Transmission and Processing of the Measurement Signals Generated by a Transformer for the Current Measurement in Medium Voltage Networks

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Abstract— **The trends to improve the performances of the classic instrument transformers was oriented to introducing new materials, components and methods in its design, manufacturing and operation. This paper presents the technical solutions adopted to implement the measuring system at medium voltage based on this current instrument transformer. The transformer uses a fiber optic link to send the measuring signal from the medium voltage point to the monitoring point. The structural block diagram of this transformer is presented and the operation of the main blocks is described. On the monitoring side, the measuring signal is converted from the voltage signal at the current signal which flows through a current loop for remote control and telemetry. Also, analog to digital conversion and the sending of the result of measurement at master monitoring system is possible. A simple algorithm for remote control of the operation of transformer is presented. If the transformer is integrated into a digital measurement system then it operates as a slave unit under the control of the master unit. The samples taken from the measurement signal are used for digital processing. It is analysed the possibility to realize a network of transformers using the communication bus RS 485. Finally, the waveforms, recorded during the performed tests, are presented.**

I. INTRODUCTION

Nowadays, in industry, automation, control processes, laboratory tests, for the measuring of electric currents are used four types of transducers: resistive shunt, the electromagnetic current transformer, the transducer based on Hall sensor and the Rogowski sensors.

The resistive shunts have the advantage that they do not require external power supply in secondary circuit for measuring, they have not an offset and the measurement signal is proportional to the measured quantity. Instead, they does not provide electric isolation between the measured quantity and the measurement signal and, sometimes, this signal must be amplified to be used [1].

The current measurement transformers have the main advantages: provide electric isolation between the measured quantity and the measurement signal, the output signal is a current (hardly distorted) and not requires external power supply. Its main disadvantage is the working only in A.C.. Also, the saturation and the limited range of frequency are disadvantages.

The transducer based on the Hall effect sensors can be used both in the measurement of D.C. and the A.C.. They provide electric isolation between the measured quantity and the measurement signal and a wideband frequency of operation (from d.c. to few kHz). He have the disadvantage that they require external power in secondary circuit for measuring.

Frequently, the current transformer is used as instrument transformer in the monitoring, testing and control systems. On that basis, the experts want to improve the performances of these instruments.

In the last years, many components and technologies has been tested to isolate and to transmit the measuring signal from measuring point to the monitoring point.

This is very important in the case of a current transformer of medium and high voltage, where, a fiber optic link has been introduced for measurement signal transmission [2], [3] between the unit which generates the measuring signal and performs electro-optic conversion and the unit which receives the optical signal to perform opto-electric conversion.

The first unit is placed near the measuring point (on line or bus bar) and it requires external power supply for the instrumentation amplifier and the electro-optic converter. The solution of self-supplying it was adopted.

The second unit is placed in the monitoring point and converts the optic signal to electric signal for display, control or protection devices. For a measuring transformer it is very important:

►to operate with the specified accuracy into the range of measuring of the primary current;

►to have a safe operation to the operational voltage and protection against overvoltage;

►to have high stability of the measurement result to temperature variation.

The paper presents some aspects to integrate the previous presented structure in the actual measuring systems, the transmission and processing of measurement signal generated by the transformer which has a fiber optic link between the two units. The second section of the paper presents a brief overview of the structure of the current transformer. The main functions of its structural blocks are presented. The third section of the paper presents the solution to transmit the measurement signal from the output of the second unit of the transformer to the input of a remote device by a D.C. link. The fourth section presents an analog to digital converter to integrate the transformer in the digital measurement systems. Also, the algorithm for digital processing of sampled signal is presented. The fifth section presents a software application for the remote control of the transformer by an intelligent master device. The last two sections show experiments, results and conclusions resulted from the transformer's tests.

II. A BRIEF OVERVIEW OF THE TRANSFORMER. THE OPERATION OF MAIN BLOCKS.

The current transformer consist of two main units linked by the fiber optic: a transmitter unit -TU- which generates the measurement signal and converts the electric signal into optic signal, and a receiver unit -RU- which converts the received signal from optic signal to electric signal. Fig.1. shows the structural diagram of the current transformer for medium voltage network.

