Journal of Physics: Conference Series

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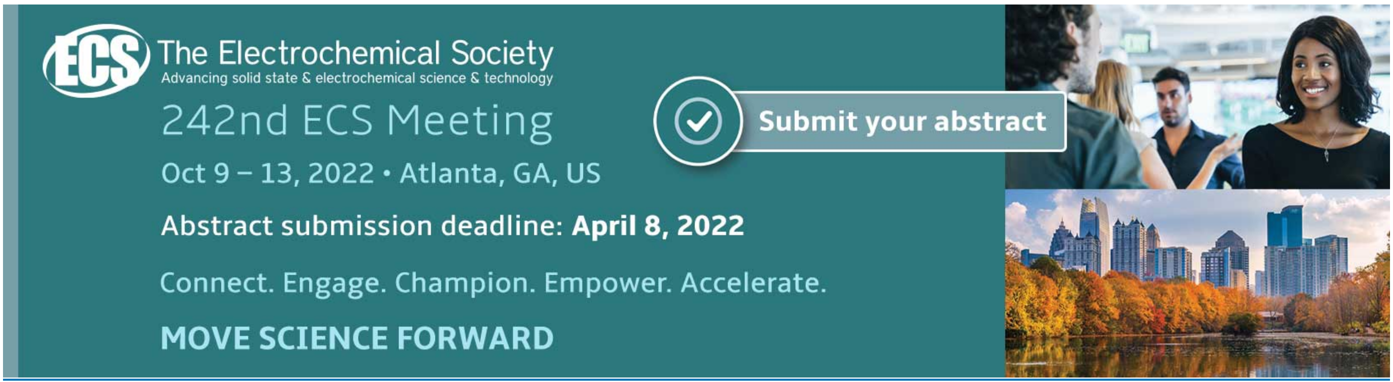
To cite this article: B Mashrapov 2021 *J. Phys.: Conf. Ser.* **2096** 012172



International Conference on Automatics and Energy (ICAE 2021) IOP Publishing
Journal of Physics: Conference Series **2096** (2021) 012172 doi:10.1088/1742-6596/2096/1/012172

Centralized Protections of Busbars and Electric Motors Connected to Them

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Abstract. Centralized protections have several advantages over autonomous protections; however, incorrect actions of the former can result in more serious consequences. The reliability of their operation can be ensured with the help of majorization principle, but the number of devices with different principles of operation is insufficient so far. Three centralized protections are suggested; one of them allows duplication of current transformers. They all are based on the fact that the electric motors of feeders feed a short-circuit point; as a result, the current in a feeder damaged becomes higher than the current at the power input, and the currents in undamaged feeders change the direction to opposite. The conditions for protection actuation are presented. Operation of the protections in different modes is described in detail.

1. Introduction

The overwhelming majority of short circuit protections of electrical network elements, including those based on new principles [1–4], are autonomous. However, they cannot always provide the required sensitivity and speed [5]. In certain cases, this problem can be solved by centralized protections [6], which receive information from several connections and, hence, have more flexible and perfect operation algorithms. In addition, the replacement of autonomous protections with centralized ones is to facilitate unification and maintenance of equipment at power plants and substations and to reduce the amount of the equipment [7]. However, incorrect operation of centralized protections or their failure can have more serious consequences in comparison with autonomous protections. The reliability of centralized protections can be enhanced with the use of the majorization principle (a tripping signal is sent to a damaged network element if two of three protective sets actuate) [6]. This principle has become much easier to implement since the widespread use of microprocessors in relay protections. To maximize its effect, it is necessary, first, to have three protections with different principles of operation. Unfortunately, as far as we know, a very few such protections have been suggested for electric motor substations by now [7]. Second, they should duplicate current transformers. In this work, we try to fill in these gaps.

2. Centralized protections with current transformers

2.1. Fast protection of feeders connected to common busbars

The principle of operation of the protection is based on the fact that the current in the *i*th feeder becomes higher than the current I_{in} at the power input in the event of a short circuit (SC), because electric motors (EM) feed the short circuit point. As is known [8], the current I_{suppl} exceeds the rated current of EM and can approach its starting current; I_{suppl} and I_{in} are almost in phase. Based on the above said, we can write the following condition for the protection operation and opening the circuit breaker of a feeder damaged (KZ Patent no. 29656):

$$\frac{I_i^{\text{SC}}}{I_{\text{IN}}^{\text{SC}}} \geq p, \tag{1}$$

where I_i^{SC} is the absolute magnitude of the current in the *i*th damaged feeder; $I_{\text{IN}}^{\text{SC}}$ is the absolute magnitude of the input current under a short circuit to the *i*th feeder; *p* is the operation parameter.

