Construction of Resource-Saving Differential Protections for Converter Units with Transformers with 2N Secondary Windings and 2N Rectifiers

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***Abstract*—Relevance of the development of resource-saving differential protections without current transformers for converter units with transformers with 2n secondary windings (n is the number of star- and delta-connected secondary windings of the transformers) and 2n rectifiers is justified. Two new techniques are suggested for the construction of such protections. The first technique consists in measuring EMF at the leads of inductance coils mounted near the busbars of all phases from the low voltage side of the transformer of a converter unit, equalizing and subtracting EMFs induced by currents in these busbars obtained from the coils for the same phases, and the comparison between the resulted differences with the reference value. In the second technique, in addition to inductance coils mounted like as in the first technique, a reed with a control winding is suggested to mounted near the DC conductor busbar. The difference between the magnetic fluxes generated by the current in this busbar and by the current in the reed winding, proportional to the total rectified EMFs received from the coils mounted near the busbars of the same phases, is compared with the magnetic flux sufficient to trigger a reed which indicates a damage when its contacts are closed and sends a signal to disconnect the protected unit from the network. Models of the devices which implement the protection techniques suggested are described, and their behavior in different converter units operating modes is analyzed.**

Keywords—converter unit, transformer, differential protection, reed, inductance coil, busbar, winding

I. Introduction

Overcurrent protections without time delay [1, 2] are commonly used as short-circuit protections in converter units. They are simple, reliable, and cheap, but insufficiently sensitive sometimes because of a need in offset from load currents, which can result in serious damage of converter units (up to its complete failure). Differential protections developed in Russia, USA, China, and Sweden [3–13] can be more sensitive. However, all these protections use metal-intensive current transformers [14], which have other well-known disadvantages [15, 16]. Therefore, the problem of constructing relay protection devices without current transformers has been considered as one of fundamentally unsolved problems of global power industry at the International Conferences on Large Energy Systems (CIGRE) since 2000 [17, 18]. Use of magnetic-sensitive elements is one of the directions of solving this problem. Thus, principles have been developed and several current, differential, and remote protection devices have been deigned with the use of these elements at S. Toraighyrov Pavlodar State University since 1980s [19–25], including an attempt to design a reed switch differential protection device without current transformers for converter units [26]. However, the patent study has shown that no differential protection has been designed so far for converter units with transformers with 2n secondary windings (n is the number of star- and delta-connected secondary windings of a transformer) and 2n rectifiers. In this work, we suggest protection techniques for these units and the devices which implement these techniques with the help of inductive coils and reed.

II. Inductance Coil Protection Technique

A. Description of the technique

The technique [27] consists in the following: 6n inductance coils are mounted in the vicinity of 6n busbars, which connect the low-voltage leads of 2n secondary windings of the converter unit transformer to 2n rectifiers, and EMFs are measured at their terminals. The EMS values serve for estimation of the currents in these busbars. The EMFs obtained from inductance coils, mounted near the busbars which connect the leads of n star-connected secondary windings of the transformer with n rectifiers, are shifted in phase. From the EMFs obtained after the phase shift, the EMFs received from the inductance coils mounted near the busbars which connect the leads of n delta-connected secondary windings of the transformer with n rectifiers are subtracted. These differences are compared with a reference value, and if at least one of them exceeds this value, a converter-unit trip signal is sent.

B. Layout and Operation of the Device Implementing the above Protection Technique

Let us consider implementation of this technique for converter units with, for example, transformer 1 (Fig. 1) of $2{,}5\ \mathrm{MV \cdot A}$ in capacity (rated voltage of the primary winding is 10 kV) with two secondary windings, two rectifiers and rectified voltage of 450 V. The windings are delta-connected on the high-voltage side of the transformer, and one winding is star-connected and another one is delta-connected on its low-