The current I flows through line LN and the primary circuit of the electromagnetic current transformer (IT). The secondary current of this transformer produces a voltage drop across the resistor Rs. If the value of this voltage rises above 1.5 V the overvoltage limiter OVL2 protects the input of optic transmitter unit, OTU.

The second current transformer ST (Fig.2.) provides energy to power supply PS and for optical transmitter unit. The voltage Us across the resistor Rs is a function of primary current, I. Bridge rectifier BR provides to output the D.C. voltage U_d which depends on the value of the line current, I.

The converter D.C. to D.C. offers constant output voltages, +V and –V, while the input voltage U_d takes values inside a wide range.

The safe operation and the protection of power supply PS is ensured by the overvoltage limiter, OVL1 (Fig.3.). The value of active power consumption of optic transmitter unit is about 1W.

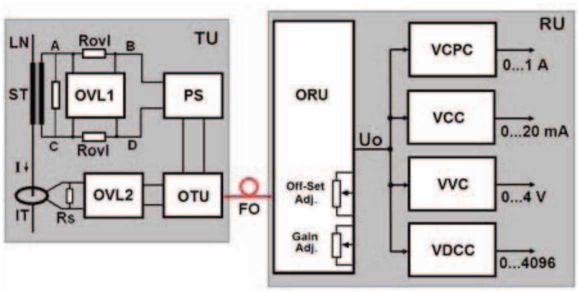

Fig.1. Block diagram of the current instrument transformer

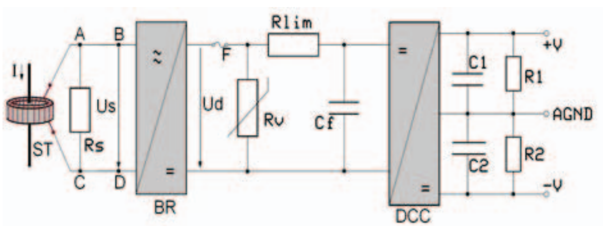

Fig.2. The power supply of optic transmitter unit.

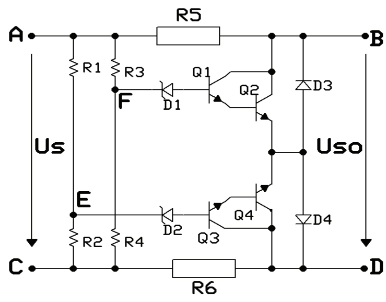

Fig.3. The wiring diagram of overvoltage limiter OVL1.

The reference levels for the limiting thresholds are provided by the dividers R1-R2 and R3-R4. For the positive half-cycle, the reference voltage levels results from the next equation:

$$U_F = \frac{R_4}{R_3 + R_4} U_s = U_{D1} + U_{BEQ1} + U_{BEQ2} + U_{D4} \qquad (1)$$

Similarly, for negative half-cycle, it can writes,

$$U_E = \frac{R_1}{R_1 + R_2} U_s = U_{D2} + U_{BEQ3} + U_{BEQ4} + U_{D3} \qquad (2)$$

With the approximation,

$$U_{BEQ1} + U_{BEQ2} + U_{D4} \cong 2V \qquad (3)$$

$$U_{BEQ3} + U_{BEQ4} + U_{D3} \cong 2V \qquad (4)$$

the limit value of the voltage Us results from the previous equations:

$$U_s = (1 + \frac{R_2}{R_1})(U_Z + 2V) \qquad (5)$$

Uz is the breakdown voltage of Zener diodes D_1 and D_2.

By the conversion of optic signal to electric signal, the frequency modulated signal from the input of the optic receiver unit (ORU) generates to output the voltage, U_0.

In order to integrate the current transformer both into conventional and modern measurement systems, several types of adapters are used as interface between the transformer output and the system input:

●the voltage - current, power converter (VCPC): this adapter uses the output voltage, U_0 from range [0,4] V, to control the output current, I_e in range [0,1] A;

●the voltage - current, converter (VCC): this adapter uses the voltage, U_0 from range [0,4] V, to control the output current I_e in range [0,20] mA;

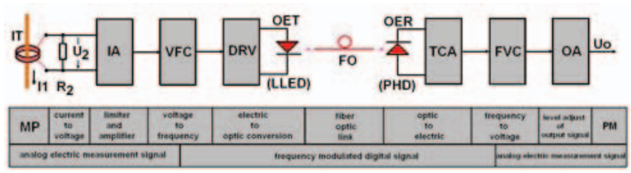

Fig.4. Block diagram of the measurement channel with FO link

● the voltage - digital code, converter (VDCC): this adapter uses the voltage, U_0 from range [0,4] V, to control the digital output code with 12 bits resolution;

●the voltage - voltage, converter which operates as voltage repeater (VR).

