Invariant protection of high-voltage electric motors of technological complexes at industrial enterprises at partial single-phase ground faults

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Abstract. Development results of invariant protection of high-voltage motors at incomplete single-phase ground faults are observed in the article. It is established that current protections have low action selectivity because of an inadmissible decrease in entrance signals during the short circuit occurrence in the place of transient resistance. The structural functional scheme and an algorithm of protective actions where correction of automatic zero sequence currents signals of the protected accessions implemented according to the level of incompleteness of ground faults are developed. It is revealed that automatic correction of zero sequence currents allows one to provide the invariance of sensitivity factor for protection under the variation conditions of a transient resistance in the place of damage. Application of invariant protection allows one to minimize damages in 6-10 kV electrical installations of industrial enterprises for a cause of infringement of consumers’ power supply and their system breakdown due to timely localization of emergency of ground faults modes.

1. Introduction
In the structure of industrial enterprises electromechanical complexes one of the main places is occupied by 6-10 kV high-voltage motorson which reliable and trouble-free operation and efficiency of production technological processes depend. The analysis of operational data has shown that the greatest number of emergencies in the 6-10 kV electrical installations is connected with single-phase ground faults [1,2]. Single-phase ground faults modes, that were not eliminated in time constitutes huge danger to high-voltage engines becauseof high frequency rate overvoltage, which leads to breakdowns of elecric motors stator windings and thus subsequent out of operation failure [3, 4]. Therefore, it is necessary to apply the effective remedies of relay protection and automatic equipment in 6-10 kV electrical installations because of ground faults. This measure allows one to reveal selectively the damaged accession to minimize economic damages and to eliminate the arisen emergency operation in proper time. The performed researches demonstrate that one of the main reasons for low efficiency of protective actions against single-phase ground faults is transient resistance in the place of damage which as one of the zero-sequence circuit parameters reduces protective working signals [5].

According to these facts, the task of the selective protection organization at incomplete ground faults (through transitional resistance) possessing invariable (invariant) action in relation to parameters of the zero sequence circuit is vital.
2. The analysis of transitional resistance influence on the sensitivity of protective actions against single-phase ground faults

As a result of analytical researches, it has been established that the zero sequence current and voltage decrease during the single-phase ground faults mode through transitional resistance happens proportionally to ground faults incompleteness factor [6, 7]:

\[ n = \frac{1}{\sqrt{(tg\delta R_p + 3\omega C_Z + \lambda d_N R_p 3\omega C_Z + 1)^2 + (R_p 3\omega C_Z)^2}}, \]

where \( tg\delta \) – a tangent of dielectric losses angle; \( R_p \) – transient resistance in the ground faults place; \( \omega \) – circular frequency; \( C_Z \) - total capacitance of electrically connected network concerning the ground, including high-voltage motors; \( \lambda \) –factor considering parameters of the grounding neutral transformer; \( d_N \) – factor characterizing the mode of a neutral grounding.

According to experimental research results, the following ranges of total network’s capacity deviations \( C_Z \) in a range of 0.01…9.2 mcF, dielectric loss tangent \( tg\delta \) in a range of 0.02…3.5, factor \( \lambda \) in a range of 0.96…0.99, transient resistance \( R_p \) in a range of 1…7000 Ohms and factor \( d_N \) in a range of 0…4 [8, 9, 10] were obtained. Having taken typical extreme value from the chosen variation ranges of total network capacity, a dielectric losses angular tangent, transitional resistance as the basis, one can receive \( C_Z^* = 0.001…1 \) p.u., \( tg\delta^* = 0.006…1 \) p.u.; \( R_p^* = 0.00014…1 \) p.u. respectively. The incompleteness factor dependencies of the ground faults and protection sensitivity factor against transitional resistance in the place of damage and total capacity concerning the electrical network grounding \( (d_N=0, \lambda=0.99, tg\delta=0.001 \) p.u.) are presented in Figures 1a and 1b.

