International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 7, No. 1, March 2016, pp. 152~158
ISSN: 2088-8694

Novel Active Current Transducers for Diesel Power Stations

Denis B. Solovev, Alena E. Merkusheva
Far Eastern Federal University (FEFU), Engineering School, Department of Innovatics, Russia

Article Info

Article history:

Received Oct 14, 2015
Revised Dec 27, 2015
Accepted Jan 13, 2016

Keyword:

Active current transducer
Current transformers
Autonomous power supply
Mining companies
Diesel power station
Differentiating inductive current transducers
Rogowski coil

ABSTRACT

Autonomous diesel power plants found the active application at the organization of autonomous power supply of the mining enterprises. In article the problem of increase of efficiency of use of control units is considered by the active power of synchronous generators of diesel power plants. As a solution the new innovative offer in the form of the developed device of the measuring converter of active current which is one of the main components of game-trolno-measuring equipment of diesel power plants is offered. The developed scheme is simpler, in comparison with the similar converters of active current executed on the basis of current transformers. In the developed scheme of the measuring converter it is offered to use the differentiating induction converters of current as primary measuring converters. It allows reducing many times number of the elements entering the standard scheme, and also mass-dimensional characteristics of the device.

Corresponding Author:

Denis B. Solovev,
Engineering school, department of innovatics,
Far Eastern Federal University (FEFU),
City of Vladivostok, Russky Island, Russian Federation.
Email: solovev.db@dvfu.ru

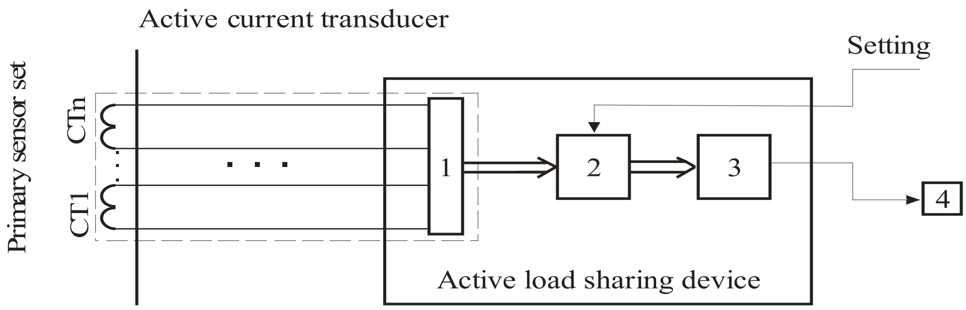
1. INTRODUCTION

Presently it is typical of mining companies operating in remote areas to feed their main loads from centralized power supplies located at large distances. Specific geological conditions at mining sites and continuous movement of the working front towards remote areas result in considerable growth of expenses for building and servicing of power transmission lines. For example the erection cost of one kilometer of 6 kV overhead lines may be as high as $50,000…150,000 (prices of 2014). Thus the share of costs associated with power supply provision for the majority of mining companies may reach 40% to 60% of the whole expenses for production startup. Therefore many mining companies have chosen fully autonomous power supply systems based on diesel power stations (DPS). This solution is the most efficient in terms of some parameters [1, 2]. DPS can be used as the primary power supply or as backup supply for the first and second category loads.

2. MATERIAL AND METHODS

As is stressed by many authors [1-6], autonomous power supply facilities of mining companies is always a customized solution adapted for site-specific features of mining and processing of mineral resources. Operation of DPS installed in harsh climatic conditions of remote northern areas of Russian Federation, Canada or the USA requires specific approach both to design and to selection of principal and auxiliary equipment since power generation expenses have considerable impact on the total production cost.

Analysis of available literature [7] and integration of information obtained during discussions at international conferences, workshops and "round tables" suggest that standards and regulations concerning design works, installation and operation of DPS under conditions of mining industry are rather obsolete and specialists designing equipment for mining companies usually do not study such documentation. Therefore mining companies, as a rule, purchase DPS of regular design with standard set of measuring instrumentation [6]. To minimize specific fuel consumption such DPS have devices for active load (i.e. active power of synchronous generator) sharing. Typical functional diagram of such device is shown in Figure 1.