Second and third adapters can be used for long distance transmission of measurement signal.

III. REMOTE TRANSMISSION THROUGH CURRENT LOOP

The VCC converter can be used as current loop with 250 ohms terminal resistor. The value of transfer factor of the current loop is 100 μA/A.

The following figure presents the wiring diagram of this adapter. It can be seen that the adapter contains:

-an ideal full wave rectifier [5], [6], [7], [8] which consists of operational amplifiers AO_1, AO_2, the diodes D_1, D_2 and the resistors R_1-R_5 ;

The output voltage of the second operational amplifier can be written using the next equation:

$$U_{OUT} = \frac{2U_{0\max}}{\pi}\frac{R_2}{R_1}\frac{R_5}{R_4} = \frac{2\sqrt{2}}{\pi}\frac{R_2}{R_1}\frac{R_5}{R_4}U_0 \qquad (6)$$

If the resistors R_1-R_5 have equal values then the previous equation becomes:

$$U_{OUT} = \frac{2\sqrt{2}}{\pi}U_0 = 0.9U_0 \qquad (7)$$

-a low-pass filter [9], [10], [11] which consists of the resistors R_6, R_7 and the capacitors C_4, C_5;

If $\tau=R_6C_4=R_7C_5$ is the time constant of the circuits R_6-C_4 and R_7-C_5, then the cut-off frequency, f_c, results from the equation [12], [13], [14],

$$f_c = \frac{1}{2\pi\tau} \qquad (8)$$

Because the frequency of rectified voltage is f=100 Hz the value of time constant τ can be (3…5)/f.

-a voltage to current coverter [15], [16], [17] which consists of operational amplifier, AO_3, transistor, Q , and associated resistors R_{10}, R_{12} and R_{13}.

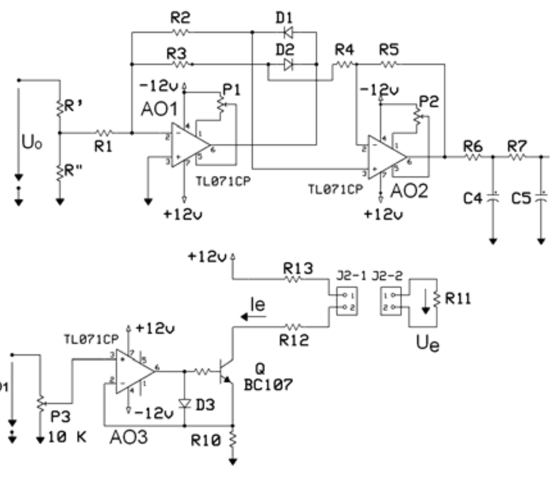

Fig.5. Wiring diagram of voltage to D.C. current converter

The value of resistor R_{10} must to be,

$$R_{10} = \frac{U_{01\max}}{I_{e\max}} \qquad (9)$$

If the range of the current, I_e, is [0, 20] mA then the output voltage across the terminal resistor has the range [0, 5] V.

IV. THE VOLTAGE TO DIGITAL CODE CONVERTER

The VDCC converter contains a level shift module [3] which sends the analogue measurement signal, U_0, from its input to the input of a mini controller. After analog to digital conversion the result is sent by RS232 or RS485 bus to a master unit. The following figure shows the block diagram of the VDCC adapter.

The use of the assembly from Fig.6 creates the possibility to connect several transformers to a single personal computer through a single serial port on RS 485 bus. This way, a “network of transformers” can be achieved, in order to carry out measurements in different points.

Each transformer works as a “slave” device subordinate to the computer which plays the role of “master” device.