The value of *p* is chosen so as the protection does not operate when EM is started at the *i*th feeder when the others are off. Then, $I_{\text{IN}}^{\text{C}} = I_i^{\text{C}}$ (where I_{IN}^{C} and I_i^{C} are the currents at the power input and in the only connected feeder at the instant of EM starting). Taking into account the effect of errors ε_1 and ε_2 of the current transformers and the implementing device and setting $\varepsilon_1 = 0.1$ and $\varepsilon_2 = 0.05$, we get

$$p = \frac{I_{\text{IN}}^{\text{C}}}{I_{\text{IN}}^{\text{C}}} \cdot \frac{1+\varepsilon_2}{1-\varepsilon_1-\varepsilon_2} = 1.23. \tag{2}$$

Let us take the conservative value $p = 1.25$.

The protection circuit is shown in Fig. 1. For each *i*th ($i = 1, 2, ..., n$) feeder and input n+1 connected to busbar n+2, it contains current relays n+3 and n+4, current transformers n+5 and n+6 in phases A and C of the feeders, units n+7 and n+8 (each contains n comparators, where the currents in phase A (C) are compared in absolute value in each feeder and at the input), logic part n+9, current relay n+10, elements AND n+11, and actuators n+12 and n+13. The operation parameter of current relay n+10 is detuned from the open-circuit current. Units n+7 and n+8, with n+1 inputs and n outputs, signal if condition (1) is true.

The protection works as follows. Under the load, the current at input n+1 is higher than the current in the *i*th feeder, and condition (1) is wrong. The currents in relays n+3 and n+4 are lower than the standard (it is specially selected for each feeder). Hence, they do not signal, like units n+7 and n + 8. Protection does not operate.

In the event of a two-phase short circuit between phases B and C at point M1, for example, on feeder 2, when at least one of the electric motors at undamaged feeders supplies the current I_{suppl} to the short circuit point, the current I_2 through current transformer n+6, connected to the break of phase C of feeder 2, is equal to the sum of the currents I_{IN} and I_{suppl}. The current I_{IN} is obviously lower than I_2. Therefore, condition (1) is fulfilled, and a signal is sent to the second output of unit n+8 and is applied to element AND n+11 of feeder 2. Relay n+10 signals to the second input of feeder 2, since the input current is higher than the open-circuit current. A signal from the output of element AND n+11 goes to actuator n+13, which sends a tripping signal to breaker n+15 of feeder 2. The protection operates without time delay. Relay n+4 is simultaneously activated and signals to the input of logic part n+9. However, a signal appears at its output only after the delay time, as in traditional overcurrent protections.

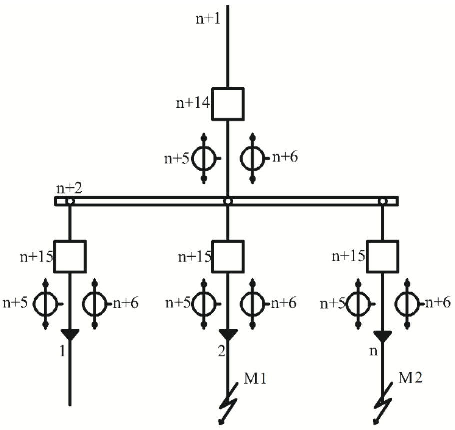

Figure 1. System diagram.

In the case of a short circuit at busbars n+2, the current at input n+1 is higher than the current in the consumer feeders. Therefore, comparing units n+7 and n+8 do not signal. In this case, current relay n+3 or n+4, connected to current transformers n+5 and n+6 of input n+1, operates since the currents in it exceeds a value specified, and a signal is sent to the corresponding input of logic part n+9, which processes the information and sends a signal from the corresponding output to actuator n+12 with a time delay. The protection operates and opens breaker n+14.