1 – secondary circuit deriving and amplifying signal proportional to active power;
2 – comparison circuit (reference signal is formed by device determining sum of active powers of all synchronous generators);
3 – signal amplifier;
4 – automatic controller of synchronous generator speed

Figure 1. Typical functional diagram of synchronous generator active power controller

The most widespread design of active power controller has an external set of primary current sensors incorporated by the active current transducer (encircled with dotted line in Figure 1) realized as a standalone unit. Since the automatic speed controller of synchronous generator is actuated by electric motor, active power controllers represent pulse-type regulators. The accuracy and response time of such controllers depend considerably on the design of the active current transducer. Therefore improvement of the transducers results in better operation of the whole system.

Practical experience in use of conventional active power controllers has shown a number of their shortcomings [3]. The first one is the use of current transformers as primary current transducers. Such transducers have large dimensions and weight rising with the value of current to be measured and the voltage rating. For instance the weight of 10 kV current transformer (CT) exceeds 10 kg while of 220 kV – 100 kg although the capacity of its secondary winding is as small as 40 VA. Besides most active power control circuits employ a matching resistor connected to the CT secondary winding used to convert current to voltage. The second drawback of the conventional structure is the use of isolation transformers and use of matching transformer for the current transformer. The need for the three abovementioned transformers results in increase in the dimensions and weight of the whole device. The third shortcoming is the use of a voltage transformer of nonstandard design having two toroid cores and two secondary windings encircling both the cores. Such design complicates manufacturing of the transformer and makes it more expensive.

3. THEORY/CALCULATION

Research aimed at improvement of performance indicators of the device for measurement of three-phase active current of three-phase voltage source has been done in Far Eastern Federal University (FEFU). The technical result to be obtained in the course of the research was the following:

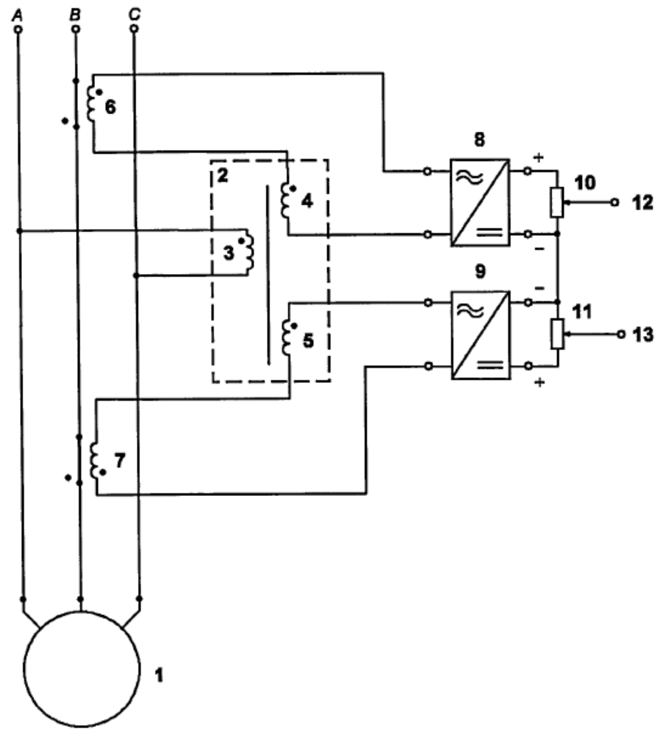
- reduction of materials consumption by replacement of the two bulky and expensive current transformers (used as primary current transducers) with two Rogowski coils. A current sensor of this type has no magnetic core and represents a toroid coil encircling the conductor with current to be measured. The coil is installed on the HV circuit breaker bushing in the place adjacent to the entry connecting insert. The mass of the winding wire for a coil does not exceed 200 g while the mass of a current transformer rated for the same voltage is about 200 kg.
- simplification of design and consecutive reduction of labor hours needed for production of the device.

In the device developed in FEFU for measurement of three-phase voltage source active current two Rogowski coils are used as primary a.c. transducers. These coils are inductively coupled with the same conductor connected to the second terminal of the three-phase voltage source through which flows the load current. The device also contains a single-phase voltage transformer that allows replacing heavy current transformers with lightweight Rogowski coils. The mutual inductance e.m.f. induced in the coil by the sinusoidal current to be measured leads this current by π/2. Consequently the vector of the e.m.f. induced by active component of current in the conductor connecting the synchronous generator to the load is collinear to the vector of line-to-line voltage of this source between the first and the second terminals thereof.

Therefore the device developed provides measurement of active current of three-phase voltage source with balanced load. The output signal of the device is proportional to the active current of the synchronous generator.

The proposed solution is illustrated by the drawings. Functional diagram of a single-phase device for measuring active current is shown in Figure 2. The operating principle of the device is explained by phasor diagrams shown in Figure 3.