For identification purposes, to each device is assigned an indicator or its own address. Any request sent by the “master” device to the “slave” device, respectively any response sent by the “slave” device to the “master” device will be accompanied by this address.

The addresses and requests or commands used in the communication protocol have the size of 1 byte. The VDCC adapter is fitted with a low cost microcontroller [18]. Its programming is achieved with the MicroBasic development environment, using a board for applications development [19], [20]. In case of using the VDCC adapter, a reception and decoding sequence of a

```
et48: while true

    if Usart_Data_Ready = 1 then    'wait its own address
        receive = Usart_Read  end if
    if receive=0x31 then receive=0x00 goto et end if
     wend
 et: while true    'wait a command to choose a function
    if Usart_Data_Ready = 1 then receive = Usart_Read end if
      if receive=0x40 then receive=0x00 goto et40 end if
      if receive=0x41 then receive=0x00 goto et41 end if
      if receive=0x42 then receive=0x00 goto et42 end if
       wend
```

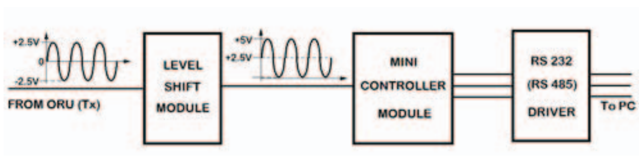

Fig.6. Voltage to digital code adapter – principle diagram

There are two infinite loops “while”:

● in the first loop, the “slave” device expects its own address (e.g. 0x31). For this purpose, a test is performed to see if the data in the microcontroller’s reception registry is available to be read. Usart_Data_Ready function returns the value 1 if the data can be read. The variable “receive” is assigned the value in the reception registry.

This value is read by the Usart_Read function. The condition to returning from the loop is that variable “receive” contain the 0x31 value. By assigning receive = 0x00, the conditions for a new reading are set.

● in the second loop “while”, the “slave” device with the 0x31 address, expects the command to perform a function. Depending on the value the variable “receive” taked from Usart_Read function, the leaving of this loop can be carried out for the following destinations:

►if “receive” = 0x40, the sequence of instructions that starts with et40 label will be followed;

►if “receive” = 0x41, the sequence of instructions that starts with et41 label will be followed;

►if “receive” = 0x42, the sequence of instructions that starts with et42 label will be followed.

These sequences can be identified in the flowchart from Fig.7., where, a simple algorithm for VDCC operation is presented.

The next paragraphs will present the source code for the functions F1, F2, F3. In the F1 function sequence the “slave” device acquires the samples that will be sent to the “master” unit, when this sends a appropriate command (0x43).

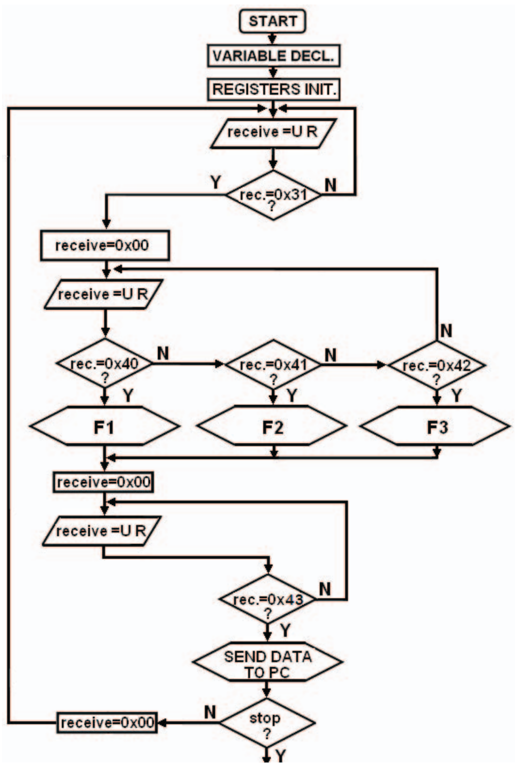

Fig.7. Flowchart of a simple algorithm for VDCC operation

Thus, the value of each sample returned by the function ADC_read(1) is stored into a word component of the vector t[i]. The ADC_read(1) function reads the result of the analog to digital conversion for analog input INA1 of mini controller.

```
et40:                    'here begin the function F1
        i=1
        while i<291
        t[i]  = ADC_read(1) 'collect 291 sampl. from
        current tr.
        i=i+1
        wend
        while true
        if Usart_Data_Ready = 1 then    'wait for SEND
        DATA   TO PC command
        receive = Usart_Read end if
        if receive=0x43 then receive=0x00 goto et43
        end if     wend
```

