Reed Switches Differential Protection of Conversion Facilities with the Second-harmonic Lockout

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***Abstract*—Advantages and disadvantages of traditional differential protections of conversion facilities and reed switch protections are discussed. A reed switch differential protection is suggested, the sensitivity of which is ensured by the second-harmonic lockout in the case of a magnetizing inrush of the conversion facility transformer. Another difference is that to obtain information about the current in the phases from the high voltage side of the transformer, windings of reed switches mounted near their current conductors are used. A technique for selecting trip set points of such protections is described and the sensitivity of its is estimated. Special attention is paid to the choice of parameters of reed switches mounted near the DC busbar and their windings. Behavior of the protection is considered under different operating modes of the conversion facility, and the field of its use is determined.**

Keywords—conversion facility; differential protection; reed switch; magnetizing inrush; second-harmonic; sensitivity

I. Introduction

A change of current transformers (CTs) in a relay protection to some small-size sensors would allow significant copper, steel, and insulating material saving, decrease in the weight and size of devices, and getting rid of other known shortcomings of CTs. Therefore, the design of protections without CT was many times called a fundamentally unsolved problem of power engineering at CIGRE sessions. We are working towards solving this problem based on the use of reed switches – magnetically controlled contacts (0.7 to 5 cm long and no more than 3 g in weight), mounted at a safe distance from the busbars of an electrical installation. Thus, reed switch protections for different electrical installations has been suggested in [1-9] and developed in [10-14]. As for the differential protection of conversion facilities (CF), we have patented nine such schemes. However, some of them have insufficient sensitivity, mainly due to a need in detuning from a magnetizing inrush; others, insufficient reliability due to the difficulty of this detuning; and still others solve the problem only partially (they have CTs on the high voltage side of the CF). In addition, these patents do not provide a technique for selecting set points. In this work, we suggest a protection where the above disadvantages are excluded to some extent.

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II. Protection Suggested

A. Protection Circuit

The protection suggested differs from the known ones in that information about the currents in the phases from the high voltage side of CF transformer 1 (Fig. 1, where 2 is a rectifier; 3 is a load) is obtained from windings 4-6 of reed switches 7-9, mounted under its conductors, with the use of EMF induced at the terminals of windings 4-6 connected to amplifiers 10-12. The voltage from the outputs of the amplifiers through full-wave rectifiers 13-15 and resistors 16-18 are fed to windings 19-21 of reed switches 22-24 fixed in the magnetic field (MF) of the busbars of the DC conductor 25 of CF. The same voltages are used to determine the presence of the second-harmonic in the current. For this purpose, the inputs of

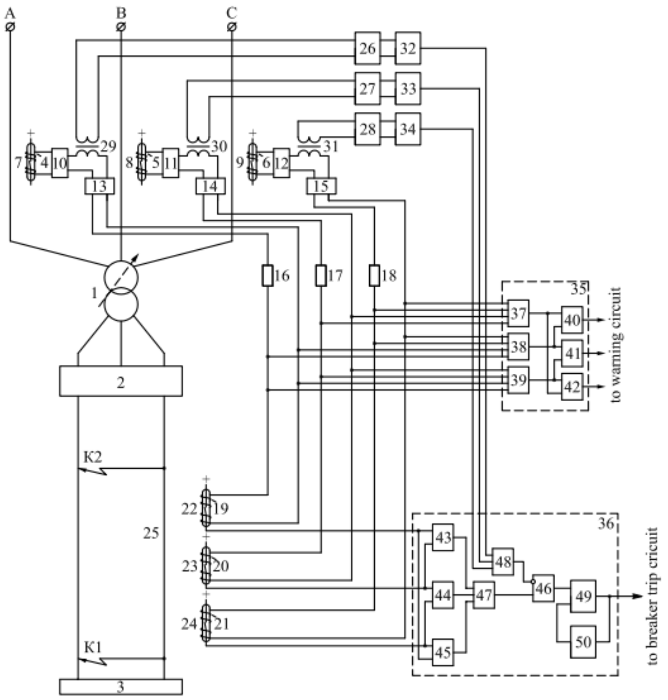

Fig. 1. Circuit of the protection suggested

second-harmonic filters 26-28 are connected to amplifiers 10-12 through isolating transformers 29-31, and the outputs are connected to threshold elements 32-34. The protection circuit also includes functional diagnostics block 35 and logic block 36. Block 35 includes comparators 37-39 and AND components 40-42; block 36 – AND components 43–46, OR components 47 and 48, MEMORY component 49, and TIME component 50. Note that reed switches 7-9 from the high voltage side of transformer 1 can function as overcurrent protection (if connecting the contacts of the reed switches to the logic block).

