DSP Based On-line Partial Discharge Monitoring System for High Voltage Power Cable

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Abstract: - In high voltage power cable system, partial discharge (PD) is a common phenomenon which reflects the degradation of insulation. When partial discharge happens inside the cable, leakage current will flow through the grounded conductor. To couple the partial discharge current, one feasible and effective method is placing a clamp-on high frequency current transformer around the grounded strap. In order to precisely monitor the insulation degradation, a digital signal processor (DSP) based partial discharge on-line monitoring system is developed and presented in this paper. The system mainly consists of PD sensor, pre-amplifier, front-end sample device and remote server center. The front-end device is the kernel part of the system, as it performs PD signals sampling and some essential digital signal processing such as noise filtering, pulse extraction and parameters statistics. Then, the derived characteristic parameters are sent to the remote server center by ethernet communication for further analysis. The field test and data analysis show the presented system is effective and helpful for power cable condition diagnosis.

Key-Words: - High voltage, Power cable, Partial discharge, DSP, On-line monitoring, Signal Processing, Ethernet communication

1 Introduction

With the increasing population of cross-linked polyethene (XLPE) power cable in power grids, the accidents and failure of power cable and cable accessories arising from insulation degradation, is becoming one of the main challenges against power system stability. As most cables are laid underground in form of direct-buried, pipeline and tunnel, condition monitoring of power cable is much difficult. Therefore, it has great practical significance to evaluate the insulation status of the suspected cable by many detection methods for early maintenance.

Nowadays, the commonly used detection techniques of power cable involve DC component method, DC voltage superimposition method, low frequency superimposition method, loss current measurement method and partial discharge method [1-3].

PD method is considered to be a distinct diagnostic tool that attracts more and more attention [4, 5]. PD detection picks up the discharge characteristic from insulation degradation inside the power cable. Preferable sensitivity is achieved with certain digital signal processing. Compared with other diagnostic methods, the most attractive advantage of PD detection is the non-invasive nature. It means that all in-service high voltage apparatuses being detected can still be on-line and keep working. This makes it possible to execute continuous power system equipments monitoring, insulation degradation trends determination, condition based maintenance (CBM), and asset management [6, 7]. Due to the features of PD detection technique, some international organization such as IEEE and CIGRE, have issued some guides and standards to normalize the application of PD method [8, 9].

Additionally, associated research has been done on on-line monitoring of power cable [10]. Reference [11] describes some on-site experiences and lost-effective insulation diagnosis about PD measurements for power cable. In [9], sensors are placed around grounded conductor of power cables and couple the high frequency current signal to display on oscilloscope. Reference [12] reports an investigation of intelligent DSP-based PD analyzer using wavelet analysis. The advantages of this approach are the portability and high performance with low cost. Reference [13] puts forward a PD detection scheme employing field programmable gate array (FPGA) instead of general-purpose high-speed data acquisition system. Reference [14] introduces an on-line PD monitoring system of

XLPE power cable based on virtual instrument design conception, which uses a PCI digitizing acquisition board and LabView software. Reference [15] develops a technique to transmit the analog PD signal to remote observation equipment, such as oscilloscope, through optical network, and uses an electro-optic modulator to modulate the intensity of the transmitted laser light approximately proportional to the voltage of detected PD signal.

While ordinary observation equipment, such as oscilloscope, is not practical for on-site continuous monitoring because of its limitation of storing memory. The analog PD signal can not transmit for long distance, as it will be interfered by much more ambient noise. A better way is to sample the PD signal close to the coupling sensor and send the results to remote server through digital interface, which is immune to much outer noise. In this way, the data communication bandwidth should be considered carefully. Fortunately, advances in analog-to-digital converter (ADC) and developments in digital signal processor techniques provide with some available solution to PD on-line continuous monitoring. Based on this idea, this paper introduces a scheme utilizing high performance DSP to realize an on-site PD on-line monitoring system.

The presented system realizes PD monitoring based on new high performance DSP chip and high speed ADC. Due to placing the amplifier and digitalization stage close to sensor, the outer noise is suppressed to the maximal extent. The DSP chip performs some necessary pre-processing to release the pressure of background computation. Through ethernet communication, both the raw sample data and statistical parameters can be sent to server for post processing.

2 PD Monitoring System Set-up

XLPE cable is widely used in power network interconnection, and Gas Insulated Switch (GIS) is the common equipment in new constructed power station. XLPE cable and GIS are jointed by cable termination, which has a conductor strap connecting the metallic screen of cable to the ground. According to the manufacturing quality and assembly techniques, the cable terminations are always of high accident risk. When PD happens inside the cable termination, the adjacent cable body or GIS bushing, there will be some high frequency pulse PD current flowing through the grounded strap. Clamping the sensor around the earthing strap may pick up the high frequency PD current information caused by the defects inside the cable termination and adjacent devices.