If a data request is received from “master” unit, then the next sequence will be worked. The function WordToStr() converts the value of a sample (type word) into text. USART_Write() function sends the character “T”, followed by the text associated to the sample, t[i].

```
et43:

        i=1
        while i<291
        WordToStr(t[i],txt)           'converts t[i] to text
        USART_Write($54)              'transmit T character
to PC
        USART_Write_Text(txt)   'transmit t[i] as text to
PC
        i=i+1
        wend
```

In the F2 function sequence the samples acquired during a cycle of the measuring signal are compared with tmax and tmin values. The final values of tmax and tmin are sent to “master” if this sends a request.

```
et41:              'here begin the function F2
        tmax=0
        tmin=2048
        i=1
        while i<291
        if (t[i]>tmax) then tmax=t[i] end if
        if (t[i]<tmin) then tmin=t[i] end if
        i=i+1
        wend
```

F2 function contains a sequence for computing of effective value using all samples of the measurement signal during a cycle.

```
et42:              'here begin the function F3
        i=1
        while i<291
        suma=suma+t[i]*t[i]
        i=i+1
        wend
        sf=suma/291
        sf=Sqrt(sf)
```

Function F2 can be used to calculate the average value of all samples acquired:

```
et42:          'here begin the function F3
     i=1
     while i<291
     suma=suma+t[i]
     i=i+1
     wend
     sf=suma/291
```

V. THE CONTROL PANEL OF MASTER UNIT.

In the previous section was described the operation of the transformer as converter analog to digital, with serial transmission of conversion result to another device. This section presents a simple software application for PC, developped under Delphi IDE. The interface between user and application is control panel which contains some controls and indicators.

By pressing B1 button an On Click event occurs (Fig.8). The procedure that treats this event creates a serial port for communication between PC and the "slave" device. All communication parameters are initialized: speed of the serial link in bits per second, number of parity bits, number of data bits per character, data flow control. If the PC has its own serial port then this can be COM1 or COM2 port. Otherwise, an adapter USB to serial can be used and the number of COM port will be assigned in the space of virtual COM ports.

The second button, B2, denoted by "START ACH", will start the communication protocol. The operation of a Timer component type is allowed. A repetitive procedure will be executed until Timer will be stopped.

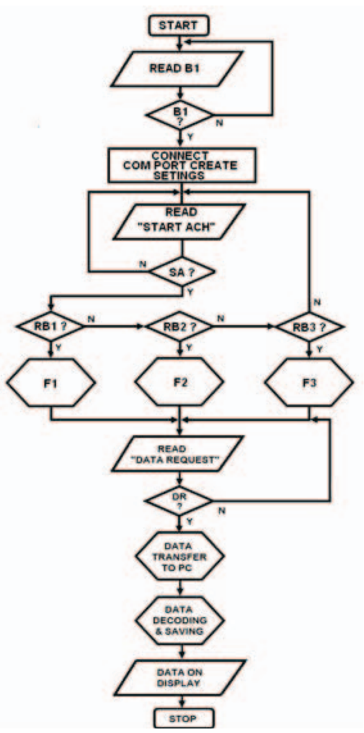

Fig.8. Flowchart of a simple algorithm for application operation on PC

The interval parameter of Timer it is greatest or equal with the cycle necessary as the slave unit to perform its selected function (F1, F2, F3) and of the data transfer between the two units. One of the radio buttons, RB1-RB3, will indicate the function that will be performed by the "slave" unit. The radio button that will be selected will direct the execution to the branch denoted by "Y" in the decision block.

If the "master" unit sends a data request to the "slave" unit, then the answer will contain the result of the function execution. The answer is a string that includes five characters:

- the control character "T";
- four characters signify the decimal value of the result of analog to digital conversion.

