A NOVEL MICRO PMU FOR DISTRIBUTION POWER LINES

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ABSTRACT

Miniaturization, low cost and easy live installation are development directions of phasor measuring unit (PMU) in power distribution network lines. In this paper, a new distributed PMU device for wide area measurement system (WAMS) of distribution network was designed. It gained energy from the line by high-density inductive draw-out power module, measured current and voltage waveforms by PCB Rogowski coils and spatial capacitive voltage divider respectively, and achieved voltage and current collection in the whole network by distributed synchronous sampling. It provided a new solution to the development of new PMU in the distribution network lines. At present, prototypes of PMU have been tested online in Shandong province and the monitored data have been returned. Each module could work normally and stably. Measurement results could reflect the line current and voltage accurately.

INTRODUCTION

Wide area monitoring and control technology plays an important role in the safe operation of power grids. Developing a distributed wide area measuring system (WAMS) of running status is of great significance to the high-efficient economic operation of power distribution network.

Nowadays, WAMS which takes synchronization PMU as the core measuring equipment is becoming mature gradually. Existing PMU in main networks is not inferior to foreign products in performance indexes and functions. The application of PMU device in power distribution network is challenged by following problems. Compared to the main network, power distribution network lines cover a wider area, more branches, more complicated operating environment, greater load changes and construction lagging. Considering big quantity, wide coverage and great length of power distribution lines, a detector with low cost and easy live installation is needed. The FNET monitoring system developed by Yilu Liu could monitor and identify dynamic process of large power grids at high voltage side through the information measured at the low voltage side. However, it mainly focused on the frequency and phase parameters. Although existing fault location device in GPS meets the requirement of WAMS Light, it still has shortcomings in functions and couldn't measure voltage accurately. The μPMU developed by UCB defined functions and operation mode of PMU in power distribution network lines. PMU in power distribution network could realize phasor measurement, synchronization sampling and telecommunication, but data processing and analysis have to be accomplished in backstage due to the limited installation conditions. With the high accuracy of phasor measurement and the function of evaluating power quality, the μPMUs were mainly applied in the primary nodes, such as transformer substations and users. Nevertheless, it is still difficult for μPMU to serve on power distribution network lines.

In this paper, a new minimization and low-cost PMU device which is applicable for power distribution network was designed. It gained energy from the line by high-density inductive draw-out power module and had a lithium battery as the emergency power supply. It used PCB Rogowski coil as the current transducer to realize anti-interference and low cost of the transducer. Spatial capacitive voltage divider was used as the voltage transducer, which could ensure the voltage measurement accuracy when installed at the appropriate position. The PMU device, which was of small volume, light weight, low cost and applicability to install in wide area, provided a new solution for development of a novel micro PMU for distribution power lines.

DESIGN INDEXES AND OPERATING MODE OF PMU

Design Indexes

The designed PMU device was applicable for medium and lower voltage distribution networks, with the voltage level of 10kV and maximum running current of 800A. Therefore, the range of designed current measurement was 0～600A. According to the national standard on power frequency withstand voltage of 10kV mutual inductor, the range of designed voltage measurement was 0～30kV and the voltage and current transducers have to achieve a measurement accuracy of 0.5%. Since the current at the end of distribution power lines will be as low as only a few amperes during low load, the high-density inductive draw-

out power module of PMU device must be able to supply power for the whole system when the current is higher than 10A. Combining with practical situations of distribution power lines and rules related with line security, main technical parameters of the designed PMU were: voltage measurement range: 0~30kV; voltage measurement accuracy: 0.5%; current measurement range: 0~600A; current measurement accuracy: 0.5%; area of applicable wire: 35~240mm^2; power supply mode: inductive energy acquisition + lithium battery; installation mode: live installation; clock synchronization mode: GPS/ Beidou; sampling frequency: 1～4kHz; running current: 5～600A.