B. Protection Operation

If all circuit elements proper operate in the CF load modes and with external short circuits (SC), the $B_{act} > B_c - B_d$, where B_{act} is the magnetic induction of the MF required for actuation of reed switches 22-24; B_c the MF induction created by direct current I_c in the control winding of each of them; B_d is the MF induction created by the current I_d in conductor 25. Since the currents I_c in windings 19-21 are equal, there are no signals at the outputs of comparators 37-39. In the event of open circuit in rectifier 15 circuits or under a SC between phases in it or in the "rectifier 15-winding 21" circuit, or in the event of an open circuit in winding 6, the output voltage of rectifier 15 decreases and comparators 37 and 38 send signals, since the level of output voltages of rectifiers 13 and 14 do not change. AND component 40 actuates and sends a malfunction signal in the warning circuit. If an open circuit occurs in the "rectifier 15-winding 21" circuit, then its output voltage increases, comparators 37 and 38 signal, and AND component 40 operates and alarms. If the condition $B_d > B_{act}$ ($B_c = 0$) is satisfied, then reed switch 24 is triggered and signals are sent to the second and first inputs of AND components 44 and 45, respectively. However, the CF switch (not shown in Fig. 1) is not turned off, since there are no signals at the other inputs of these AND components.

Let us consider a SC in rectifier 2 as an example. In this emergency mode, the current increases in windings 4-6 and decreases in conductor 25. The condition $B_c - B_{SC} > B_{act}$ is fulfilled (where B_{SC} is the MF induction which is produced by the current in conductor 25 under a SC in the rectifier and acts along the longitudinal axis of reed switches 22-24). Reed switches 22-24 are triggered (or only two of them, for example, 22 and 23 if reed switch 24 is faulty or rectifier 15, winding 21, or the cable connecting the rectifier and winding are damaged). Signals are received at the inputs of at least one of AND components 43-45 and then are fed to the direct input of AND component 46 (there is no signal at its inverse input) through OR 47 component. From the output of the latter, the signal is sent to the write input of MEMORY component 49, which sends a tripping signal to the CF circuit breaker and starts TIME component 50. A signal from its output comes to the reset input of MEMORY component 49 in the time $t = 0.1\,\text{s}$.

When transformer 1 is powered on or the voltage is restored after external SC clearance, a magnetizing inrush occurs with prevalence of the second-harmonic in it (relative to the first, it is always higher than 17%). Reed switches 22-24, like under a SC in the zone protected, are triggered, and a signal is sent to the direct input of AND component 46. Threshold elements 32-34 also send signals to the inverse input of AND component 46 through OR component 48. Thus, there is no signal at its output, and the protection does not actuate.

The use of filters 26-28, threshold elements 32-34, AND component 46 with one inverse and one direct inputs, and OR component 48 allows (in comparison with known circuits) an increase in the protection sensitivity due to its lockout in the case of magnetizing inrush, due to which there is no need in detuning of trip set points from them.

C. Technique for Selecting Protection Trip Set Points

The technique developed is reduced to the following.

1. One of the types of closing reed switches 22-24 with control windings 19-21 is selected (for example, with the minimal rated value of MF induction required for their operation), produced by Ryazan Metal Ceramic Structures Plant (Ryazan, RF), which are supposed to be mounted in the MF of the busbars of DC conductor 25 (similarly, reed switches 7-9 with windings 4-6 are planned to be mounted near the conductors of the phases on the high voltage side of transformer 1 of CF). For the reed switches with windings selected, in addition to B_{act}, the number of winding turns w_{wind}, its length l_{wind}, and the resistance R_{wind} are known. It is advisable to mount reed switches 22-24 not at the beginning of conductor 25 (i.e., immediately after rectifier 2 in Fig. 1), but at its end, which is to allow expanding the protection coverage area, since it will respond not only to a SC at the high- and low-voltage terminals of transformer 1 and damage in rectifier 2, but also to a SC at most part of conductor 25.