If steady-state voltage and load current waveforms of synchronous generator are sinusoidal the vectors form two balanced systems: line-to-line voltages and load currents. The e.m.f. vectors if Rogowski coils have the same magnitudes but opposite directions as shown in Figure 3a and Figure 3b:



1 – synchronous generator; 2 – voltage transformer; 3 – primary winding of voltage transformer; 4, 5 – secondary windings of differentiating inductive current transducers; 6, 7 – differentiating inductive current transducers; 8, 9 – single-phase bridge rectifiers; 10, 11 – adjustable resistors; 12, 13 – output terminals of active current measurement device

Figure 2. Functional diagram of single-phase device for measurement of active current

a) at input of rectifier 8; b) at input of rectifier 9

Figure 3. Phasor diagrams of currents and voltages

$$\underline{E}_6 = jx_m \underline{I}_B \exp(-j\varphi),\ \underline{E}_7 = -jx_m \underline{I}_B \exp(-j\varphi),\ x_m = \omega M \quad (1)$$

where j is imaginary unit, φ – angle by which the generator phase voltage leads the load current, x_m - mutual reactance; ω – angular frequency of the generator voltage; M – mutual inductance between the coil of the differentiating current transducers and the conductor.

The moduli of vectors of input voltages can be derived in accordance with Figure 3a and Figure 3b using the cosine rule:

$$U_8 = \sqrt{(k_u U_{AC})^2 + 2k_u U_{AC} x_m I_B \cos\varphi + (x_m I_B)^2} \quad (2)$$

$$U_9 = \sqrt{(k_u U_{AC})^2 - 2k_u U_{AC} x_m I_B \cos\varphi + (x_m I_B)^2} \quad (3)$$

where k_u is the transformation ratio of the voltage transformer.

In the course of design the following condition should be met: e.m.f. of the coils in normal operating modes of the synchronous generator must not exceed 10% of the voltages across the secondary windings of voltage transformer Rogowski coils. In this case we can neglect the addend $(x_m I_B)^2$ in expressions (2) and (3). Also, in expansion of the resulting expressions into Maclaurin series all terms except the first two ones can be neglected. In this case the input voltages of the bridge rectifiers can be approximated with sufficiently precise expressions:

$$U_8 \approx k_u U_{AC} + x_m I_B \cos\varphi,\ U_9 \approx k_u U_{AC} - x_m I_B \cos\varphi \quad (4)$$

The mean voltages across the output terminals of the rectifiers can be obtained by multiplying input voltages U_8 and U_9 by the rectification factor equal to 0,9 for single-phase bridge rectifiers. The voltage between the output terminals of these rectifiers equal to the difference between the output voltages thereof is proportional the active component of the synchronous generator load current (I_a=$I_B\cos\varphi$):

$$U_{out,\max} = AI_a,\ A = 1{,}8x_m \quad (5)$$

The output voltage of the device derived from its output terminals connected to the sliders of the adjustable resistors is lower than $U_{\text{out,max}}$ and depends on the position of the said sliders. Adjustment of the resistors allows compensation of influence of factors not considered in the above formulas, such as non-ideal properties of the voltage transformer and differentiating inductive current transducers as well as voltage drop on the rectifier diodes. The sliders are set so that the following conditions are met:

- zero voltage on the device output when the active component of load current is zero;
- set value of the output voltage when the active component of load current is equal to its rated value.

Thus the output voltage of the proposed device at balanced load is virtually proportional only to active current of the synchronous generator.

The operation of the device with two Rogowski coils for measurement of active current of three-phase voltage source was simulated using Micro-Cap v.10 schematic simulation software. This software provides simulation of analog and digital circuits and features simple and user-friendly interface. At the same time its capabilities are comparable with professional schematic design tools such as ORCAD and PCAD [8-10]. Basing on the proposed schematic of the device (Figure 2) a simplified simulation diagram shown in Figure 4 was developed.

Rogowski coils can be simulated in Micro-Cap software as linear transformers [8]. So, the Rogowski coils in the diagram (Figure 4) are represented by elements K1 and K2. Transformers K1 and K2 operate under conditions close to open-circuit mode; therefore the output voltage of the transformers will lead the input one by 90 electrical degrees. Due to presence of air gap the core of the Rogowski coil does not saturate and its magnetization characteristic *B = f(H)* remains linear. For simulation in Micro-Cap a transformer must be set with three parameters: primary winding inductance *L1*, primary winding inductance *L2*, and coupling coefficient *K* varying between 0 and 1 and calculated with the following formula:

$$K = \frac{M}{\sqrt{L_1 L_2}} \tag{6}$$

where M is mutual inductance between the Rogowski coil and the conductor (in H).

