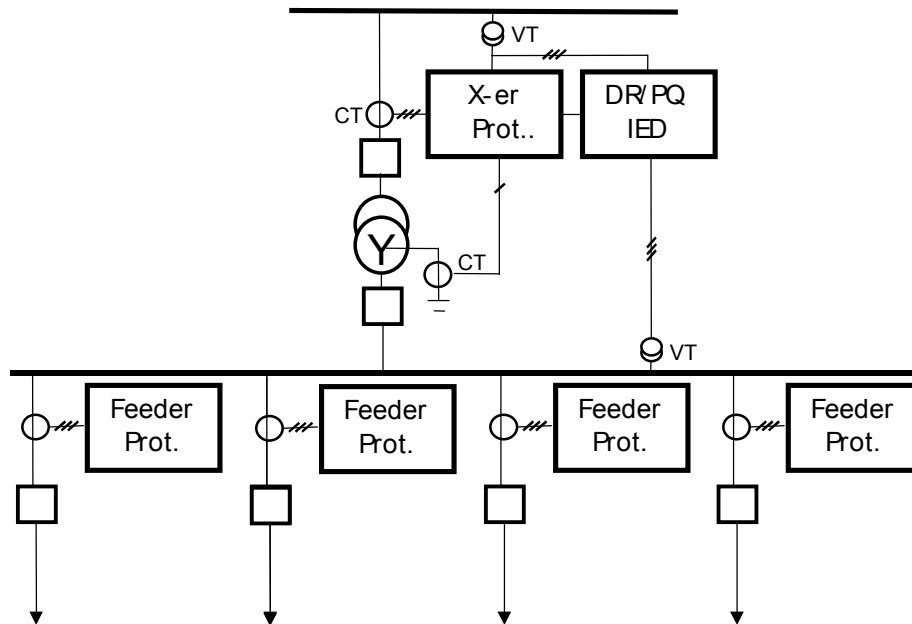


Fig. 5 Simplified one-line diagram of a distribution substation with electromechanical relays

In the above configuration a power quality monitoring and/or recording device is installed at the substation and monitors the voltages on both the transmission and distribution side. Since voltage variations on the distribution side will be monitored based on measurements from a voltage transformer connected to the distribution bus, a single device is sufficient for that.

Detection of voltage interruptions on each of the distribution feeders is based on monitoring of the individual distribution feeder breakers. Their auxiliary contacts should be wired to opto inputs of the power quality monitoring device. Thus it can detect, time-stamp and record the changes of state of the breaker in order to determine an interruption.

1. VOLTAGE VARIATION EVENTS DETECTION FUNCTIONS

Power quality monitoring devices have multiple elements that are designed to detect specific power quality events defined by different international or national standards such as EN 50160, IEEE 1159 or NRS 048. They can detect events upon crossing of thresholds based on user programmable hysteresis. Since our focus is voltage variation events, following are the voltage fluctuation events ranges that are being typically monitored:

- nominal voltage range
- voltage swells
- voltage sags (dips)
- voltage interruptions

All of the above may have numerous (10 to 20) intermediate sub-ranges that can be used to provide greater detail in the evaluation and classification of these power quality events. Fig. 6 shows multiple thresholds available in a multifunctional power quality monitoring device for the detection of different voltage variation events.

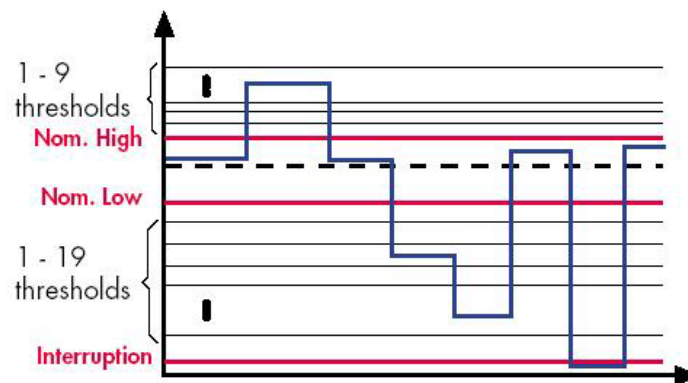


Fig. 6 Voltage variation event detection thresholds

Every threshold detection is stored as a new event in the memory with its date, time, voltage magnitude and min/max magnitude of the previous event.