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voltage side. The secondary windings of transformer 1 are connected to Larionov-bridge-connected rectifiers 2 and 3. The rectifiers include six diodes 4–9 and 10–15, respectively, and are connected in series. The outputs of rectifiers 2 and 3 are connected to load 16 with a capacity of 1.8 MW. Under this load, the currents in the busbars connecting the winding leads of the transformer on the low voltage side to the rectifiers are as follows (obtained from the model described below): on the side of star-connected secondary winding $I_{2YA} = 4000e^{-j44^0}$ A, $I_{2YB} = 4000e^{j196^0}$ A, $I_{2YC} = 4000e^{j76^0}$ A; on the side of delta-connected secondary winding, $I_{2\Delta A} = 4000e^{-j14^0}$ A, $I_{2\Delta B} = 4000e^{j226^0}$ A, $I_{2\Delta C} = 4000e^{j106^0}$ A. Inductance coils 17–22 with the number of turns $w = 8000$, the cross-sectional area $s = 0.0007\ \text{m}^2$, and $l = 0.03$ m can be used to measure and convert the induction of magnetic field, created by the currents in the busbars connecting the secondary transformer windings with rectifiers, to EMF. The inductance coils are mounted under the busbars which connect the low-voltage leads of windings of transformer 1 with rectifiers 2 and 3 at a safe distance, e.g., $h = 0.12$ m [28]. Under the load, when the above specified currents flow in these busbars, EMF is induced at the leads of inductance coil 17:

$$\underline{E}_1 = \mu_0 fws \frac{I_{2YA}}{h} e^{-j90^0} = 11.72e^{-j134^0} \text{ V}, \qquad (1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant.

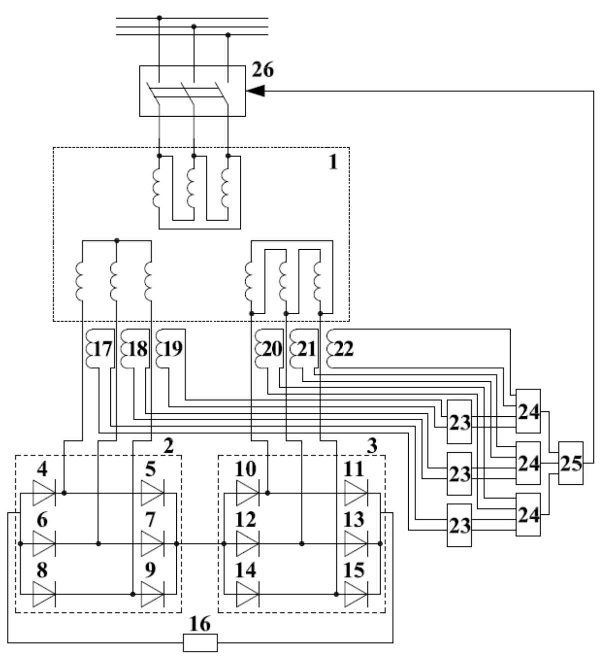

Fig. 1. Functional Diagram of the Protection Device

By analogy with Eq. (1), EMFs $\underline{E}_2 = 11.72e^{j106^0}$ V, $\underline{E}_3 = 11.72e^{-j14^0}$ V, $\underline{E}_4 = 11.72e^{-j104^0}$ V, $\underline{E}_5 = 11.72e^{j136^0}$ V, and $\underline{E}_6 = 11.72e^{j16^0}$ V at the leads of inductance coils 18–22, respectively.

EMFs $\underline{E}_1 \div \underline{E}_3$ are fed to the inputs of phase-shifting circuits 23, which shift them by 30^0. As a result, EMFs $\underline{E}_{11} = 11.72e^{-j104^0}$ V, $\underline{E}_{21} = 11.72e^{j136^0}$ V, and $\underline{E}_{31} = 11.72e^{j16^0}$ V arise at the outputs of phase-shifting circuits 23. EMFs $\underline{E}_{11}$, $\underline{E}_{21}$, $\underline{E}_{31}$, $\underline{E}_4$, $\underline{E}_5$, $\underline{E}_6$ are fed to the inputs of circuits 24 for the comparison between the EMF differences with a reference value. Here, the absolute values of EMF differences $|\underline{E}_{11} - \underline{E}_4|$, $|\underline{E}_{21} - \underline{E}_5|$, and $|\underline{E}_{31} - \underline{E}_6|$ are calculated and compared with the reference EMF $E_{ref} = 2$ V. This value is found as a result of offset from the EMF unbalance, which depends on the error of mounting of inductance coils 17–22 and the error of the device under study. Since the differences specified do not exceed the reference EMF $E_{ref} = 2$ V, under the load, the protection is not triggered.