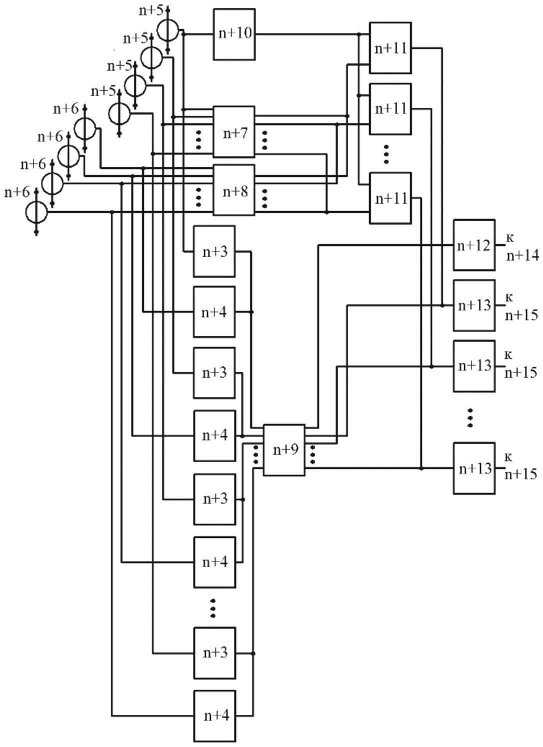

Figure 2. Block-diagram of the centralized protection and feeders connected to common busbars.

2.2. Fast protection of busbars and feeders connected to them

The principle of operation of the protection is also based on injection from electric motors. To increase the protection sensitivity, the numerator in Eq. (1) is artificially increased and the denominator is decreased under a short circuit. The protection operation condition is written as (KZ Patent no. 29655):

$$\left| U_{\mathrm{A_{out}}} - 2\sum_{i=1}^{n,i\neq k} U_{\mathrm{A}i} \right| \geq p \left| U_{\mathrm{Aout}} + 2\sum_{i=1}^{n,i\neq k} U_{\mathrm{A}i} \right| \tag{3}$$

in this case, where U_{Aout} and $U_{\mathrm{A}i}$ are the voltages at the output of current transformers n+2 (Fig. 3) proportional to the currents in phase A at input n+1, and in the *i*th feeder; $p = 1.25$ is the protection operation parameter.

For phase A (B, C) of the *i*th (i = 1, ..., k, ..., n) feeder and input n+1, the device includes current-to-voltage converter n+2 (n+3, n+4); current transformer n+5 (n+6, n+7); adders n+8 (n+9, n+10) and n+20 (n+21, n+22); subtractors n+11 (n+12, n+13) and n+17 (n+18, n+19); amplifier n+14 (n+15, n+16) with a gain equal to 2; comparator n+23 (n+24, n+25); elements OR n+26, AND n+27, and AND with inverse input n+30; actuators n+28 and n+31, and current relay n+33.

Current relay setpoint n+33 is detuned from the open-circuit current. It ensures the correct protection operation in the case of power-off coasting of the electric motor. Comparator n+23 (n+24, n+25) signals when condition (3) becomes true for the current in phase A (B, C) of the corresponding feeder, e.g., the *k*th feeder.

The protection operates as follows. Under the normal network operation, a voltage appears at the output of adder n+8 (n+9, n+10) proportional to the sum of the load currents in the 1st, ..., nth feeders, is applied to subtractor n+11 (n+12, n+13), and is decreased there by the output voltage of current-to-voltage converter n+2 (n+3, n+4) of the 1st, ..., nth feeders. The voltage difference is applied to amplifier n+14 (n+15, n+16), where it is doubled. Then, from the amplifier outputs, it goes to subtractor n+17 (n+18, n+19) and adder n+20 (n+21, n+22), other inputs of which are energized from current converter n+2 (n+3, n+4) of input n+1. Subtractor n+17 (n+18, n+19) and adder n+20 (n+21, n+22) contain the values of the numerator and denominator of Eq. (1). These values are sent to the inputs of corresponding comparator n+23 (n+24, n+25), at the output of which there is no signal, since condition (1) is not fulfilled. Therefore, OR n+26, AND n+27, and AND n+30 elements and actuators n+28 and n+31 do not signal, and the protection does not operate.

In the event of a short circuit between phases A and B of the nth feeder (point M2 in Fig. 1), when the busbar voltage drops to $0.5U_{\mathrm{r}}$ (U_{r} is the rated network voltage), the electric motors switch to generator mode and feed the short circuit point. Hence, a voltage appears at the output of adder n+8 (n+9) proportional to the difference in the current in phase A (B) of the nth feeder and the injected currents in phases A (B) of the 1st, ..., (n–1)th feeders. This voltage is converted in subtractor n+11 (n+12) and amplifier n+14 (n+15) and applied to subtractor n+17 (n+18) and adder n+20 (n+21). In this case, voltages appear only at the outputs of subtractor n+17 (n+18) and adder n+20 (n+21) of the nth feeder, proportional, respectively, to the sum of and difference between the current in phase A (B) at input n+1 and the doubled sum of the injected currents in phases A (B) of undamaged feeders. This can be explained by inverting the currents in the undamaged feeders with respect to the input current (they all are directed to the busbars). Therefore, condition (1) is fulfilled for the current in phase A (B) of the nth feeder, and signals appear at the output of comparator n+23 (n+24) of the nth feeder, element OR n+26, and actuator n+28, and breaker n+29 is open.