Each string of five characters is written to a file on the hard-disck. If the string is denoted by s then the value of result r will be obtained using the next sequence:

```
for i:=0 to 4 do
        begin
         if Char(s[i])='T' then
            begin
r:=1000*s[i+1]+100*s[i+2]+10*s[i+3]+s[i+4];
            end;
        end;
```

If the first character of the string s (s[0]) is "T" then the next characters will represent:

- ►s[i+1]=s[1] the thousands digit;
- ►s[i+2]=s[2] the hundreds digit;
- ►s[i+3]=s[3] the tens digit;
- ►s[i+4]=s[4] the units digit.

The value of the result, r, can be in range [0, 4096] if an analog to digital converter, with twelve bits resolution, provides the digital code. The value of measured current, I, is obtained by multiplying the result r with D-the maximum of range of the current variation.

$$I = rD \tag{10}$$

Some indicator components can be used to show the result: "Edit", "Label" and "String grid" for digital format or "Chart" for graphical format.

Fig.9 shows the control panel and the graphical reprezentation of the points of with data recorded during the parallel monitoring of the current, using this current transformer and a standard instrument transformer, 0.2 accuracy classes. The red line is the recording of data provided by the new transformer. Intentionally was introduced an off-set to this recording. This control panel was used to perform a single function: the monitoring of effective value of measured current.

The sampling frequency value was chosen by setting the value of Timer interval parameter to 5 seconds. By pressing "Save Chart" button an "on click" event result, the image of the Chart is saved on hard disk. At the same time, all values of the samples are saved in a data file. An USB to RS232 converter allows to use the high speed universal serial bus to communicate with the VDCC using the simple protocol presented in previous paragraphs at the rate of 57600 bits/second.

Fig.9. Control panel of the application on PC, used as current monitor

VI. EXPERIMENTS

Some experiments has performed to determine the steady-state and dynamic performances of the transformer. The primary circuit of the transformer was supplied from a power current generator. The primary current of the transformer was changed from zero to the maximum value of the range and the output signals was measured and recorded. The output voltage of the power supply, PS, (Fig.1.) was measured to draw the function U_d=f(I) in steady-state operation. The output voltage of VCC converter was measured to determine the relative errors of measurement for this adapter type.

The parallel monitoring of the output voltage of VDCC converter and of a standard current transformer was recorded to verify the relative errors of measurement for this adapter type. Also, were carried out tests to determine the response of the optical fiber transmission channel to step input signal, and the response to variable frequency sinusoidal signal.The output signal of VCC converter was analyzed. The first response was used to identify the transient parameters and the second response was used to draw and to analyze the amplitude-frequency characteristic.

VII. RESULTS. CONCLUSIONS.

This section presents some characteristics resulted from the tests performed and the parameters of the instrument transformer. Figure 10 shows the graphical representation of function U_d=f(I) based on the experimental data. It can see that the voltage Ud has the value great than 10 V if the current value of the current is great than 40 A. Always, this solution can be used if the values of the current don't falls below 20 % of rated current. The minimum value of input voltage of the converter, DCC, is 9 V. For the values of the current under 40 A (and under 10 V for the voltage U_d) another technical solution must be found to supply OUT unit.

Also, the operation of OVL1 has verified. The waveforms of output voltage U_{s0} and of the current through R5 resistor was recorded (Fig.11.), by using the test probe 1:10, respectively by using test probe 1:1. The output voltage was limited at 22 V. Finally, this threshold will be increased to 30 V.

The value of the secondary voltage, U_2 of the transformer, IT, is 1 V at 200 A primary rated current, I1n and 1.2 V at 1.2I1n.

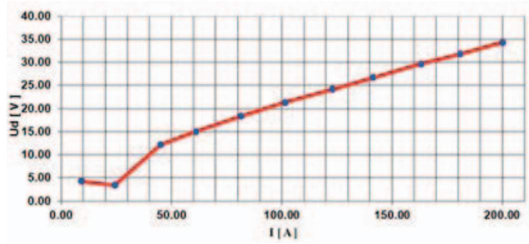

Fig.10. Uncontrolled output voltage of PS as a function of primary current I.

Figure 12 shows the graphical representation of output voltage U_e (fig.5) as a function of input voltage U_2. The voltage U_2 was measured across the terminal resistor R_{11}=250 Ω, placed at the end of a long cable line (100 m length).