Resistors R5 and R6 represent the resistances of the Rogowski coil secondary windings. Resistors R7 and R8 represent the resistances while inductors L1 and L2 – the reactances of transformer TV1 secondary windings. Resistors R1 and R3 represent the load of the active current transducer.

As is recommended by Micro-Cap documentation, resistors R2 and R4 are introduced between primary and secondary windings of transformers K1 and K2 to avoid convergence problems during transient analysis of circuits containing inductively-coupled elements. The shown resistance value, 1/GMIN, is equal to 10^{12} Ohm (GMIN is the minimum conductance that is by default equal to 1 pS) [10].

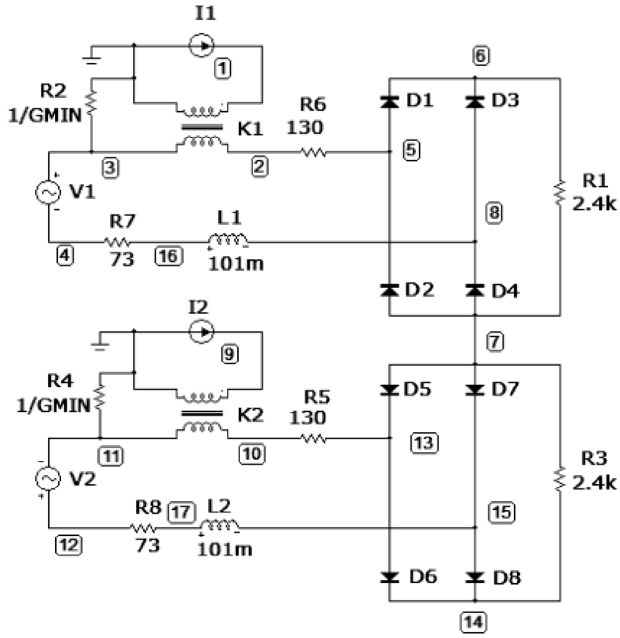
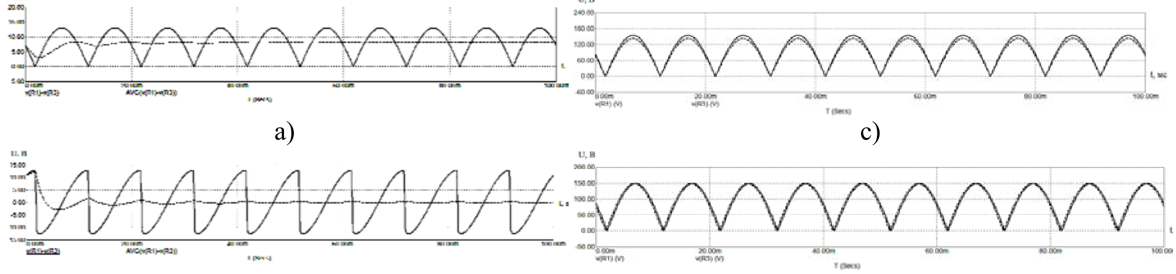


Figure 4. Simulation diagram of device for measurement of active current

During transient analysis with Micro-Cap the steady state mode was selected. Simulation of single-phase active current transducer at balanced load of the synchronous generator yielded transient waveforms shown in Figure 5.



a, c – instantaneous value (solid line) and mean value (dotted line) of voltage on output of transducer at balanced resistive and inductive load (I = *50* A); b, d – graphs of instantaneous voltages on resistors R1 (solid line) and R3 (dotted line) at balanced resistive and inductive load (I = *50* A)

Figure 5. Simulation of active current transducer with Rogowski coils in Micro-Cap 10

As it can be seen from the graphs, the mean voltage on the output of the active current transducer (between nodes 6 and 13 in Figure 5) is proportional to the active load of the synchronous generator (dotted line in Figure 5, a) while in case of reactive load it goes to zero (dotted line in Figure 5, c)

In the model shown in Figure 4 there is a certain voltage drop across elements R5, R6, R7, R8, L1, and L2 not considered in the theory. Therefore the mean value of *Uout* in Figure 5, a is below the calculated value (derived using formula 5). The voltage drop, $\Delta Uout$, depends on the load of the active current transducer. If the load resistances of the transducer (resistors R1 and R3 in Figure 4) increase the current in the active current transducer circuit decreases, so decreases the voltage drop $\Delta Uout$ across the internal impedances of windings of the Rogowski coils and voltage transformer.