In the case of a two-phase short-circuit, for example, from the - low-voltage side of transformer 1, the currents $I_{2YA} = 3700e^{-j49^0}$ A, $I_{2YB} = 3700e^{j157^0}$ A, $I_{2YC} = 3340e^{j62^0}$ A, $I_{2\Delta A} = 3700e^{-j28^0}$ A, $I_{2\Delta B} = 3340e^{j220^0}$ A, and $I_{2\Delta C} = 3700e^{j107^0}$ A between phases B and C at the leads of the star-connected transformer winding. According to Eq. (1), $\underline{E}_1 = 10.84e^{-j139^0}$ V, $\underline{E}_2 = 10.84e^{j67^0}$ V, $\underline{E}_3 = 9.79e^{-j28^0}$ V, $\underline{E}_4 = 10.84e^{-j62^0}$ V, $\underline{E}_5 = 9.79e^{j130^0}$ V, and $\underline{E}_6 = 10.84e^{j17^0}$ V at the leads of inductance coils 17–22.

Then, $\underline{E}_{11} = 10.84e^{-j109^0}$ V, $\underline{E}_{21} = 10.84e^{j97^0}$ V, and $\underline{E}_{31} = 9.79e^{j2^0}$ V at the outputs of phase-shifting circuits 23, while the absolute values of EMF differences

$$|\underline{E}_{11} - \underline{E}_4| = \left|10.84e^{-j109^0} - 10.84e^{-j62^0}\right| = 8.64 \text{ V},$$

$$\left|\underline{E}_{21}-\underline{E}_{5}\right| = \left|10.84e^{j97^0} - 9.79e^{j130^0}\right| = 5.95 \text{ V},$$

$$\left|\underline{E}_{31}-\underline{E}_{6}\right| = \left|9.79e^{j2^0} - 10.84e^{-j17^0}\right| = 2.89 \text{ V}.$$

Since these differences exceed the reference EMF $E_{ref} = 2$ V, the signals from the outputs of circuits 24 are fed to the inputs of control element 25. The control element actuates and sends a trip signal to switch 26. It should be noted that, if necessary (typically at low load currents), the above protection device can be supplemented with amplifiers, inputs of which are connected to the outputs of phase-shifting circuits 23 and of inductance coils 17–22, and outputs of which are connected to the inputs of circuit 24.

Values of currents flowing in case of two-phase short circuit in the busbars connecting the low-voltage winding terminals of transformer 1 with rectifiers 2 and 3 were obtained (as well as under the load) with the converter unit model implemented in the MatLab Simulink dynamic simulation environment with the SimPowerSystems software package. Adequacy of implementation and mathematical description of all package elements were verified by the Canadian electricity producer Hydro-Quebec [29]. Transformer 1 was simulated with the use of the Three-Phase Transformer (Three Windings) element, for which the followings parameters are set: rated power (in $\text{MV}\cdot\text{A}$), layout of connection of primary and secondary windings, their active linear voltages (in V), active resistance and inductance of windings (in p.u.), and active resistance of magnetizing branch (in p.u.). Rectifiers 2 and 3 are implemented by means of Universal Bridge elements. Series RLC Branch elements are used as load 16 and a smoothing filter (not shown in Fig. 1). The electrical network transformer 1 was connected was simulated with the Three-Phase Source unit, for which active linear voltage (in V), frequency (in Hz), network resistance (in Ohm), and inductance (in H) are specified. Three-Phase Breaker element is used to simulate switch 26.