Therefore, the PD on-line monitoring system is developed as shown in Fig. 1, which includes three main parts: high frequency current transformer (HFCT), front-end sampling device and remote server center. HFCT is the clamping sensor to couple the PD pulse current leaking from the inside cable termination. The pre-amplifier and the front-end sampling device are placed close to the sensor. The derived results are transmitted to remote server center by commonly used ethernet cable. The server display and store both the raw sample data and the statistical parameters for operators' reference. The server will give out warning signal if the PD level exceeds the pre-set threshold after analyzing the acquisition result.

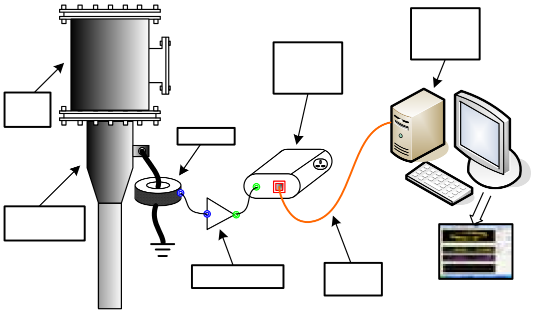


Fig. 1 Architecture of power cable on-line monitoring system.

2.1 Coupling sensor and pre-amplifier

PDs may be excited by the inside defects, and a high frequency current pulse will flow through the earthing conductor. To detect PDs, an effective way is to place a clamp-on high HFCT around the conductor strap, which connects the cable metallic screen to the earth. In the proposed system, the rogowski type sensor is adopted for PDs detection, and it is recognized as the best means to detect high frequency current flowing through earthing conductor for its non-contact nature and high frequency response [16, 17].

Fig. 2 HFCT installed around the earthing strap of cable termination.

The corresponding designed HFCT installed in field cable termination is shown in Fig. 2.

However, as the PD pulse signal from HFCT is too weak, about some milli-volts, a pre-amplifier is needed to enlarge the original signal into a measurable scale. The structure of the rogowski coil together with the integral resistor and pre-amplifier is shown in Fig. 3.

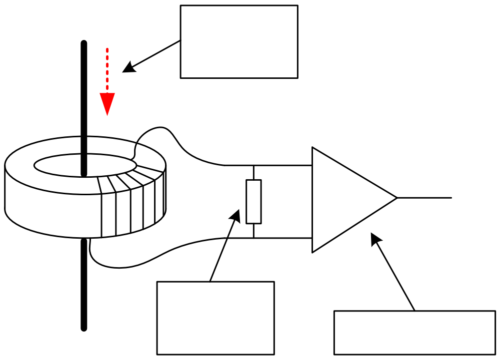


Fig. 3 The analytical diagram of HFCT sensor structure.

The bandwidth of the designed HFCT is up to 10MHz, which is not only considered to be high enough to cover the main frequency range of PD pulses [9], but also can suppress some upper frequency bandwidth disturbance. Moreover, a stage of band-pass filter is added to the pre-amplifier with the selected bandwidth about 2MHz to 10MHz to suppress the discrete spectral interference (DSI), from radio broadcasting, which is the dominant noise in on-site power cable PD detection. Field data analysis shows some amplitude modulation (AM) radio emissions, within some hundred kHz to 2MHz, may swamp interested PD pulses.

2.2 Sampling device

The PD pulse signals should be digitized for post digital signal processing. As analog signal is more sensitive to outer noise than digital signals, reducing the distance from sensor to acquisition device should be as short as possible for effectively suppressing surrounding noise coupled to the real PD signal. Thus, it is designed to place the digitization stage near the signal sensor within 10 meters for high measurement signal-to-noise ratio (SNR). Additionally, the front-end sampling device should have the capability of high acquisition rate satisfying the Nyquist Theorem, and long distance digital communication method such as ethernet needs to be realized for sending the pre-process result from front-end device to remote server center. It will be introduced in detail in Section 3.

2.3 Remote server center

Remote server center plays the role of human-machine interface in the designed monitoring system. With it, the operator or user can place the sample command to the front-end device and control all the sampling procedure. The statistic parameter and phase-resolved PD diagram associated with power frequency can also be displayed on the server. The server automatically alarms when the detection of PD signals reaching or climbing above the threshold set by users. The history trends of PD level help operators to determine the insulation status of the monitored apparatus and whether maintenance is needed. All these contribute significantly to condition based maintenance, which gradually moves the maintenance effort from traditional scheduled preventative approach to a more flexible and accurate condition based predictive approach.