Operating mode

PMU devices were installed on distribution power lines. Each PMU was composed of three phases terminals. The phase A was a coordinator and the three phases terminals exchanged data through ZigBee networks. The coordinator communicated with backstage through GPRS/ CDMA/ 3G (general packet radio service/code division multiple access/the 3rd generation telecommunication). Each device achieved distributed synchronous sampling through GPS/ Beidou synchronization. The operating mode of PMU device is shown in Fig.1.

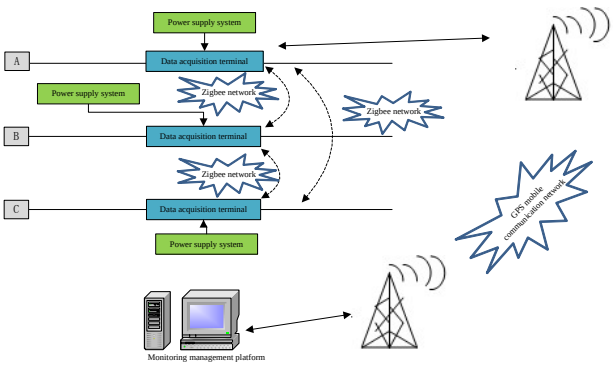

Fig.1 Operating mode of PMU device

The structure of PMU device is shown in Fig.2. Each PMU was mainly composed of four different modules: the

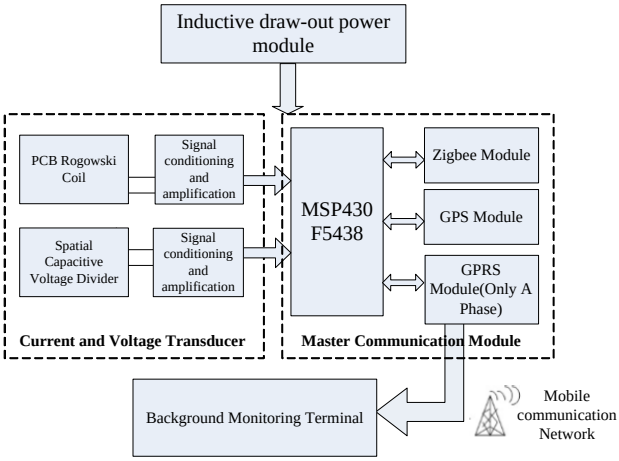

Fig.2 Module block diagram of PMU device

inductive draw-out power module, voltage transducer module, current transducer module and the master communication module. The inductive draw-out power module mainly gained energy from lines to supply power for the PMU device. The voltage and current transducers were responsible for collecting voltage and current signals from lines. The master communication module realized synchronous collection, storage and transmission of voltage and current signals.

FUNCTION DESIGN OF DEFFERENT MODULES

Inductive draw-out power module

Since PMU devices have to be hung on overhead lines for a long time, the weight of it should be lower than 1.5kg and consequently the weight of magnetic core should be lower than 500g. The running current of lines should be higher than 5A and the minimum power consumption of PMU should be about 300mW. To sum up, the draw-out magnetic core should be equipped with a power density of 300mW/ 5A/ 500g to ensure stable power supply to the PMU device. Microcrystal alloy, which has small density, high initial permeability and high power output even under small current was chosen as the magnetic core material. The power estimation formula of inductive draw-out power module was:

$$E_2 = 2\pi f N_2' \mu S \frac{I_\mu}{l} > V_{\min}$$
$$P = \frac{V_{\min}}{N_2'} \sqrt{I_1^2 - \left(\frac{V_{\min} \cdot l}{2\pi f N_2' \mu S} \right)^2} > P_{\min} \quad (1)$$

where μ is the magnetic conductivity of the magnetic core; S is the sectional area of the magnetic core; l is the length of a magnetic path which could be calculated from the size of magnetic core; I_1 is the primary current (10 A in this paper); N_2' is the number of coils; $V_{\min}$ is the minimum operating voltage of the post regulator chip (9V in this paper); $P_{\min}$ is the minimum power output (0.55W in this paper), considering output efficiency and power consumption of the magnetic core.