The above considered protection device was also simulated. Inductance coils 17–22 were simulated with the Three-Phase VI Measurement, From, Goto, Demux, and Gain elements. Transport Delay elements were used to simulate phase shifting circuits 23. Diagrams 24 for comparing EMF differences with the reference value were simulated with the use of the Add, Abs, and Compare To Constant elements; and control element 25, with the use of the Logical Operator element.

Figures 2 and 3 show oscillograms of differences $\left|\underline{E}_{11}-\underline{E}_{4}\right|$, $\left|\underline{E}_{21}-\underline{E}_{5}\right|$, $\left|\underline{E}_{31}-\underline{E}_{6}\right|$ derived from simulation of diode 4breakdown and open fault. The EMF differences exceed the reference EMF $E_{ref} = 2$ V in these emergency modes. Hence, the protection is triggered and control element 25 generates a trip command for switch 26.

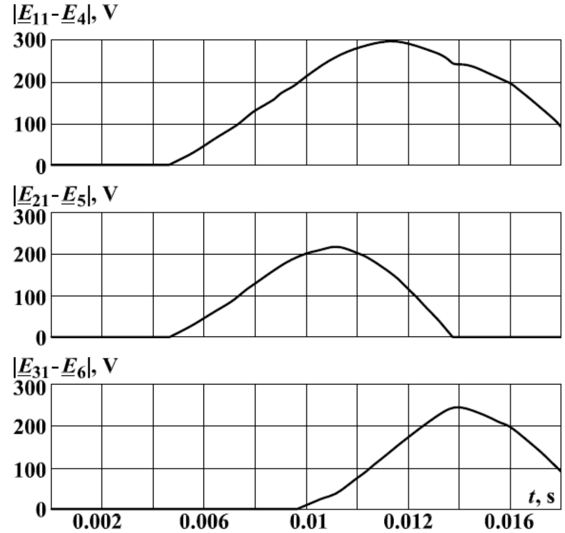

Fig. 2. EMF differences in diode 4 breakdown

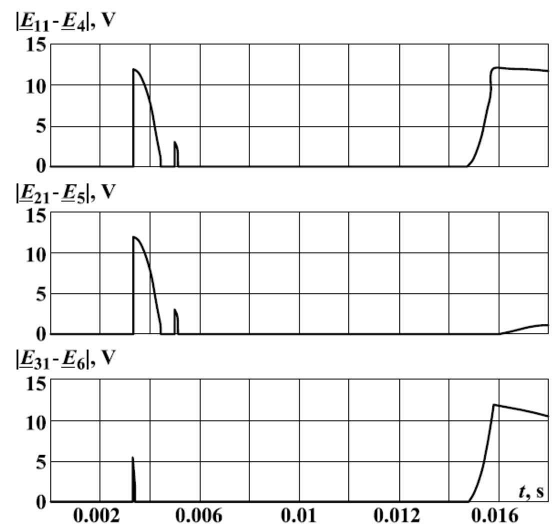

Fig. 3. EMF differences in diode 4 open fault

III. Reed and Inductance Coils Protection Technique

A. Description of the Techique

The technique consists in the following; 6n inductance coils are mounted near 6n busbars, which connect the low-voltage leads of 2n secondary windings of the converter unit transformer to 2n rectifiers, and a reed with a control winding is mounted near the DC conductor busbar in the load circuit of the converter unit. EMFs are measured at inductance coil leads (which allow judgment on the currents in 6n busbars), and EMFs from inductance coils mounted near the like busbars of like phases are summed up. They are rectified and fed into the control winding of the reed. The difference between the magnetic fluxes produced by the control current in the reed winding (Fig. 4) and the current in the DC conductor busbar of the converter unit is compared with a reference magnetic flux required to trigger the reed. If this difference becomes equal to or higher than the reference value, the reed contact closure indicates a damage and a trip signal is sent to the converter unit.