3 DSP based front-end device

Due to the nature of PD pulse shape, i.e. high rising slope and short duration time within a microsecond, a high acquisition rate is necessary. The front-end device is developed based on high performance DSP microchip, acting as the kernel part in the PD monitoring system. The system has the capability of high sampling rate as well as high speed data communication bandwidth for the dedicated design structure of sampling data routine. It is sufficient for on-line PD monitoring.

3.1 Hardware structure

The Hardware structure of front-end device is displayed in Fig. 4, and the DSP chip TMS320C6713B is adopted as the central core. Its advantages in high operation speed and instruction execution efficiency guarantee the implementation of PD processing related algorithms.

The real PD signals from sensor and pre-amplifier are captured with a high speed sampling channel, and the sinusoidal waveform is acquired by a low speed serial ADC. A power frequency related square waveform for triggering high speed sampling is produced by zero-cross detection from a comparator. The peripheral set of DSP is utilized for external memory connection with SDRAM and NOR FLASH. The power management supplies the system with a strong and stable power source. The watchdog chip restarts the overall front-end device when the program running away. The ethernet interface connected with remote server is implemented with a hardware protocol stack chip W3100. The hardware realization of ethernet related protocol substitutes the traditional software approach, and it really reduces the workload of development and shortens research time. The ethernet communication also ensures the enough length distance from front-end device to remote server center.

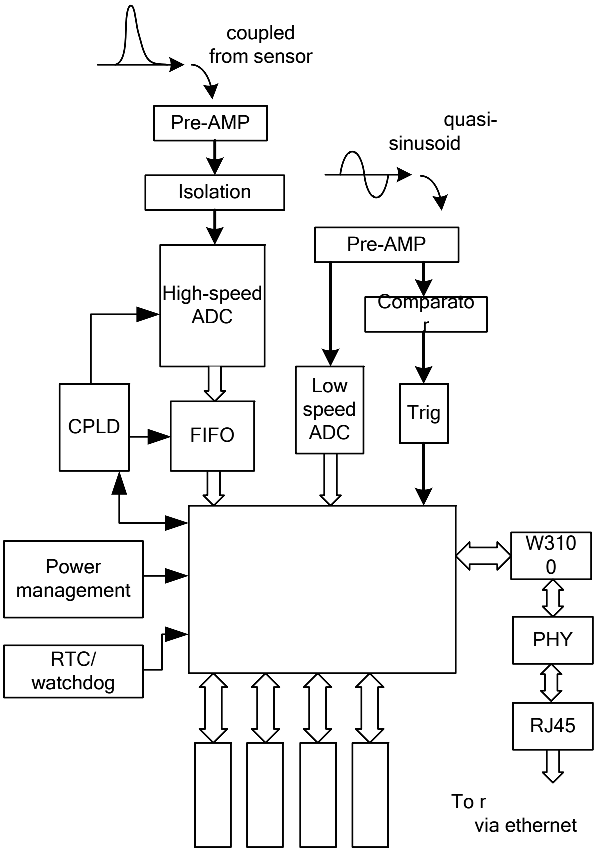


Fig. 4 Architecture of front-end device.

3.2 Control unit

As shown in Fig. 4, DSP chip TMS320C6713B plays the core role in front-end device with the function of acquisition timing control, related algorithm implementation and ethernet protocol resolution. In possession of excellent running speed as high as 225MHz, C6713B is competent for the acquisition timing control and high speed data transfer from ADC to SDRAM via FIFO. It also performs up to 1350 million floating-point operations per second (MFLOPS), which attributes to realizing all the filtering and PD statistical process. After the algorithm implementation, DSP control the external memory interface to send the results back to remote server by use a hardware stack chip. The scheme of DSP control unit board is shown in Fig. 5.

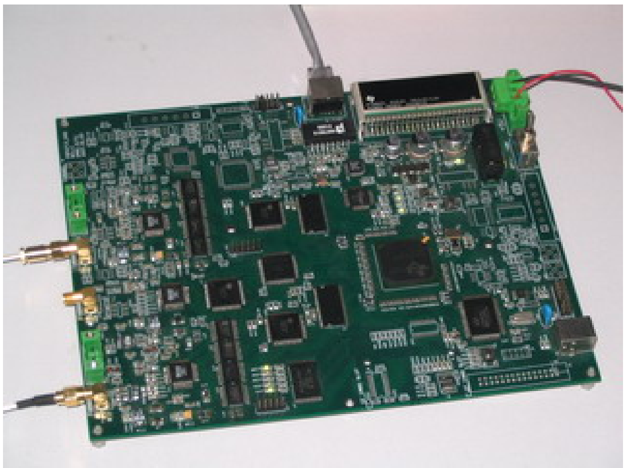


Fig. 5 Scheme of DSP control unit board.