2. POWER QUALITY EVENTS RECORDING FUNCTIONS

Since power quality events include changes in the monitored system parameters that can range from fractions of a cycle to several minutes, it is impossible to record the variety of events using the most commonly available waveform capture. Many of the power quality events are also based on the changes in the RMS value of the voltages, so the waveform capture is not appropriate for the recording of such events.

That is why specialized monitoring and recording devices have multiple recording types that allow the coverage of any possible type of power quality or other system events.

Depending on the monitored power quality events, the different type recordings should run in parallel in order to cover different applications, power system conditions and triggering criteria specified by the user.

Waveform recording: Waveform recording is required to capture power quality voltage variation events with very short duration and sub-cycle characteristics such as instantaneous voltage sags or swells. They capture individual samples of the current or voltage waveform with a sampling rate that should be high enough to allow the recording of transients with duration of less than 1 millisecond.

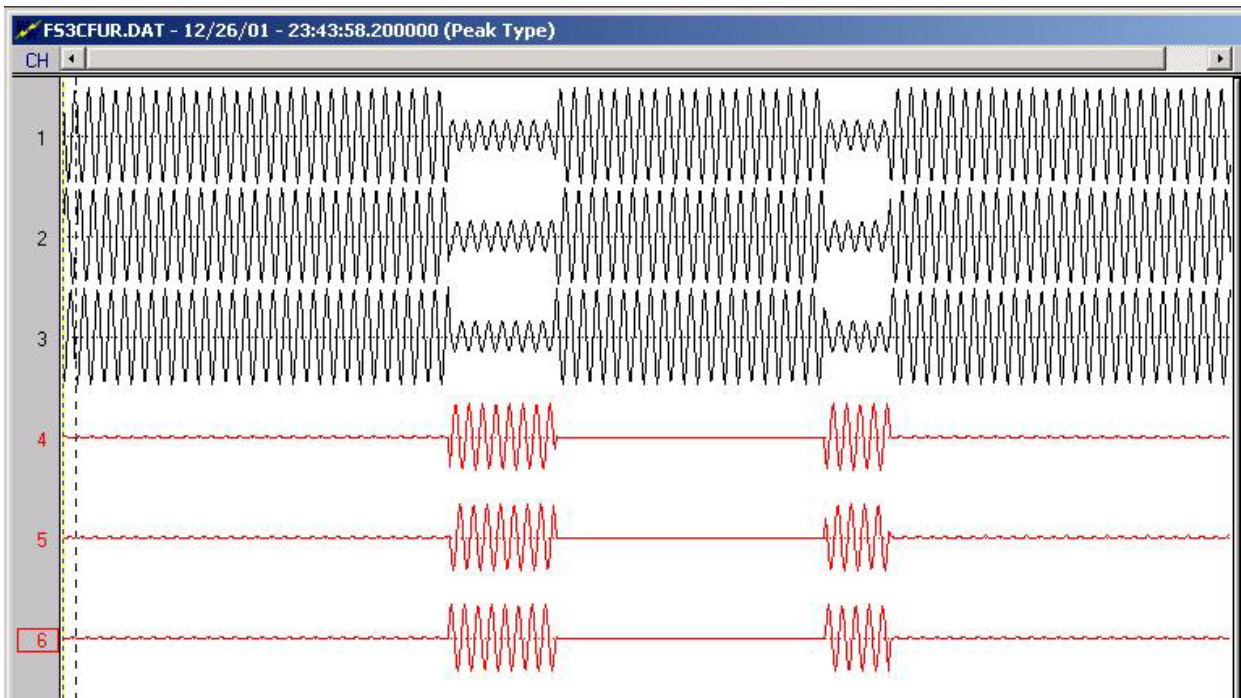


Fig. 7. Waveform capture record

The trigger can be defined as a threshold on different measurements and the user should be able to define multiple independent triggers.