Based on (1), the main parameters of magnetic core were: 55mm inner diameter, 85mm outer diameter, 30mm height and 200 coils, which could meet the requirements of PMU devices.

Current transducer

Measurement Principle of current transducer

Rogowski coil was the measuring element of current transducer. The line charged with measuring current ran through the coil center vertically and changes of the measuring current were reflected by changes of the produced magnetic field. Rogowski coil induce voltage signal from changes of magnetic flux, through which the

measuring current signal could be restored.

Ignoring the distributed capacitance, the transfer function of Rogowski coil was:

$$H(s)=\frac{U(s)}{I_1(s)}=\frac{MR_S s}{L_C s+R_C+R_S} \tag{2}$$

Where M is the mutual inductance between the conductor and Rogowski coil; L_C is the equivalent self-inductance of Rogowski coil; R_C is the equivalent resistance of Rogowski coil; R_S is the external sampling resistance.

According to the frequency of measuring current, the Rogowski coil could be applied to different integral circuits (self-integral or external integral operating mode) to restore the output voltage signal into the measuring current signal.

In practical measurement, due to the interference of vertical magnetic field B_Z in the space, turns of the Rogowski coil winded densely on the whole coil former, forming an equivalent big turn in the winding direction. Since B_Z was perpendicular to the plane where the big turn lies in, the magnetic flux passing through the big turn would change with B_Z and produce an induced electromotive force in the Rogowski coil, which would bring in significant measurement error. A loop is often used to avoid interference of B_Z in practical application.

Besides, since PMU device requires live installation, the Rogowski coil must be light in weight and have an open structure. However, the traditional enclosed dense coil couldn't meet the requirement. PCB Rogowski coil, which has advantages of low cost, light weight and flexible routing pattern, could solve problems of interference from vertical magnetic field as well as the open structure. Therefore, it was used as the measuring element in the current transducer.

Differential winding design of bi-semi ring PCB Rogowski coil

Differential pair transmission is superior to single-line transmission for strong anti-interference ability, effective inhibition of electro-magnetic interference (EMI), accurate timing and positioning and so on. It has been widely used in PCB design. Traditionally adding single loop line will cause poor matching between the loop line radius and the clockwise line radius. Hence, differential pair winding was used. It used a twisted pair of signal lines, one clockwise and one counterclockwise, thus making the equivalent radius of clockwise and counterclockwise lines strictly equal. This could eliminate interference completely. Meanwhile, to meet the requirement of live installation, the PCB Rogowski coil adopted the bi-semi ring closed integral structure for the convenience of PMU close and open. The connection of turns was designed in multiple rows of via interconnect (Fig.3).

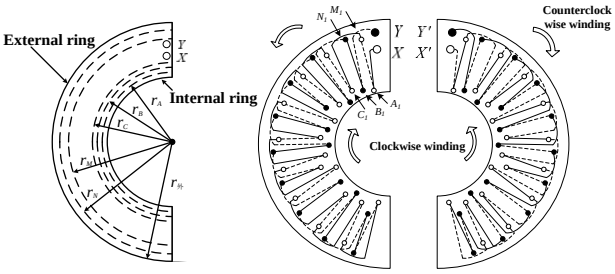

Fig.3 Design of turns connection

In each semi ring, the same wire was folded into two and winded onto two semi rings toward the same direction. These two differential pair twisted closely, but currents flew oppositely. The produced coupling magnetic fluxes were equal in value, but had opposite directions, thus enabling to offset the common-mode interference signal produced on the vertical direction. It could be proved that when two semi rings closed into an integral coil, the loop outlets of two semi rings were connected to a short circuit (X-X' in Fig.3), while the clockwise outlets were combined into the output end (Y-Y' in Fig.3). The designed PCB Rogowski coil is shown in Fig.4. Its main parameters were: inner diameter of skeleton: 24.0mm; outer diameter of skeleton: 39.0mm; number of coils: 232; thickness: 3.0mm.