2. According to generally accepted requirements, the differential protection sensitivity coefficient k_s should be higher than or equal to 2. In the protection considered, we suggest to calculate the sensitivity coefficient by analogy with traditional differential protections by the equation

$$k_s = \frac{B_{c,\min}^{int.SC}}{B_{p.o.}}, \tag{1}$$

in the case of a SC at the end of the zone protected (point K2 in Fig. 1) taking into account that the induction created by the current in the busbars of conductor 25 does not affect reed switches 22-24 is this mode. Here, $B_{c,\min}^{int.SC}$ is the MF induction produced by the minimal current of an internal SC $I_{c,\min}^{int.SC}$ in the control winding of a reed switch and acting along its longitudinal axis.

Detuning from unbalance currents always takes place in traditional differential protections. In our case, the currents correspond to the MF inductions created by them. Then, the condition

$$B_{act} \geq B_{unb} = k_{detun.1}\left(B_{c,\max}^{ext.SC} - B_{d,\max}^{ext.SC}\right) \tag{2}$$

should be satisfied to prevent false operation of reed switches 22–24 under external short circuits. Here, $k_{detun.1} = 1.5$ is the detuning coefficient; $B_{c,\max}^{ext.SC}$ is the MF induction which is produced under the maximal current of an external SC (e.g., SC at point K1 in Fig. 1) by the current $I_{c,\max}^{ext.SC}$ in the reed switch control winding and acts along its longitudinal axis; $B_{d,\max}^{ext.SC}$ is the resulting MF induction produced by the current $I_{d,\max}^{ext.SC}$ (equal to the current of the maximal external SC) in the busbars of conductor 25, which also acts along the longitudinal axis of the reed switch.

The induction $B_{p.o.}$, which is the parameter of protection operation, should satisfy the condition

$$B_{p.o.} \geq k_{detun.2} B_{act}, \tag{3}$$

where $k_{detun.2} = 1.3$.

For each of reed switches 22-24, one can calculated

$$B_{c,\min}^{int.SC} = \frac{\mu_0 I_{c,\min}^{int.SC} w_{wind.19}}{l_{wind.19}}, \tag{4}$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ is the air permeability; $w_{wind.19}$ and $l_{wind.19}$ are the number of turns and the length of winding 19 (20 and 21).

From the protection circuit in Fig. 1,

$$I_{c,\min}^{int.SC} = \frac{k_{amp} E_{4,\min}^{int.SC}}{R_{16} + R_{wind.19}}, \tag{5}$$

where k_{amp} is the amplification factor of amplifier 10 (11 and 12); $E_{4,\min}^{int.SC}$ is the EMF at the terminal of winding 4 (5 and 6) induced by the MF of the minimal current $I_{1m,\min}^{int.SC}$ in the conductor of the phase A (B and C) of transformer 1 from its high voltage end under a SC in the end of the zone protected; $R_{wind.19}$ is the resistance of winding 19 (20 and 21); R_{16} is the resistance of resistor 16 (17 and 18) unknown at the initial stage.

In (5), the EMF

$$E_{4,\min}^{int.SC} = 4.44 B_{1m,\min}^{int.SC} f w_{wind.4} s_{wind.4}, \tag{6}$$

where $B_{1m,\min}^{int.SC}$ is the MF induction produced by the current $I_{1m,\min}^{int.SC}$; $f = 50$ Hz is the power-line frequency; $w_{wind.4}$ and $s_{wind.4}$ are the number of turns and the cross section area of winding 4 (5 and 6).

The induction $B_{1m,\min}^{int.SC}$ in (6) is defined by the Biot-Savart law as

$$B_{1m,\min}^{int.SC} = \frac{\mu_0 I_{1m,\min}^{int.SC}}{2\pi h}, \tag{7}$$

where h is the safe distance from the conductor of the phase A (B and C) to the point of mounting reed switch 7 (8 and 9) with winding 4 (5 and 6).

