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BEHAVIOUR OF THE BUSBARS DIFFERENTIAL PROTECTION UNDER TRANSIENT CONDITIONS

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Pentru sistemele de bare colectoare, cea mai utilizată protecție este protecția diferențială. Această protecție poate fi influențată de regimurile tranzitorii, pentru că transformatoarele de curent pot fi afectate de fenomenul de saturație.

Lucrarea se bazează pe prezentarea în viziunea autorului a aspectelor principale legate de protecția diferențială de bare în legătură cu modul de comportare a transformatoarelor de current în regimuri tranzitorii. De asemenea, contribuția personală a autorului constă în rezultatele unor analize efectuate cu privire la comportarea în regim tranzitoriu a transformatoarelor de curent şi a protecției de bare.

The most common protection of the busbars is the differential protection. This protection can be influenced by the transient regimes so that, considering the high level of currents, current transformers may be affected by the phenomenon of saturation.

This paper is based on the presentation in author's view of the main aspects related to the busbar protection in connection with the behaviour of the current transformer under transient conditions. The personal contribution of the author consists also of the results of an analysis performed by the author regarding the behaviour of the current transformers and the busbar protection during transients.

Keywords: differential protection, current transformer, transient regime

1. Introduction

In power transmission and distribution systems, the central distribution point for many feeders is the busbars system. A fault occurring on the busbars could be very dangerous because the fault current has very high level and the damages could affect all feeders and the result is a supply interruption. That's why the busbars system is a special one and needs a special attention from protection point of view.

Busbar protection must comply with the performance requirements of fast operating time for all busbar faults, security for external faults with heavy current transformer (CT) saturation, security during normal switching conditions, security with subsidence current present after clearing an external fault, and minimum delay for evolving faults [1], [2].

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Busbars have often been left without specific protection because they could be protected by the feeder's protection (the primary or the backup protection). Another reason consists of the idea that a miss-operation of busbars protection might cause instability of the power system which, if it is not quickly cleared, would cause more losses than the possible busbars faults. For instance, in case of a distance protection foreseen for all feeders, the busbars will be protected in its second zone. This means that a busbar fault will be cleared relatively slowly, with consequences on the rest of the system.

In order to maintain the stability of the power system, the high-speed fault clearance is needed and the busbar protection is required. Another reason which sustains the high speed operation of the busbars protection is related to the current transformers.

Due to the possible high level currents, the current transformers used to measure the current could be affected by the saturation phenomena [3]. A fast relay will allow the tripping decision before this happens.

The most common bus protection is based on the current differential approach. All connections (or only the connections to power sources) to the busbars are monitored through current transformers to detect unbalance. Under normal conditions, there is a balance between incoming and outgoing currents. If an internal bus fault occurs, this balance is disturbed and a tripping decision is made by the differential protection and the bus is isolated from the rest of the system. The proper behaviour of the differential protection depends on the behaviour of the currents transformers in case of transients conditions of a short circuit [4]. If a current transformer gets saturated, the protection can not make the difference between an internal and an external fault. In order to solve the problem of CT saturation, there are used different types of differential principle based on the differential and the restraint criteria.

2. Influence of current transformers saturation on the busbar differential protection

Busbars differential protections are designed taking into consideration two situations caused by fault current or abnormal regimes, respectively [2], [5]:

-to act fast and secure for all faults on the busbars, this condition is reflected by sensitivity coefficient;

-not act for an external fault or an overcurrent, this condition is reflected by the stability coefficient.

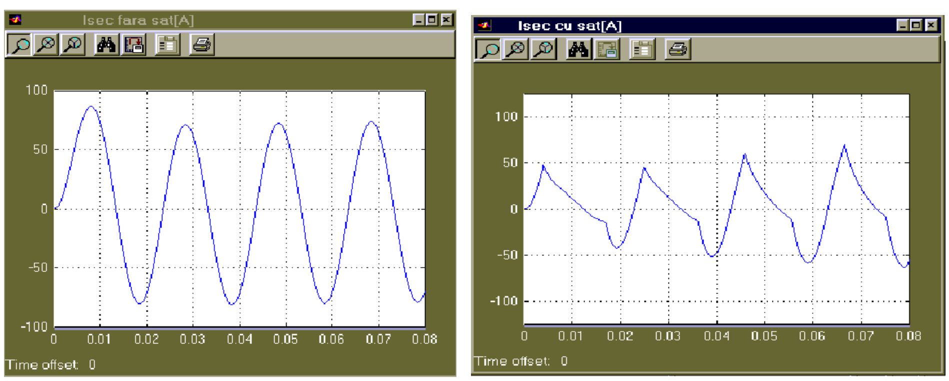
The external faults close to the busbars may have adverse consequences on the operation of current transformer-busbar differential protection ensemble due to saturation of the current transformers.

Current transformer saturation depends on many factors among which the most important are [6], [7]:
-time-constant of the system (T1) seen at the CT installation point;
-current value;
-time-constant of the CT secondary circuit (T2);
-CT secondary burden;
-constructive characteristics of CT.

The errors as result of current transformer saturation are extremely high and they can not be directly approximated by simple methods.

For these reasons it is important to know the processes in detail, so that it can be approximated as real as possible and the additional errors and stability coefficient can be correctly determined and undesired operation eliminated.