The theoretical representation and the experimental representation are overlapped. This is a good result and the amplitude errors are between the standard limits of 0.5 accuracy class (see Fig.13.). Figure 14 shows the phase errors of output signal U_0 relative to the input signal U_2. Also, these errors are between the limits of 0.5 accuracy class. All the tests to verify the accuracy class have been carried out on basis of the comparison with a standard transformer [22]. A high speed data acquisition system and an appropriate software application were used for data acquisition and data processing [23].

Figure 15 shows the recording of primary current, I and of secondary voltage, Ue in transient operation of the current transformer.

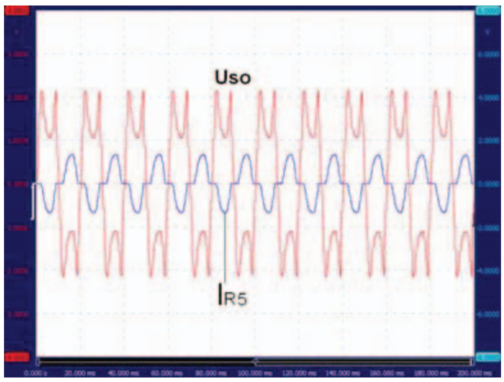

Fig.11. Waveforms recorded during the tests of OVL1 module.

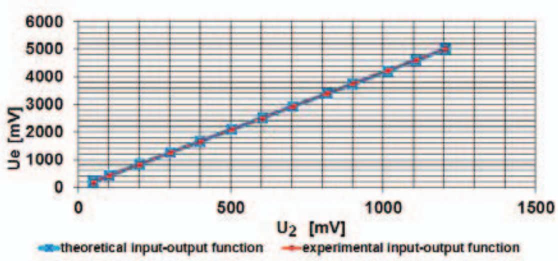

Fig.12 Input-output function of the transmission channel with VCC adapter.

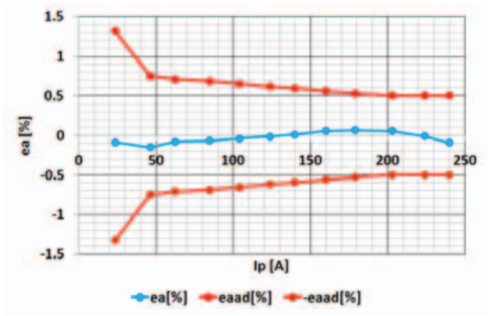

Fig.13.The amplitude errors of the transmission channel, with adapter VCC.

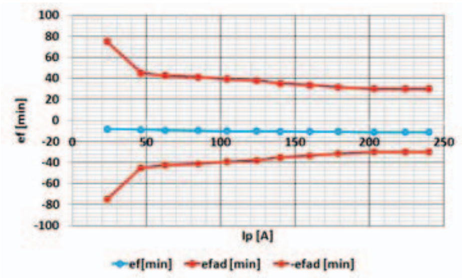

Fig.14. Phase errors of the transmission channel, at the output of ORU.

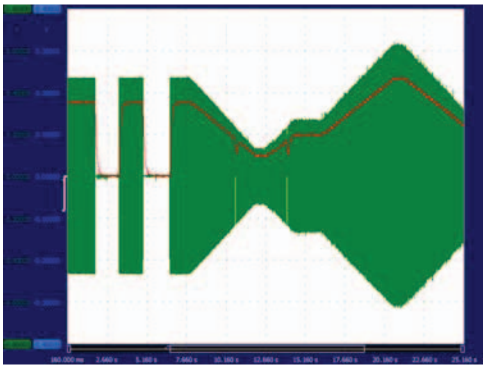

Fig.15. Primary current, I and secondary voltage, Ue in the transient operation of the transformer

If we analyze carefully the figures we see that the amplitude errors and the phase errors can fit right between the limits of accuracy class 0.2.

This is a consequence of using a tracking system based on PLL in fiber optic link. The measurement signal is a variable reference signal applied to input of tracking system.

The tracking loop is placed in the unit RU. The reference signal generating element (the converter voltage-frequency, VFC) is placed in the unit TU. The stability of this system is very important for the accuracy of the measurement result.