Finally,

$$\begin{aligned} B_{c,\min}^{int.SC} &= \frac{4.44 \mu_0^2 f w_{wind.4} s_{wind.4} w_{wind.19} k_{amp} I_{1m,\min}^{int.SC}}{2\pi h l_{wind.19} \left(R_{16} + R_{wind.19}\right)} = \\ &= k_1 \frac{I_{1m,\min}^{int.SC}}{R_{16} + R_{wind.19}} \end{aligned}. \tag{8}$$

Let $k_s = 2$. Then, from (1) together with (8), the required resistance

$$R_{16} = \frac{k_1 I_{1m,\min}^{int.SC}}{2.6 B_{act}} - R_{wind.19}. \tag{9}$$

After the calculation of R_{16} by (9), the resistance of resistors 16-18 is taken equal to the nearest minimal value of the index list of resistors, which allows the required protection sensitivity to be ensured with a certain margin.

3. Next, it is necessary to determine the coordinates of the reed switch mounting point relative to busbars 51 and 52 (Fig. 2) of DC conductor 25, where condition (2) of protection nonoperation is satisfied if taking into account the final R_{16} value.

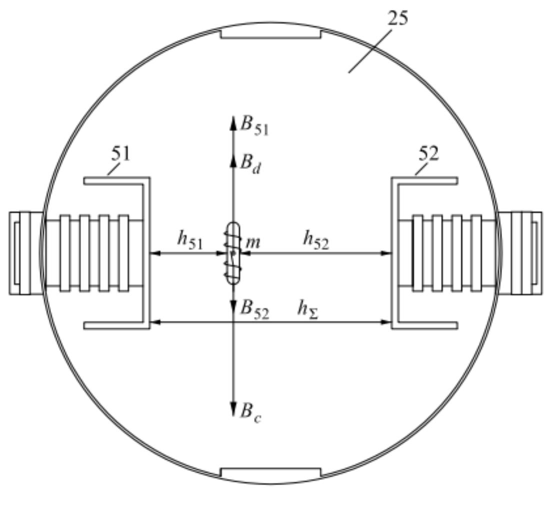

Fig. 2. Reed switch fixed inside DC conductor 25

The induction $B_{c,\max}^{ext.SC}$ is calculated by (8) with the corresponding change of indices (“int.SC” and “min” are changed to “ext.SC” and “max”). If a reed switch is fixed at the point m (coinciding with its center of gravity) at safe distances h_{51} and h_{52} from busbars 51 and 52, respectively, at the angle $\gamma = 0$ between its longitudinal axis and a plane parallel to the busbars, then, following the Biot-Savart law and Fig. 2,

$$B_{d,\max}^{ext.SC} = B_{51,\max}^{ext.SC} - B_{52,\max}^{ext.SC} = \\ = \frac{\mu_0 I_{d,\max}^{ext.SC}}{2\pi}\left(\frac{1}{h_{51}} - \frac{1}{h_{52}}\right) = k_2\left(\frac{1}{h_{51}} - \frac{1}{h_{52}}\right), \quad (10)$$

where $B_{51,\max}^{ext.SC}$ and $B_{52,\max}^{ext.SC}$ are the MF inductions produced by the current $I_{d,\max}^{ext.SC}$ in busbar 51 directed from the plane of Fig. 2 toward a reader and the same current in busbar 52 directed from a reader.

The distance h_{51} can be found from the quadratic equation derived from (2) accounting (10) and the corresponding change of indices in (8):

$$a h_{51}^2 - b h_{51} + c = 0, \quad (11)$$

where $a = \left(\frac{k_{detun.1} k_1 I_{1m,\max}^{ext.SC}}{R_{16} + R_{wind.19}} - B_{act}\right) / k_2$, $b = -(2 + a h_\Sigma)$, and $c = h_\Sigma$, h_Σ is the distance between busbars 51 and 52 of conductor 25; $I_{1m,\max}^{ext.SC}$ is the maximal current in the conductor of each phase of transformer 1 from its high-voltage side under an external SC.