4. DISCUSSION

The simulation model developed considers the influence of the impedances of windings of the Rogowski coils and voltage transformer. The simulation results confirm the theoretical statements regarding operation of the active current transducer proposed in the beginning of the article. The influence of voltage drops in the windings of Rogowski coil and voltage transformer as well as that of the Rogowski coil angular error upon the output voltage of the active current transducer can be reduced by making the ratio of the transducer load impedance to the total impedance of the circuit (considering impedances of Rogowski coils' windings, voltage transformer windings, and transducer load) close to unity.

5. CONCLUSIONS

Use of the proposed active current transducer for DPS powering autonomous networks of mining companies will allow improvement of power quality and reduction of the mass and overall dimensions of DPS measurement equipment.

REFERENCES

[1] O.V. Marchenko, *et al.,* "Economic Efficiency Assessment of Autonomous Wind/Diesel/Hydrogen Systems in Russia", *Journal of Renewable Energy*, Vol. 2013, p. 10, 2013. [Online]. Available: http://dx.doi.org/10.1155/2013/101972.

[2] A. Banerji, *et al.,* "Review of Static Compensation of Autonomous Systems", *International Journal of Power Electronics and Drive Systems (IJPEDS)*, Vol. 2, pp. 51-66, 2012. [Online]. Available: http://www.iaesjournal.com/online/index.php/IJPEDS/article/view/174/157.

[3] D.B. Solovev, *et al.,* "Instrument current transducers with Rogowski coils in protective relaying applications", *International Journal of Electrical Power and Energy Systems*, Vol. 73, pp. 107-113, 2015. [Online]. Available: http://dx.doi.org/ 10.1016/j.ijepes.2015.04.011.

[4] D.B. Solovev, "Determination of rational exciting currents in synchronous drives of quarry mechanical shovels", *Gornyi Zhurnal*, Issue 3, pp. 70-72, 2005.

[5] G.B. Sudeshna, et al., "Challenges to Power–Mining Integration", The Power of the Mine: A Transformative Opportunity for Sub-Saharan Africa Published, pp. 81-98, December 2014. [Online]. Available: http://dx.doi.org/10.1596/978-1-4648-0292-8_ch5.

[6] R.J. Wills, et al., "New local diesel power stations: An economic assessment", *Utilities Policy*, Vol. 2, Issue 2, pp. 108-119, April 1992. [Online]. Available: http://dx.doi.org/10.1016/0957-1787(92)90030-M.

[7] D. Banda, et al., "Feasibility assessment of the installation of a photovoltaic system as a battery charging center in a mexican mining company", Power, Electronics and Computing (ROPEC), 2014 IEEE International Autumn Meeting. IEEE, pp. 1-5, on 5-7 Nov. 2014. [Online]. Available: http://dx.doi.org/ 10.1109/ROPEC.2014.7036352.

[8] D.B. Solovev, et al., "Analysys of modeling of current differential protection", *International Journal of Power Electronics and Drive Systems*, Vol. 6, Issue 3, pp. 423-428, 2015. [Online]. Available from: http://iaesjournal.com/online/index.php/IJPEDS/article/view/7701.

[9] OrCAD cadence PCB solutions. [online] Available: http://www.orcad.com/.

[10] Spectrum-soft. [online] Available: http://www.spectrum-soft.com/index.shtm.

BIOGRAPHIES OF AUTHORS

Denis B. Solovev is a graduate of Far Eastern State Technical University (Diploma with honours), Vladivostok, Russia. In 2011 he received a PhD in electric engineering. From 2011 to 2015 he took internship in the leading Russian and international universities and research laboratories: MATI - Russian State Technological University named after K.E. Tsiolkovsky, Moscow; University of Maastricht, Maastricht (Netherlands); Laboratory of the Ministry of Energy of the United States of America, Seattle and Richland, Washington. He is currently the head of the educational program “Innovatica” (cluster of energy and electronics) at the Engineering School of the Far Eastern Federal University, Vladivostok, Russia.

Alena E. Merkusheva student of chair “Innovatica” (cluster of energy and electronics) at the Engineering School of the Far Eastern Federal University, Vladivostok, Russia.