The tests to determine the response of the system to the step input signal showed that the transient regime is characterized by the following parameters:

► the overshoot of output signal U_0, σ=13.5 %;
► the settling time of output signal, ts=470 μs;
► the delay time, td=100 μs;
► the rise time, tr=100 μs.

They are good parameters and allows for a quick response and a bandwidth corresponding to our application (about 5 kHz).

Figure 15 shows the evolution of output signal Ue when the power supply of the unit RU is switched on and switched off and the measured current has some variations.

To improve the evolution, the time constant of the low pass filter can be reduced as long as the measurement accuracy is not affected.

For the power supply, has been tried an alternative solution based on a tuned transformer [24], [25], TT (Fig.16.).

This was made in order to reduce the primary current through the R_1 resistor and to increase the output current, I_0, and the voltage to terminal of load resistor R_0. The resistor R_1 is medium voltage dividers which pass through composite insulator used as support for the transmitter unit.

Using a transformer of 2.4 VA , the value of current absorbed in the primary was 5 mA (Fig.17.) and the active power consumed was 57.8 W for a supply voltage of 20 kV.

It is necessary to reduce the primary current and the active power dissipated by the source.

The equivalent circuit of the power supply must be considered with all parameters reported to the primary side of the transformer.

A high value of the transformer ratio can be an advantage to obtain a low value of the primary current in full load working.

The operating in conditions of resonance decreases the absorbed active power compared to the case of operation without resonance.

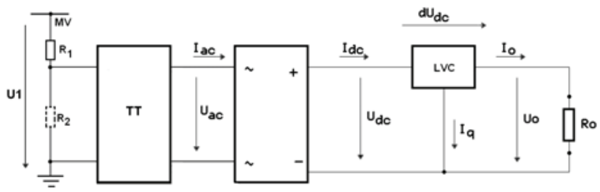

Fig.16 Alternative solution for power supply used in TU.

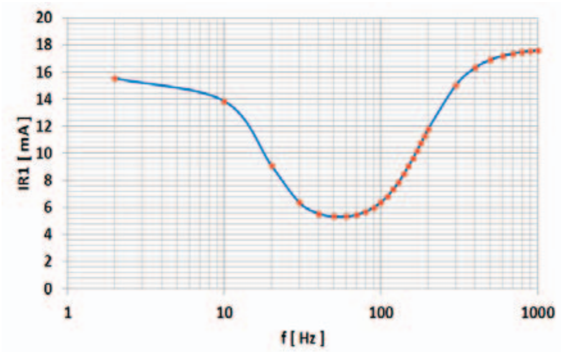

Fig.17 Current through R1 resistor as a function of frequency.

Fig.18 shows a simple structure of network based on current instrument transformers, used to measure the current in a three phase electric network.

All receiver units are connected to RS 485 bus by RS232 to RS 485 converter in order to keep the previous communication algorithm and the protocol.

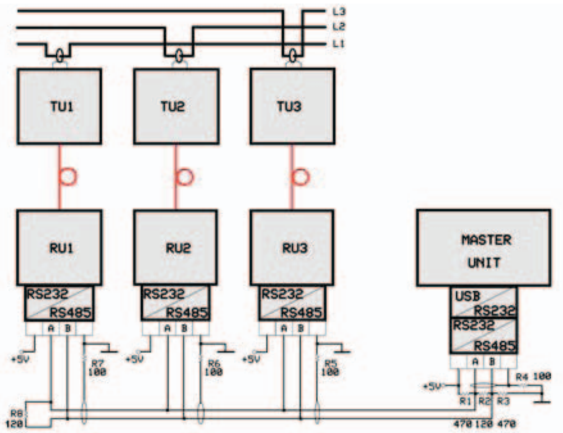

Fig.18 Network transducers based on current instrument transformer.

By using USB port of PC the communication speed can be increased. In our software application a speed of 57600 bits per second was used. An USB to RS485 converter can be used to communicate between the master unit and the slave units [26].

Using the same protocol as the previous protocol and RS485 to RS 232 converter to each slave unit, the previous structure can operate efficiently. The RS 485 transmission bus allows safe operation for the length less than 1200 m. If the length of the line exceeds 1200 m then the repeater devices can be used.

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