Fig.4. PCB Rogowski coil physical map

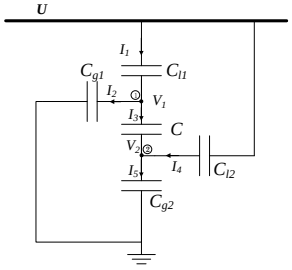

Fig.5 Equivalent measurement circuit of spatial capacitive divider

Voltage transducer

Measurement Principle of voltage transducer

The voltage transducer took the principle of the spatial capacitive divider to measure the phase voltage of line to ground, forming an equivalent circuit shown in Fig.5. In Fig.5, node 1 and 2 are two poles of the dividing capacitance; C is the value of dividing capacitance, which could be determined manually; C_{l1} and C_{l2} are capacitances from two plates to the high-voltage line; C_{g1} and C_{g2} are capacitances from two plates to the ground.

According to the relationship between current and voltage in Fig.4 as well as the Kirchhoff's Current Law, supposing $\Delta U = V_1 - V_2$, the rate of capacitor voltage and line voltage could be calculated:

$$C_0=\frac{C_{l1}C_{g2}-C_{g1}C_{l2}}{C_{l1}+C_{l2}+C_{g1}+C_{g1}} \tag{3}$$

where the range of C_{l1}, C_{l2}, C_{g1} and C_{g2} is between several pFs to dozens of pFs. C could be chosen as several magnitudes of range manually. Therefore,

$$\alpha \approx \frac{C_0}{C} \tag{4}$$

After C was determined and appropriate installation conditions were chosen to fix C_0, the voltage transducer could gain stable voltage division ratio. Hence, line voltage could be estimated from the measured capacitor voltage.

However, in practical engineering application, the influences of height and installation position on C_0 shall be considered. According to the result of calculation and experiment, the height should be higher than 4m when the capacitance variation was lower than 0.1%. Generally, the height of 10kV distribution power lines was over 10m and the capacitance variation could be neglected.

Design of the voltage transducer

In practical measurement, C was welded directly onto the PCB and high-voltage lines connected to the plates on C directly through the metal cable clamp on PMU device. The following conditioning circuit of voltage transducer shown in Fig.6 includes amplification, smoothing and protective circuit. The stray distributed capacitance of PMU device to ground was calculated about 0.8 pF by Comsol Multiphysics. Therefore, the designed capacitance value C was 40nF. In Fig.6, C_{40}, C_{41} and C_{42} were in parallel connection and their capacitance value were 4 magnitudes larger than the stray capacitance value. The collected voltage signal was filtered by the RC filter circuit and then connected to the instrumentation amplifier ADS8237ARMZ which could add 1.5V DC bias for the convenience of voltage signal collection by CPU. Amplification factor of the signal could be adjusted by adjusting R_{24} and R_{21}.

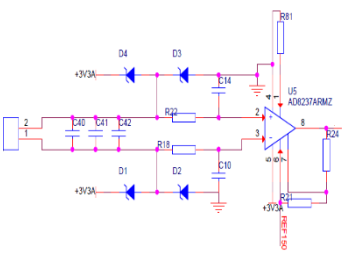

Fig.6. Circuit diagram of voltage sensor

Fig.7 Physics map of PMU

PMU TEST

The designed PMU device is shown in Fig.7. To test its performance and measurement accuracy, the designed PMU device was installed on a 10kV line for field test. Voltage and current linearity tests as well as overall power consumption test have been carried out.

Linearity test of the current transducer

The linearity of current transducer module was tested to verify the data collection accuracy of the current transducer. The wire of the high current generator passed through the Rogowski coil and the output signal of Rogowski coil connected to the oscilloscope after passing through the designed integrator and conditioning circuit. In this test, the high current generator increased the current from 50A to 800A gradually at a step length of 50A. The linearity test results of the Rogowski coil are displayed in Table 1.