3.3 High speed sampling strategy

PD analysis requires two kinds of sampling information, one with high frequency PD current coupling signal, and the other with reference power frequency phase.

3.3.1 High frequency PD signals sampling

As the interested bandwidth of sensor is about 500k to 3MHz, the sampling rate of 20MHz is enough. An analog-to-digital converter chip of ADS805 is chosen for its merits of 20MSPS, high dynamic range, 12-bit, pipelined ADC, which satisfies the high speed and high precision demand of PD sampling.

The developed system adopts the sampling strategy of ADC-FIFO-DSP-MEMORY as depicted in Fig. 6.

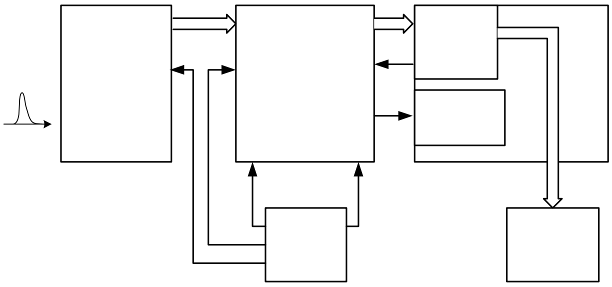


Fig. 6 Interconnection of high speed sampling structure.

CPLD provides the necessary control logic, including sample clock and read/write time sequence. ADC runs on 20MHz sampling clock, which comes from CPLD. Sampling results come out from ADC and are stored in FIFO (First-in First-out) continuously. The FIFO has two data-bus interfaces. One is connected to ADC, and the other to DSP. It will interrupt DSP when it reaches its half-full volume. Then DSP responses to the interrupt signal by fetching data from the right side of FIFO to the attached SDRAM. Data fetching procedure will be terminated when DSP counts to the half-full volume of FIFO, and switch to waiting status for next interrupt. The important point is that the speed of data transferred from FIFO to DSP, should be always kept faster than that of from ADC to FIFO. This allows FIFO available for new resulting data to store and not to overflow.

3.3.2 Power frequency synchronization

As most of PD sources in power system are correlated with power frequency phase in time domain, it is necessary to acquire the phase information and synchronize the high speed PD sampling with dedicated phase moment.

Two ways are designed in the presented system to realize the power frequency synchronization. One method is to sample the power voltage sinusoidal waveform simultaneously with the high speed sampling channel by using a comparative low speed serial ADC. Then compare both results to find the corresponding phase information of PD signals. The other method is to forward the power voltage to a zero-crossing comparator as shown in Fig. 7, and a square waveform is induced after comparison. The rising or falling edge will trigger DSP to start high speed sampling procedure. And this can ensure the PD signals relatively to a fixed phase location to power frequency. The user should choose one of the two ways to realize synchronization. If user needs to shift the start phase angle which is control by the remote server, the simultaneously sampling method is preferred. However, the zero-cross comparison method is simpler and more stable while the start phase point can not be changed.

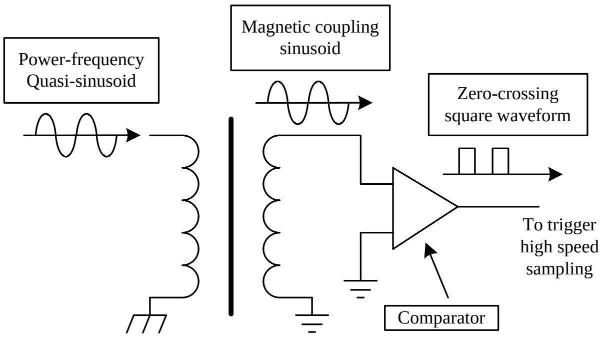


Fig. 7 Trigger square waveform produced by zero-crossing comparison.

3.4 Ethernet communication

Ethernet is a common used method for high-speed data transfer nowadays. The design of using ethernet contributes to enhancing the capability and flexibility of this monitoring system. However, the implementation of communication protocols of ethernet, such as TCP/IP and UDP, is considerable difficult on DSP-based system. Therefore, the designed system employs a new-coming ethernet controller, namely W3100, from Wiznet Inc., which integrates hardware protocol stack in itself. All communication protocol exchange and analysis processes are accomplished by the embedded hardware protocol stack, instead of traditional realization of protocol programming by software method. This really reduces the development period and difficulty.