In the event of a short circuit at the busbars, voltage appears at the outputs of adder n+8 (n+9, n+10) proportional to the sum of the injected currents, since the electric motors switch to the generator mode. The voltage is converted in subtractor n+11 (n+12, n+13) and amplifier n+14 (n+15, n+16) is applied to subtractor n+17 (n+18, n+19) and adder n+20 (n+21, n+22). Voltage appears at their outputs; it is proportional, respectively, to the sum of and difference between the current at input n+1 and the injected currents. All comparators n+23 (n+24, n+25) and elements OR 26 signal. The current relay n+33 is in the triggered state; therefore, element AND n+30 actuates, but elements AND n+27 does not. As a result, tripping signals from the outputs of actuators n+28 and n+31 are sent to breakers n+29 and n+32 of feeders of consumers with high-power electric motors and of input n + 1.

Under external SCs, the currents in the feeders are directed to the busbars, and at the input, from them. Therefore, condition (1) is not fulfilled, and the protection does not operate.

To implement the suggested principles of operation, not only current transformers can be used as sources of information about the current in feeders, but also Rogowski coils or induction coils. These protections ensure fulfillment of both conditions to achieve the maximum effect from the majorization principle.

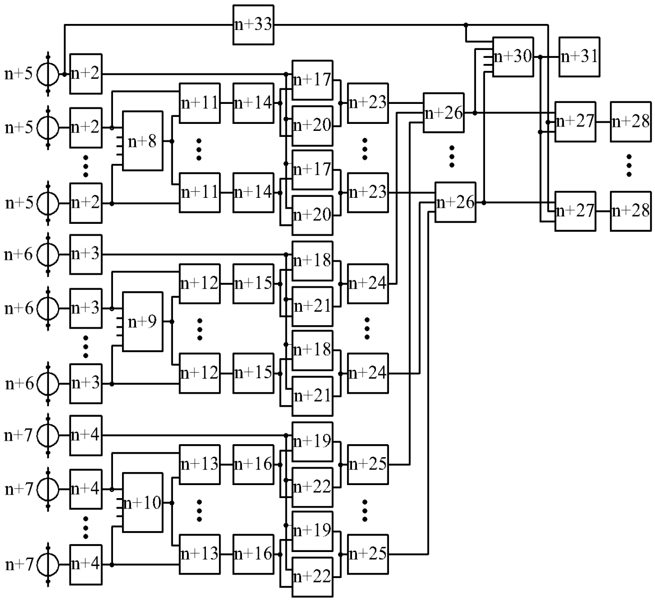

Figure 3. Block-diagram of the centralized protection of busbars and feeders connected to them.

3. Centralized reed switch protection

Protections which allow duplicating current transformers can be designed on the basis of reed switches. For example, the principles of design [9–13] and a number of protection systems [14–28], including centralized [29], have already been developed. In this work, we suggest a centralized reed switch busbar protection. In contrast to commonly used protections, it includes test fault diagnostics, which additionally increases the reliability of the relay protection system.

The protection is based on the device suggested in [29]. It includes polarized reed switches 1 with contacts 2 and 3; elements OR 4 and 6, OR NOT 5 and 7, and AND 8 and 9; actuator 10; control windings 11 worn on reed switches 1; buttons 12 and 13; intermediate relay 14 with contacts 15 and 16; intermediate relays 17 and 20 with contacts 18 and 19, 21 and 22, and signal lamp 23. Reed switches are fixed in the magnetic field of conductors of the same phases of different feeders so as contacts 2 are closed in one of the current half-waves, for example, positive, and contacts 3, in another half-wave. Relay 20 should have the same number of normally open and break contacts and of the reed switches. If there are no such intermediate relays, then several relays are used.

The protection system works as follows. Under the load and an external SC, the current polarity in at least one feeder in any half-period does not coincide with the polarity of the currents in other feeders. When contact 2 of the reed switch fixed near the busbars of this feeder is closed, the contacts of three reed switches fixed near the same phases of other feeders are closed. When its contact 3 is closed in the second half-period, contacts 2 of the other reed switches are closed. As a result, there is a reed switch with closed contact 2 and a reed switch with closed contact 3 at any time point. Therefore, there are no signals at the outputs of elements 5 and 7 and, hence, there are no signals at the outputs of elements 8 and 9. Actuator 10 does not operate.