Table 1 Coil linearity test results

Primary current /A	Output voltage /mV	Fitting current /A	Error /%
51.1	74.7	53.67	0.32
100.2	133.7	99.23	0.12
150	199.1	149.73	0.03
200.7	265.4	200.93	0.03
250.3	327.2	248.66	0.21
299.7	390.2	297.31	0.30
351.4	462.7	353.30	0.24
399.9	522.0	399.09	0.10
450.3	588.1	450.14	0.02
501.3	655.1	501.88	0.07
550.6	716.8	549.52	0.13
599.4	784.3	601.65	0.28
650.5	849.6	652.08	0.20
700.6	910.6	699.18	0.18
751.3	977.5	750.85	0.06
800	1041.3	800.12	0.01

After linear fitting, the maximum percentage error between the primary current and the fitting current was 0.32%, which proved the good linearity of the Rogowski coil used in the designed PMU device.

Linearity test of the voltage transducer

To test the measurement accuracy of the voltage transducer, an experimental environment was established and linearity of the voltage transducer was tested.

Table 2 Voltage linearity test results

Input voltage /kV	Capacitor voltage /V	Fitting voltage /kV	Error /%
5.1	0.107	5.15	0.14
10.1	0.215	10.07	-0.09
15.3	0.329	15.26	-0.12
20.2	0.44	20.31	0.33
25.4	0.549	25.28	-0.35
30.2	0.655	30.10	-0.27
34.9	0.763	35.02	0.35

The tower was simulated as a support. Lines were fixed parallel to the ground and connected to the high voltage generator. The designed PMU device was hung on the line

and the high voltage generator produced a sinusoidal voltage with an effective power frequency of 5～35kV with a step length of 5kV. The voltage transducer collected voltage difference between two ends of the capacitor (ΔU). The test results are shown in Table 2.

In Table 2, the maximum percentage error was 0.35%, indicating that the voltage transducer has satisfying linearity.

Overall power consumption test

To test the reliability of the inductive draw-out power module, the output currents of the three phases program-controlled power sources were set as 10A. The detector was set at typical operating modes, including dormancy, collection and transmission. Test results demonstrated that the designed PMU device could operate normally and stably under different conditions, indicating that the inductive draw-out power module could give adequate power supply when the output current was 10A.

Field test

The designed PMU device had been tested in Shandong province, China. It collected current and voltage data every 6 min. Each sampling had 10 cycles. Collected data were returned through GPRS. Fig.8. is the voltage variation at the testing node from February 14th, 2016 to February 20th, 2016. The three-phase current variation is shown in Fig.9. The x-coordinate ranged from 00:00 of February 14th to 24:00 of February 20th (00:00 of February 21st).

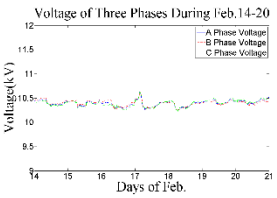

Fig.8. Historical data of voltage

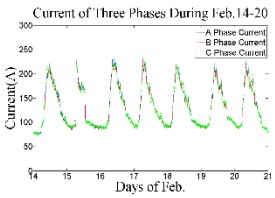

Fig.9. Historical data of current

It can be seen from Fig.9 that the current was about 90A at low load and increased to over 200A at a fixed time every day. The voltage decreased slightly upon the sudden rise of current. The current variation on February 15th was different from those of rest testing period, which may be caused by equipment debugging after China's traditional Spring Festival. According to field test results, the designed PMU device can collect line voltage and current waveforms accurately and the voltage and current variations within a certain time conform to actual load fluctuations.

CONCLUSION

The designed PMU device which is applicable for distribution power lines uses high-density inductive draw-out power module and lithium battery for power supply. It uses a bi-semi ring differential winding PCB Rogowski coil as the current transducer to measure line current, which can eliminate interference from vertical magnetic field accurately and achieve a measurement accuracy of 0.5%. It uses the spatial capacitive voltage divider as the voltage transducer to measure line voltage, which can meet requirements of minimization, open structure and inter-phase insulation and achieve a measurement accuracy of 0.5%. The designed PMU device is of low cost, minimization and live installation. It provides a new solution to development of new PMU for distribution power lines and has positive significance to related development and exploration.

Acknowledgments

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