With ethernet communication, server center can send a sample command and receive the result data from front-end device. This kind of ethernet media ensures enough data communication bandwidth of on-line continuous PD monitoring.

The W3100 ethernet interface is illustrated in Fig. 8. All the hardware protocol kernels are integrated in W3100 body. The application layer and driver module are implemented in DSP side, while the DSP access W3100 by asynchronous memory interface. The physics layer chip, ethernet transformer and RJ45 plug are also included in the interface design. The twist-pair cable acts as the transfer media in the ethernet communication.

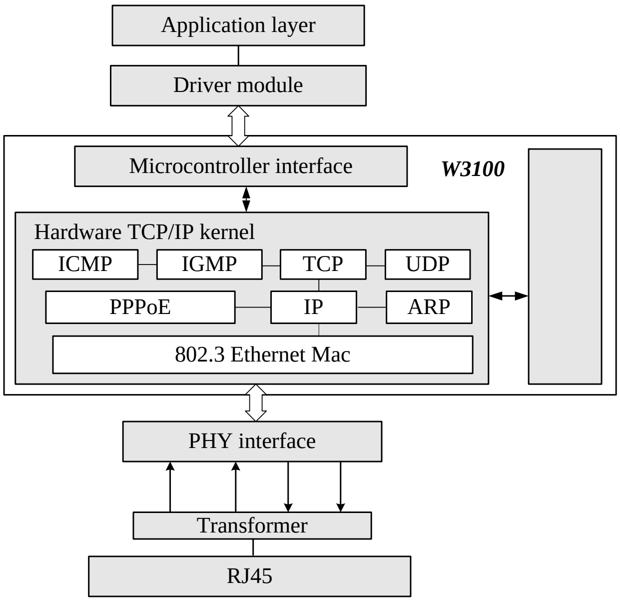


Fig. 8 Structural diagram of W3100 ethernet interface.

4 Algorithms and signal processing implementation in the front-end device

As the detected PD signals are very weak and always drowned out by the surrounding noise, post-processing in front-end device with sophisticated signal processing techniques is essentially required. Processing the data with DSP will definitely reduce workload of remote server, and save data communication volume and memory storage. The signal processing sequence steps are depicted in Fig. 9 with PDs signal sampling.

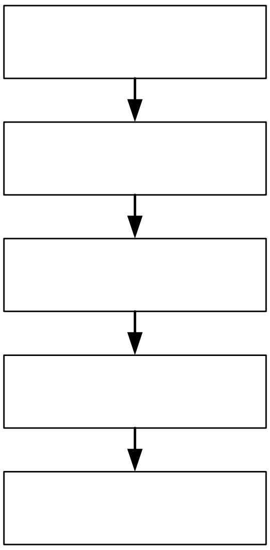


Fig. 9 Data processing in front-end device.

The raw PD pulse signals are acquired by high speed ADC. FIR filtering is utilized firstly to eliminate AM radio interference. Then the white noise is suppressed by wavelet de-noising techniques. Pulse extraction and statistics procedure gather the characteristic parameters, and all the information helps the remote server to judge the PD severity status.

4.1 Bandwidth filtering

As mentioned above, DSI is the main disturbance noise in power cable PD measurement [18]. All PD pulse signals are buried in the narrow band interference as shown in Fig. 12(a). According to former research, PD pulse is a wideband signal, and the AM broadcasting frequencies used by different broadcasting stations spread below 2MHz. Therefore, it is feasible to remove the spectrum components of broadcasting from the detecting signals with bandwidth filtering. Although this may somehow reduce some proportion power of real PD signals, the SNR can still be improved to a great extent by filtering to the bandwidth above 2MHz.

Finite impulse response (FIR) filtering is a practical and effective method for bandwidth filtering being implemented in DSP. Its magnitude and phase response are display in Fig. 10. The bandwidth of designed 200-order filter is between 2MHz to 7MMHz, within which the phase response keeps linear shift characteristic.