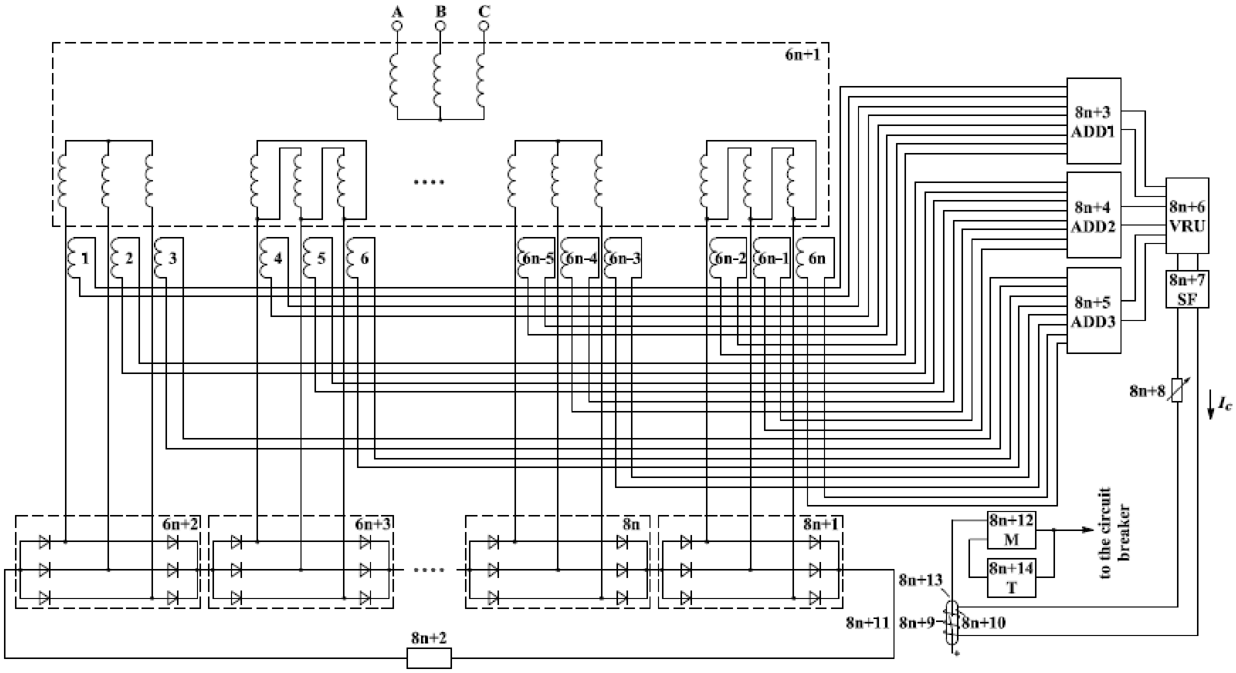

Fig. 4. Functional circuit of the protection device

B. Circuit and Operation of the Protection Device Based on the above Technique

The device [30] implements the protection technique suggested; it includes (Fig. 4): inductance coils 1, 2, 3, 4, 5, 6, ..., 6n-5, 6n-4, 6n-3, 6n-2, 6n-1, and 6n fixed near the busbars connecting the low-voltage terminals of phases A, B and C of 2n secondary windings of transformer 6n+1 with three-phase bridge rectifiers 6n+2, 6n+3, ..., 8n, and 8n+1, which feed load 8n+2. The leads of inductance coils 1, 4, ..., 6n-5, and 6n-2, fixed near the busbars connected to the terminals of phases A of 2n secondary windings of transformer 6n+1, are connected to first adder 8n+3 (ADD1); the leads of inductance coils 2, 5, ..., 6n-4, and 6n-1, fixed near the busbars connected to the terminals of phases B of 2n secondary windings of transformer 6n+1, are connected to second adder 8n+4 (ADD2); and the leads of inductance coils 3, 6, ..., 6n-3, and 6n, fixed near the busbars connected to the terminals of phases C of 2n secondary windings of transformer 6n+1, to third adder 8n+5 (ADD3). The outputs of adders ADD1, ADD2, and ADD3 are connected to the inputs of AC voltage rectification unit 8n+6. Its outputs are connected, via smoothing filter 8n+7 (SF) and control resistor 8n+8, are connected to the leads of winding 8n+9 of reed 8n+10, which is fixed in the magnetic field of DC conductor 8n+11 in load circuit 8n+2 of the converter unit. Contact 8n+13 of reed 8n+10 is connected to the write input of MEMORY element 8n+12 (M), while output of TIME element 8n+14 (T) is connected to the reset input. The output of MEMORY 8n+12 element is connected to the input of TIME 8n+14 element and to the circuit breaker of the converter unit switch (not shown in Fig. 4).