Since events in the power system can be quite complex and evolving from one type into another, it is important to allow Extended Post-trigger recording in case there is a re-trigger or a new trigger condition.

High- and Low-Speed Disturbance Recording: High-speed disturbance recording is intended for capturing high-speed power quality events such as momentary voltage sags, voltage swells or interruptions during short circuit faults on the transmission or distribution system. These records are based on the logging of RMS values or other measurements with a rate of one to several cycles per sample.

Low-speed disturbance recording is intended for capturing power quality events such as temporary voltage sags, voltage swells or interruptions during a multi-shot reclosing cycle or the abnormal system frequency and voltage during wide area system disturbances. The sampling rate in this case can be from fractions of a second to several seconds, depending of the characteristics of the event to be recorded.

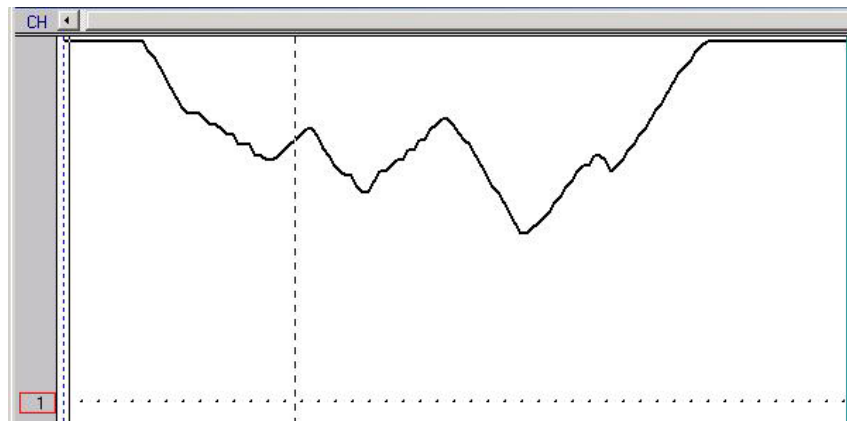


Fig. 8. High-speed disturbance record – voltage profile

The user also has to be able to specify Pre-trigger and Post-trigger time so the effect of the pre-trigger conditions can be analyzed as well.

Extended Post-trigger recording should be available if there is a re-trigger or a new trigger.

An option to trigger High-speed or Low-speed disturbance recording when a Waveform capture is triggered is achieved by using the same trigger with different recording modes. This allows the user to look into different levels of detail of the analyzed power quality event.

For each parameter the user should be able to select the recording of the current sample of the recorded quantity or to record the minimum, maximum, and average values that occurred during the previous interval recorded. The recorded values are based on measurements that are updated every cycle.

When recording is complete, a status bit is set, indicating the availability of a Disturbance Record. This allows the analysis software in the substation HMI to automatically extract and store the disturbance records on its hard drive for further analysis, if necessary.

The combination of waveform capture and high- or low-speed disturbance recording triggered by the same power quality event 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.

IV. CONCLUSIONS

Power quality events characterized by deviation of the voltage from its nominal values are the most common cause of interruptions of sensitive manufacturing processes. That is why their detection and recording is very important for the analysis of their effects on equipment and verification of system models used by different simulation or analysis programs.

Detection and recording of voltage variations is usually focused on the following event types:

- Voltage sags
- Voltage swells
- Voltage interruptions

Multifunctional distribution protection IEDs have undervoltage and overvoltage functions, that combined with programmable scheme logic and breaker status monitoring makes them suitable for detection of different voltage variation events.

They also have waveform and event recording features that can be used for capturing some of the voltage variation events.

Advanced power quality monitoring and recording devices are the preferred choice for detection and recording of voltage sags, swells and interruptions, because they can analyze and classify the events and generate the required reports. They also provide advanced recording capabilities that are better suited for the recording of instantaneous, momentary or temporary variations.

Waveform capture, high- and low-speed disturbance recording and in some cases even trend recording are identified as appropriate for the recording of voltage variation events.

V. REFERENCES

IEEE P1159.1 Guide For Recorder and Data Acquisition Requirements for Characterization of Power Quality Events