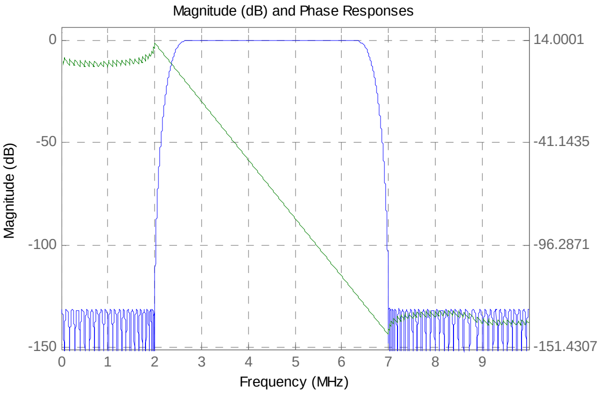


Fig. 10 The magnitude and phase response of designed filter.

4.2 Suppression of white noise

White noise is a kind of random noise that usually exists in digital sampling results. It performs as thermal noise or shot noise from amplifier, sampling circuit and ambient surroundings. Because white noise has the nature of wide frequency bandwidth, which superposes with the frequency distribution of PD signal, frequency spectrum rejection can not be used to eliminate the white noise. Wavelet is found to be a useful technique to suppress white noise [19, 20].

Wavelet transform decomposes a time series signal into time-scale domain with the expression of a set of shifted and scaled versions of a basis function, i.e. $\psi(t)$. By utilizing scaling and shifting operations of the mother wavelet $\psi(t)$, a family of continuous wavelet transform (CWT) functions are derived by equation (1),

$$\psi_{a,b}(t) = a^{-\frac{1}{2}*}\psi(\frac{t-b}{a}), a,b \in R, a \neq 0 \qquad (1)$$

where a is the wavelet scaling parameter, and b is the shifting parameter.

The applied wavelet de-noising procedure involves three steps as follows,

1. Signal decomposition. Choose the wavelet of db2 and level 8, and compute the wavelet decomposition coefficients of the signals at levels from 1 to 8. Fig. 11 shows the waveform of db2 wavelet, which is similar to the PD pulse shape.

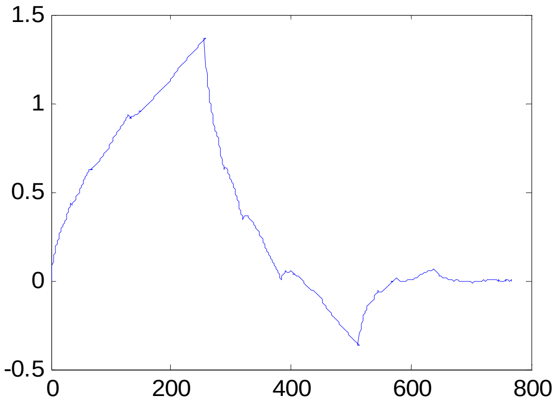


Fig. 11 The waveform of db2 wavelet.

2. Choose the threshold for each scale. Threshold values are calculated by equation (2) for each level from 1 to 8, and apply a soft or hard threshold to the detail coefficients [21, 22]. The threshold value for each j scale is computed as shown in equation (2),

$$\lambda_j = m_j / 0.675 \cdot \sqrt{2 \cdot \log(n_j)} \qquad (2)$$

where λ_j indicates the threshold value at level j, m_j is the median value of the coefficients at level j, and n_j is the length of coefficients associated with level j.

3. Signal reconstruction. Reconstruct the filtered signals by using original approximation coefficients and modified detail coefficients from decomposition levels 1 to 8.

4.3 Pulse extraction and statistics

After filtering and de-noising, PD pulses appear clearly from DSI and white noise. But as for PD analysis, periodical statistics parameters are more important than the real pulse shape, so it is necessary to extract the pulses and acquire the characteristics of each pulse. Generally, the magnitude, phase and repetition information is adequate for statistics.

Therefore, in front-end device of the proposed system, one parte of DSP code is composed to form a two-column matrix with PD pulses magnitude and phase location, and the rows indicate pulse samples. The calculated matrix is transferred to remote server center, and the server will synthesize the characteristic matrix and display diagrams according to them. The 2D or 3D diagrams are more for PD pattern identification and condition diagnosis [23].

4.4 Generation embedded C code from MATLAB

Traditionally, the digital signal processing is realized in computer and this requires the original detailed sample results sent from the front-end acquisition device to remote computer. It is not realistic when the on-line PD signals need to be captured continuously, which requires abundant data transfer and processing. A better way is to carry out the digital signal processing and related algorithm in the front-end device, which is adopted in the developed system. With the high performance DSP TMS320C6713B in the front-end device, both high speed sampling control and lots of dedicated computations are performed.