A reed relay of RGK-49 type can be used as reed 8n+10 with winding 8n+9, and a resistor of PP 1,2-3 type can be used as control resistor 8n+8. Tangda coils can be used as inductance coils 1-6, 6n-5, 6n-4, 6n-3, 6n-2, 6n-1, and 6n; a SQL rectifier can serve AC voltage rectification unit 8n+6 (VRU). A standard LC filter can be used as smoothing filter 8n+7 (SF). Adders 8n+3 (ADD1), 8n+4 (ADD2), and 8n+5 (ADD3) adders, MEMORY 8n+12 (M) and TIME 8n+14 (T) elements can be implemented at an Atmel AT89S53 series 51 microcontroller.

The device operates as follows. In the converter unit load mode, equal EMFs from the leads of inductance coils 1, 2, 3, 4, 5, 6, ..., 6n-5, 6n-4, 6n-3, 6n-2, 6n-1, and 6n are fed to the outputs of adders 8n+3 (ADD1), 8n+4 (ADD2), and 8n+5 (ADD3) and then to the inputs of rectifier unit 8n+6 (VRU). In this case, the induction B_c of magnetic flux produced by the current I_c in control winding 8n+9 of reed 8n+10, which is directly proportional to the output voltage $U_{out.vru}$ of unit 8n+6, and the induction B_{cd} of the magnetic flux of the magnetic field in conductor 8n+11 are close in value, but oppositely directed, and reed 8n+10 does not trigger, since its $B_{tr} > B_c - B_{cd}$ (B_{tr} is induction of magnetic flux, which triggers reed 8n+10). No signal is received at the write input of MEMORY 8n+12 element, and protection is not operated.

In the case of a short-circuit, e.g., a two-phase short-circuit between phases A and B at the leads of one of the secondary windings of transformer 6n+1, EMFs of different values are fed from the outputs of adders 8n+3 (ADD1), 8n+4 (ADD2), and 8n+5 (ADD3) to unit 8n+6 (VRU). In this case $B_c - B_{cd} > B_{tr}$, the reed 8n+10 actuates and sends a signal to the write input of MEMORY element 8n+12, which sends a signal to the circuit breaker of the converter unit and starts the TIME element 8n+14. A signal to the reset input of MEMORY element 8n+12 is sent from the output of TIME element 8n+14 in $t = 0.1\,\mathrm{s}$. The protection operates in a similar way when a diode is broken down in any of 2n rectifiers.

When transformer 6n+1 is switched on under the load or when the voltage is restored after an external short circuit, the magnetizing current rushes. No current flows in the busbars connected to the terminals of phases A, B, and C of the secondary windings of transformer 6n+1 as well as in current distributor 8n+11. Consequently, $B_c - B_{cd} < B_{tr}$, no signal is received at the write input of MEMORY element 8n+12, and protection does not operate.

IV. Conclusions

The techniques suggested in this work for construction of differential protection of converters with a power transformer with 2n secondary windings and 2n rectifiers allow one to avoid the use of current transformers with ferromagnetic cores. This results in considerable saving of copper and steel in relay protections. These techniques increase the sensitivity of differential protections of converter units, since there is no need to offset the power transformer from magnetizing current inrushes.

Acknowledgments

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