![Figure 1](image_url)

Figure 1. The dependencies of incompleteness factor of ground faults (a) and protection sensitivity factor (b) against transitional resistance in the place of damage and total capacity concerning the electrical network grounding.

As it follows from Figure 1a, incompleteness factor of ground faults value \( n \) is in limits of 0…1 and decreases with the transient resistance increase. Besides, with the parameters increase of the zero-sequence circuit, including the total network capacity, a tangent of the dielectric losses angle, transitional resistance \( d_N \) factor of the gradient decrease and incompleteness factor of ground faults have the greatest value. For example, at \( R_p^* = 0.714 \) p.u. and \( C_Z^* = 0.1 \) p.u. incompleteness factor’s value is 0.21 p.u., and at \( R_p^* = 0.714 \) p.u. and \( C_Z^* = 0.6 \) incompleteness factor’s value is 0.05 p.u.

The protective actions’ efficiency against ground faults is characterized by the sensitivity factor, which in the mode of incomplete single-phase ground faults is determined by the following expression:
where $U_{ph}$ – the electrical network phase voltage; $C_r$ – line capacity concerning the ground, feeding the high-voltage motors; $C_\Sigma$ – capacity concerning the ground of whole electrically connected network, including high-voltage engines; $C_m$ – capacity concerning the ground of a stator winding of the high-voltage motor; $K_{pr}$ – protection detuning factor ($K_{pr}$ is in limits of $1.5…1.8$) [11].

According to [12], it is necessary to ensure selective action of protection at single-phase ground faults through transitional resistance so that the sensitivity factor of protection under the metal ground faults mode ($R_t=0$) was not less than 2. Besides, the minimum factor’s value should be not less than 1.25 in order to protect reaction to the fault [13]. However, curves in Figure 1b show that transitional resistance reduces protection sensitivity, which leads to serious damage for the high-voltage equipment. For example, boundary values of transitional resistance and total capacity of network at which protection selectively reveals and eliminates emergency are $R_t^*=0.043$ p.u. and $C_\Sigma^*=0.42$ p.u., $R_t^*=0.143$ p.u. and $C_\Sigma^*=0.13$ p.u., $R_t^*=0.714$ p.u. and $C_\Sigma^*=0.03$ p.u.

In this regard, there is the need of algorithm development for the protective actions against single-phase ground faults through transient resistance allowing carrying out an automatic correction of zero sequence current signal according to incompleteness factor of ground faults.

3. Structure and algorithm of invariant protection actions for high-voltage motors against partial single-phase ground faults

According to numerous researches of protection efficiency against single-phase ground faults in the places of damage of transitional resistance, there was developed a structural functional scheme of invariant protection, which presented in Figure 2.

![Figure 2](image_url)

**Figure 2.** The structural functional scheme of invariant protection in electrical network with high-voltage electric motors.

In Figure 2: VMT - voltage measuring transformer [14]; TZSC - measuring transformer of zero-sequence current [14]; $i_{01}$, $i_{02}$ – instant values of current of the zero sequence of the damaged and intact line [14]; $u_0$ - instantaneous value of zero-sequence voltage [10]; $u_L$ – line network voltage [14]; RMS – block of root-means-square value calculation [14]; $I_{01}, I_{02}$ – the operating values of current of the zero sequence of the damaged and intact line; $U_0$ – the signal of root-means-square value of zero-sequence...
voltage; $U_L$ - the signal of root-means-square value of network line voltage [14]; $U_{set}$ – the setting for signal transmission (the setting of threshold element of protection system) [14]; TD - threshold device [10]; MNVD - module of phase network voltage detection [14]; $U_{ph}$ – the signal of root-means-square value of phase network voltage [14]; BIC - block of calculation of imperfection factor of single phase ground faults[14]; $n$ - imperfection factor of single phase ground faults [10]; FCC1, FCC2–modules of automatic correction of the measured currents of the zero sequence; $I_{01corr}$, $I_{02corr}$ – the corrected currents of the zero sequence of the damaged and intact line; $I_{set}$ – the setting of current for protection functioning [14]; LE1, LE2–logical elements of the damaged and intact lines.