The distances h_{51} and h_{52} are found from (11) and the protection adjustment is considered complete. If the h_{51} value turns out smaller than that required by safety conditions, it is necessary to introduce additional insulation, for example, fill a reed switch with a control winding and connecting wires with compound.

D. Field of Use of the Protection Suggested

If the protection suggested meets the requirements for speed, reliability, and selectivity, then the fields of its use can be estimated by sensitivity, which can be assessed by above technique. In this work, we have estimated the sensitivity of protection for CFs supplying consumers with load currents no higher than 6.3 kA. In such CF, DC conductors are made in the form of two single busbars located opposite each other (see Fig. 2). We have already considered the MFs produced by currents in these busbars under SC to them and designed structures for mounting reed switches near these busbars (for example, [15-17]). At load currents above 6.3 kA, DC conductors are made in the form of a busbar package, which requires additional research, since electric crosses or breaks are probable in such conductors, in addition to the SCs considered.

The calculation results show that the differential reed switch protection has the required sensitivity for all CFs with transformers of $0.25-10\ \mathrm{MV\cdot A}$ in power (primary winding voltage 6 and 10 kV) equipped with both off-circuit and on-load tap-changers (control rectified voltage U_d is from 10% to 90%). For the protection design, the entire standard set of closing reed switches manufactured by Ryazan Metal Ceramic Instruments Plant, as well as RGK-49 and RGK-54 reed switches, studied in [4], can be used.

Let us for example select the protection trip set points for a CF which supplies an electrolysis plant with the maximal load current $I_{d,\max} = 6.3\ \mathrm{kA}$ (other calculations are the same). A double wound transformer with an on-load tap-changer (control rectified voltage within 80%) of $6.3\ \mathrm{MV\cdot A}$ in power with a rate voltage of the primary winding of 6 kV and Y/Y_n-0 connection windings. The SC currents $I_{1,\max}^{ext.SC} = 19.42\ \mathrm{kA}$, $I_{1,\min}^{int.SC} = 1.51\ \mathrm{kA}$, $I_{d,\max}^{ext.SC} = 158.68\ \mathrm{kA}$. MKA-07101 closing reed switches with $B_{act} = 8.8 \cdot 10^{-4}\ \mathrm{T}$ are mounted. Standard windings with the number of turns $w_{wind} = 5000$, length $l_{wind} = 0.01\ \mathrm{m}$, and resistance $R_{wind} = 580\ \mathrm{Ohm}$ are used as control windings. Taking $k_s = 2$, we find the resistance $R_{16} = 0.17\ \mathrm{Ohm}$ by (9). Resistors with $R_{16} = 0.1\ \mathrm{Ohm}$ are accepted for mounting. A SHZK-1.2-6300 conductor can be used as a DC conductor for the CF under consideration. The distance between its busbars $h_\Sigma = 0.29\ \mathrm{m}$, and the safe distance from the point of reed switch mounting to the busbars should be at least 0.065 m. From (11), we find the coordinates $h_{51} = 0.13\ \mathrm{m}$ and $h_{52} = 0.16\ \mathrm{m}$ of the point of mounting the reed switches relative to the conductor busbars, where condition (2) for detuning from the maximal current of an external SC is fulfilled. Protection sensitivity coefficient $k_s = 2.4$.

III. Conclusions

1. The differential protection of conversion facilities suggested in this work allows solution of the problems of avoiding current transformers and, hence, saving in copper, steel, and insulating materials due to the use of reed switches.

2. A technique for selecting the trip set points of this protection has been developed. Its feature is the use of magnetic flux inductions instead of currents, like in traditional protections. To determine the parameters, we proceed from the induction B_{act} of actuation of the existing reed switches and the assumption about the protection sensitivity coefficient $k_s = 2$.

3. The second-harmonic lockout of the protection provides for higher protection sensitivity as compared to known reed switch circuits.

4. The technique suggested has allowed us to ascertain that the filed of protection use is limited by the CF power $0.25-10\ \mathrm{MV\cdot A}$, and all types of closing reed switches and reed relays manufactured by Ryazan Metal Ceramic Devices

Plant can be used for its design. At high CF powers, additional studies are required to determine the protection sensitivity.

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