While, the design and the debug processes of all the algorithms are rather difficult on the development platform of DSP, such as Code Composer Studio (CCS). Additionally, the code composed directly in CCS can neither be totally verified, nor achieve high efficiency as well. Whereas the known algorithm design and debug software, MATLAB, provides a toolbox namely Embedded MATLAB for algorithms acceleration and efficient code generation. The tested algorithm coding language is written in M files through Embedded MATLAB Function. Real-Time Workshop of Simulink calls the M files and generates all the related embedded C code and H header files. Then, the generated C code and H header files can be added to the project established in CCS for further synthesization. All the source files are complied and the download file is built to burn into the front-end device. The data processing algorithms of the programs are running after the real-time operation system, i.e. DSP/BIOS II, which is the embedded system implemented in CCS.

5 Field test and analysis

To verify the effectivity of the on-line PD monitoring system, field tests are carried out, and sample data are captured from on-site detection.

The raw data captured directly from HFCT is showed in Fig. 12. As seen in the time domain waveform, all pulse signals are buried in interference, especially some narrow band sinusoidal signals. The frequency characteristics of these DSI signals distribute from 0.3MHz to 1.5MHz. All the peaks in frequency spectrum, which are much stronger than the frequency components of pulse signals, correspond to local radio broadcasting frequency precisely.

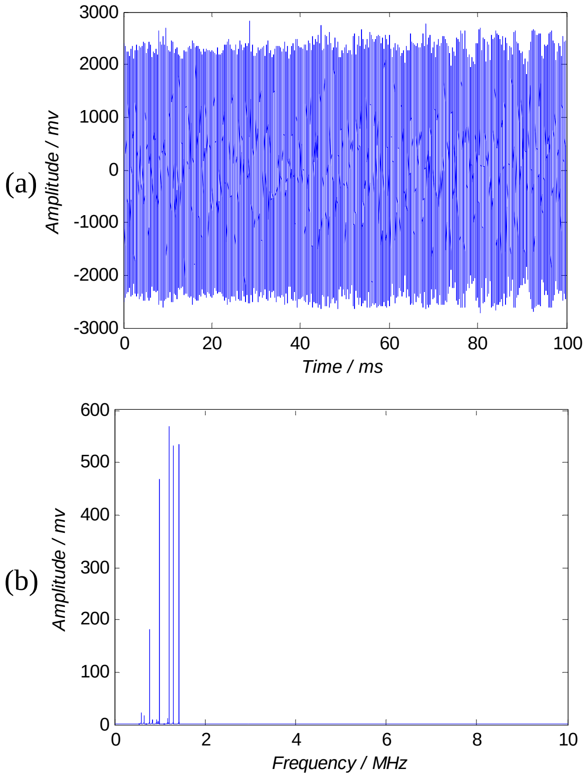
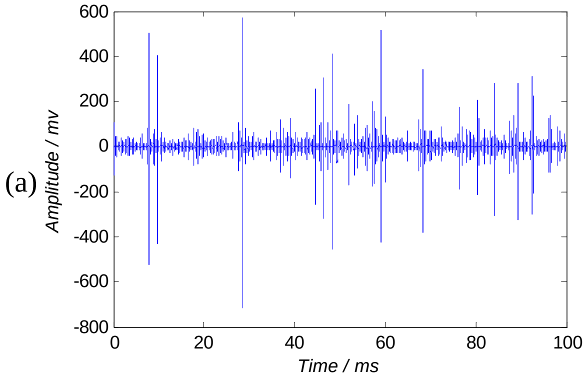


Fig. 12 Raw data from HFCT. (a) Time domain waveform, (b) Frequency spectrum.

Considering the concentrated bandwidth characteristic of narrow band interference, it is possible to suppress them by FIR filtering. A 200-order band-pass filter with bandwidth from 2MHz to 7MHz is chosen to filter out the DSI signals. The pulse signals after FIR filtering is displayed in Fig. 13(a), in which PD pulses are presented obviously. Compared Fig. 13(b) with Fig. 12(b), the overall amplitude in frequency spectrum is much lower from some hundred milli-volts to below 1mv. Although FIR filtering also wipes off some partial energy of PD signals within the frequency range overlapped with DSI, it is deserved to do the filtering because the SNR is greatly improved.



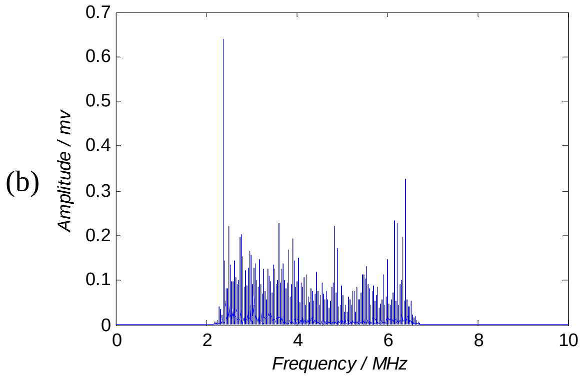


Fig. 13 Pulse signal after FIR filtering. (a) Time domain waveform, (b) Frequency spectrum.