Invariant protection works as follows. In the mode of single-phase ground faults through the transitional resistance of $R_tr$ (line 1) from the voltage transformer (VMT) signals in the form of $u_0$ and $u_L$ comes on entrances of protective threshold body (TD) and the module incompleteness factor of ground faults calculation (BIC) respectively arrive. The threshold element (TD) carries out tension comparison operations of $U_0$ with a setting of $U_{set}$ and at its excess transmits a tension signal of the zero sequence to the calculation module of incompleteness factor (BIC). The BIC module carries out calculation operation of incompleteness factor of ground faults by division of a $U_0$ signal into a signal of $U_{ph}$ which is defined in the MNVD module due to division of $U_L$ signal into factor 1.73. The signal $n$ from the BIC module exit arrives to FCC1 and FCC2 modules which carry out operation of signals division $I_{01}$ and $I_{02}$ into the incompleteness factor of ground faults. The corrected signals of the zero sequence currents of damaged and impacted $I_{01corr}$ and $I_{02corr}$ lines arrive to the corresponding logical elements LE1 and LE2 where their comparison operation with an operation setting $I_{set}$ is carried out. At the setting excess operation of the logical element LE1 generates a shutdown signal of the damaged accession.

Thus, the developed invariant protection of high-voltage engines against single-phase ground faults performs two main functions [14, 15]:

- the first is the degree incompleteness definition of line phase ground faults of an electrical network by assessment of under voltage level of the zero sequence in relation to phase voltage because of transient resistance in the place of damage;
- the second one is the automatic correction of the measured signals of zero sequence currents of the protected lines according to the calculated factor to find completeness of the ground faults.

Sharing these functions in a uniform action algorithm allows one to provide invariable protective action at ground faults as "metal", and through transient resistance.

### 4. Research results of invariant protection against ground faults actions efficiency

The research of selectivity and invariance of protective actions at ground faults through transient resistance was carried out by simulation in MatLab Simulink software package. Results of invariant protection modeling with an automatic correction of zero sequence current signal are presented in Figure 3 and in Table 1.

| $R_{tr}$, p.u. | $U_L$, kV | $n$ | $I_{01}$, A | $I_{01corr}$, A | $I_{02}$, A | $I_{02corr}$, A |
|---------------|----------|-----|------------|-------------|------------|-------------|
| 0.00014       | 3.64     | 1   | 1.98       | 1.99        | 0.99       | 0.99        |
| 0.071         | 3.36     | 0.92| 1.84       | 1.99        | 0.92       | 0.99        |
| 0.143         | 2.81     | 0.77| 1.54       | 1.99        | 0.77       | 0.99        |
| 0.214         | 2.29     | 0.63| 1.25       | 1.99        | 0.63       | 0.99        |
| 0.286         | 1.89     | 0.52| 1.04       | 1.99        | 0.52       | 0.99        |
| 0.571         | 1.06     | 0.29| 0.58       | 1.99        | 0.29       | 0.99        |
| 1             | 0.62     | 0.17| 0.34       | 1.99        | 0.17       | 0.99        |
A number of studies by means of simulation, during which the parameters variation the zero sequence circuit was carried out on the developed model that the main signals, characterizing functioning of invariant protection against short ground faults with automatic signal correction of the zero sequence current signal on the damaged and intact line of network, were carried out.