Under a short circuit at busbars 28, only contacts 2 are closed at all feeders in one half-period (currents in all feeders are in phase), and contacts 3, in another half-period. When contacts 2 are closed and contacts 3 are open, signals are sent to the outputs of elements 4 and 7. Actuator 10 is triggered and sends tripping signals to breakers 24–27. When contacts 3 are closed and contacts 2 are open, the signals are sent at the outputs of elements 5 and 6.

Test diagnostics of the protection is performed when pressing button 12. A direct current is supplied to control windings 11 of reed switch 1; it produces a magnetic field with the induction several times higher than the induction of the field produced by the load currents. This is necessary for the reed switch contacts to remain close when the load current changes from one half-wave to another. In this case, only one contact 2 is closed for all reed switches 1. Relay 14 simultaneously actuates, breaks the electrical installation breaker circuit via contact 15, and connects the output of actuator 10 to signal lamp 23 through contact 16. Since contact 3 of each reed switch is open, then a start signal is sent to lamp 23 through elements 4 and 7 and actuator 10; the lighted lamp informs about the normal operation of the elements considered. Button 12 is released. Then button 13 is pressed, and relays 17 and 20 are supplied. Relay 17 functions like relay 14 (described above). Relay 20 actuates and opens contacts 22 and closes contacts 21. As a result, signals from all reed switches 1 are not sent to the inputs of element 5; signals are sent to the inputs of element 6 through contacts 19 simulating the closure of contacts 3. If elements 5, 6, and 9 normally operate, then actuator 10 signals to lamp 23. The protection works properly, and button 13 is released.

One of the designs presented in [30–33] can be used to mount reed switches near the conductors of the feeder phases. Note that these designs can be used for fastening induction coils when protections are constructed on their basis.

4. Conclusions

Three centralized protections are suggested for clearance of short circuits to busbars and outgoing cables without time delay. The first two protections can be implemented with current transformers or without them. In the latter case, they receive information from Rogowski coils and induction coils. The third protection is constructed on the basis of reed switches. The use of magnetically sensitive elements instead of current transformers allows achievement of the maximal effect from the application of the majorization principle. The reed switch protection ensures an additional enhancement of the reliability of the relay protection system due to the built-in test fault diagnostics.

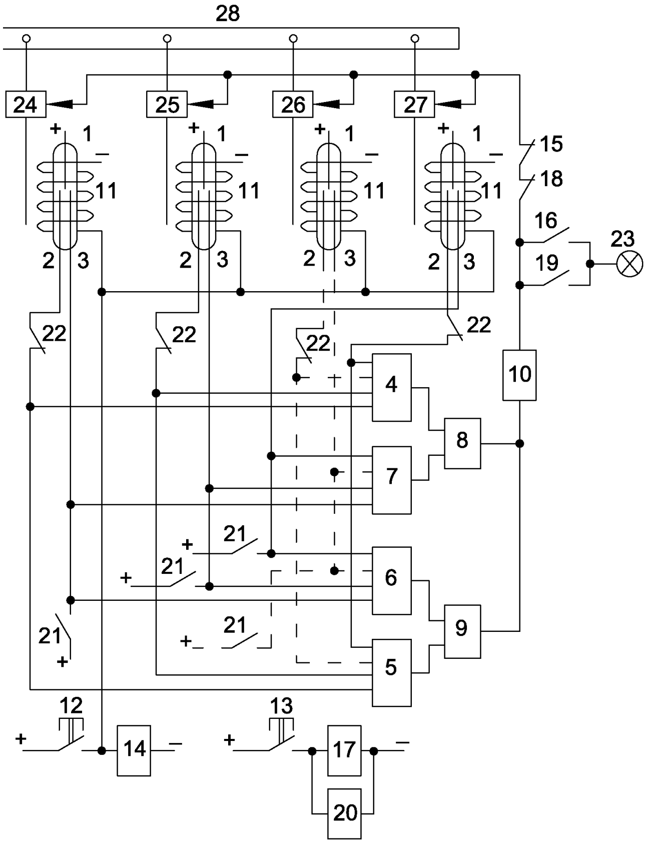

Figure 4. Block-diagram of the centralized reed switch busbar protection.

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Acknowledgment

The paper was prepared with the support of the World Bank (grant No. 00722 “Commercialization of the Manufacture of Structures for Fastening the Reed Switches of Current Protection of Open and Closed Current Conductors”) and the Ministry of Education and Science of the Republic of Kazakhstan (grant No.AP05131351 “Creation of a Globally Competitive Resource-Saving Relay Protection of Power Supply Systems”).