Wavelet de-noising procedure contributes to enhancing SNR through removing the white noise as shown in Fig. 14. Compared Fig. 14(a) with Fig. 13(a), the PD pulses are more clearly one by one because of the removing of white noise interference.

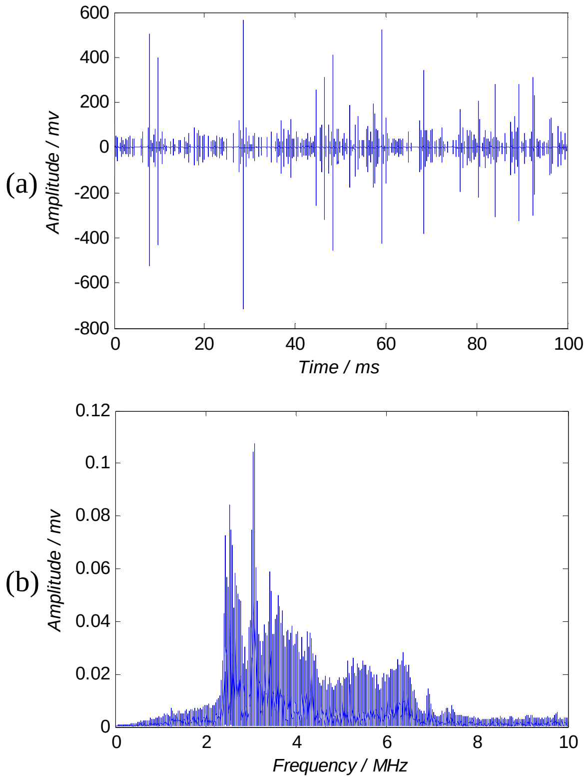


Fig. 14 Pulse signal after wavelet de-noising. (a) Time domain waveform, (b) Frequency spectrum.

All the above data processing procedures are completed in the front-end device, by transplanting the algorithms into embedded C code by Embedded MATLAB. DSP in front-end device computes and gets the statistical data and sends them to remote server center by ethernet network. Statistical data simplify the results and reduce the redundancy of storing data.

The server program draws some 3D diagrams according to the statistical parameters of PD signals calculated by the front-end device as shown in Fig. 15. The typical T-Phi-Q diagram is a common used characteristic spectrum in PD analysis. Several consecutive periods of PD characteristic parameters associated with ac cycle of 20ms are displayed in one 3D diagram, with reference to the power frequency sinusoid. One ac cycle of PD data are divided into 360 degrees in phase scale, while the phase information is critical in PD based condition analysis. Successive periods with reference to ac cycle reflect the repetitive nature of PD sources for continuous timing.

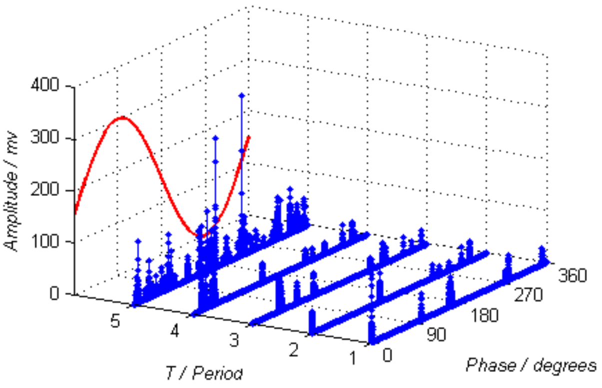


Fig. 15 T-Phi-Q diagram of PD signals.

6 Conclusion

PD detection is proved to be a useful and effective method of high voltage apparatus condition monitoring, which draws more and more attention. Its non-invasive advantage makes it possible that the high voltage apparatus under monitoring can keep working. Condition based monitoring is the trend of the maintenance mechanism in power system.

The presented PD on-line monitoring system applied to power cable termination is developed on high performance DSP. The front-end device together with HFCT realizes PD signal sensing, amplifying, sampling and some algorithms.

Through on-site testing and PD signals analysis, it is verified that the on-line monitoring system performs well and meets the system request. The stability of DSP based system monitors the status of power cable terminations continuously, and ensures the normal operation of power system ultimately.

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