![Dependences of the zero sequence currents of the damaged and intact lines of the network in the ground faults mode through transient resistance at a various total network capacity: a - $C_0^* = 0.1 \text{ p.u.};$ b - $C_0^* = 1 \text{ p.u.}$](image)

Figure 3. Dependences of the zero sequence currents of the damaged and intact lines of the network in the ground faults mode through transient resistance at a various total network capacity: a - $C_0^* = 0.1 \text{ p.u.};$ b - $C_0^* = 1 \text{ p.u.}$

It follows from Figure 3 that transient resistance increase in the place of damage leads to the decrease in the zero sequence currents signals of the protected lines that involves danger in refusal of protection functioning against ground faults. However, at the expense of the developed correction algorithm of the zero sequence current signal of the protected line, taking into account the incompleteness degree of ground faults, the corrected current signal, which is a working signal of protection, remains invariable in all range of parameters variation of the zero sequence contour, including transient resistance in the place of damage and the total capacity of the network (Figures 3a and 3b). It allows one to provide invariant protective action in the inconstancy conditions of the ground faults model.

5. Discussion
The developed invariant protection of high-voltage motors from single-phase ground faults has better response parameters and performance characteristics in comparison with known existing protection devices. The main advantages of invariant protection are the following: simplicity of the algorithm of analysis of the transient resistance in the place of damage; reliable generation of a signal when conditions for triggering appear; absolute selectivity of action; high sensitivity for incomplete single-phase ground faults. According to the presented structure of invariant protection, two patents of the Russian Federation no.168498 and 2578123 for invention were received.

6. Conclusion
According to the obtained results of the performed researches, the following important facts have been detected:

Automatic correction of the entrance protective signal against ground faults allows one to provide invariable value of a zero sequence current signal of the protected line in the range of transient resistance variations $R^*_n 0.00014...1 \text{ p.u.}$ and the total capacity of network $C_0^*0.001...1 \text{ p.u.}$ At the same time, the sensitivity factor of protection will be invariant in relation to parameters of the zero sequence circuit.
Correction of the zero sequence currents signals of the protected accessions do not lead to shutdown signal generation of the intact line that allows one to provide necessary conditions of protective actions selectivity.

The developed invariant protection of high-voltage motors against single-phase ground faults reliably functions both at metal, and at ground faults through transitional resistance. Operation of invariant protection allows one to minimize damages in 6-10 kV electrical installations of the industrial enterprises for a cause of consumers’ power supply shutdown and exit of their system due to timely localization of emergency operation of ground faults.

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References
[1] Zhao J, Yuan X, Ruan Q, Wang L, Song Y and Zhang C 2015 Pow. Syst. Prot. and Contr. 43(21) 81–85
[2] Abramovich B N and Sychev Y A 2016 Oil Industry 9 120–123
[3] Semykina I Yu and Skrebneva E V 2017 J. of Min. Inst. 226 452–455
[4] Malarev V I and Kopteva A V 2017 IOP Conf. Ser.: Earth Environ. Sci. 87 032022
[5] Zhukovskiy Y and Koteleva N 2017 IOP Conf. Ser.: Earth Environ. Sci. 87 032057
[6] Kostarev I A and Sapunkov M L 2013 Oil Industry 6 126–128
[7] Zhukovskiy Yu L 2017 IOP Conf. Ser.: Earth Environ. Sci. 87 032056
[8] Ustinov D A and Baburin S V 2016 Int. J. of Appl. Eng. Res. 11(7) 5273–5279
[9] Thomas B, Renovich F, Saunders L and Lubkeman D 2011 IEEE Trans. on Ind. Appl. 37(4) 1152–1159
[10] Ziming Z, Haimeng S and Haibin J 2013 Eng. and Pow. Eng. 5 937–940
[11] Dunki-Jacobs J R 1986 IEEE Trans. on Ind. Appl. 6 1156–1161
[12] Griffin C H and Pope J W 1982 IEEE Trans. on Pow. Appl. and Syst. 12 4490–4501
[13] Wang C, Liu X and Chen Z 2014 IEEE Trans. on Magn. 50(11) 1–4
[14] Gukovskiy Yu L, Sychev Yu A and Pelenev D N 2017 Int. J. of Appl. Eng. Res. 12 833–838
[15] Sapunkov M L 2013 Oil Industry 4 68–71