The transient performance of a transformer can be studied by modeling and therefore, the right transformer can be chosen in order to have acceptable errors [8]. For instance, the behaviour of a transformer in case of a large primary current has been analyzed and the results are the following (Fig.1):

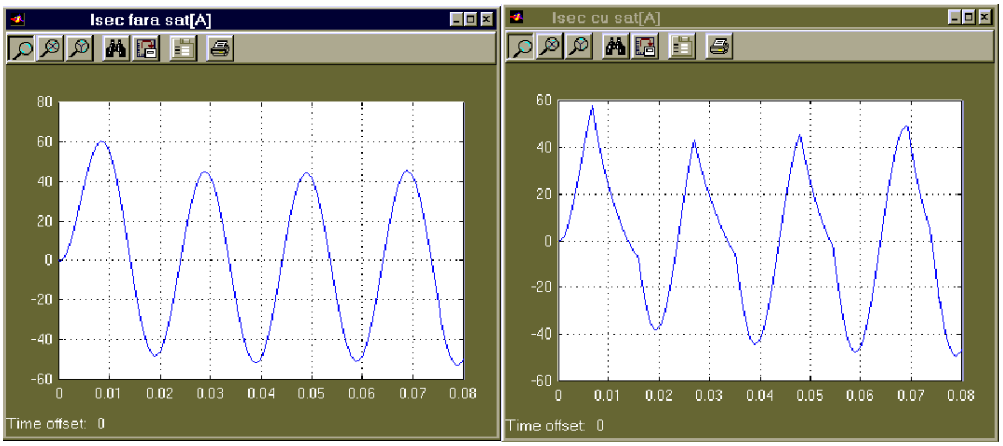


a) b)

Fig. 1 – Secondary current for a CT without (a) and with (b) saturation, depends on the value of the primary current and the magnetizing characteristic

For a transformer with a proper magnetizing characteristic (with a high knee point) the secondary current is represented in the first pictures. For a transformer with a low knee point on the magnetizing characteristic, for the same current on primary side, the secondary current looks like in the second picture.

Another factor of influence for the transient performance of a CT is the burden. Fig. 2 shows us the secondary current without (a) and with (b) saturation depends on the burden: the first picture contains a transformer with a burden under rated value, while the second refers to a transformer with a burden higher than the rated one.



a) b)

Fig. 2 – Secondary current for a CT without and with saturation, depending on the value of the burden and the magnetizing characteristic

All above pictures have been obtained by simulation and mathematical modeling.

Fig. 3 presents a simplified equivalent circuit consisting of two lines connected to the protected busbar:

- equivalent line, which is equivalent to a source that supplies the total short circuit current provided with a equivalent current transformer (TCE). TCE works unsaturated under normal conditions, because in fact, this transformer is a sum of CTs, each of them covered by a fraction of the total current, corresponding to the input element where it is mounted;

-line on which the short circuit occurs near busbars, equipped with a current transformer (TCL), which could have the smaller ratio (the worst case). Unlike TCE, through this transformer, the whole fault current will pass and therefore it has conditions to get saturated.

The total current flowing through the transformer TCL, in case of a short circuit at point K (outside the protected area), is [6]

$$i = I\left[\cos\left(\omega t + \varphi\right) - \cos\varphi e^{-\frac{t}{T}}\right] \qquad (1)$$

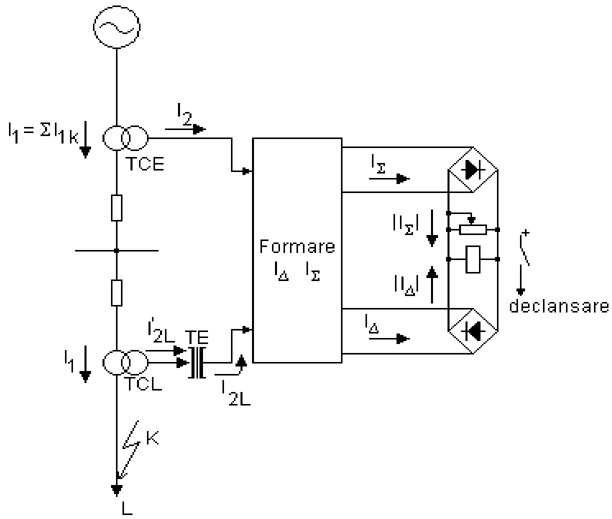


Fig. 3: Simplified diagram of the bar differential protection

In Fig. 4 the variation in time of such current and its components is presented.

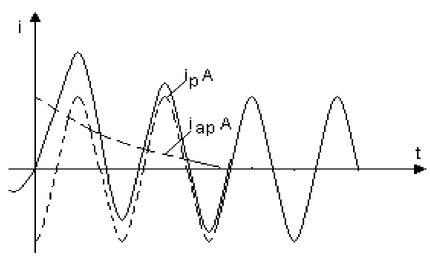


Fig 4: Variation of short circuit current

The component $i_{p\ A}$ is a stationary current (a sine wave), while the $i_{ap\ A}$ component is a non sine wave which exponentially decreases with the time constant T corresponding to the circuit and which seriously distorts the stationary during the transient regime.

$$i = i_l + i_p \tag{2}$$

The component ip is given by the following formula:

$$i_p = I\cos(\omega t + \varphi) \tag{3}$$

Where I is the amplitude of a.c.

$$I = \frac{E}{\sqrt{R^2 + (\omega L)^2}} \tag{4}$$

And the phase shift angle between current and voltage is determined by:

$$tg(\varphi - \psi) = -\frac{\omega L}{R} \tag{5}$$

The second component of short circuit current (i_l) has the following expression

$$i_l = Ke^{-\frac{R}{L}t} \tag{6}$$

The maximum possible value of il corresponds to the case when $\varphi = 0$, according to equation (1), when combined current value is:

$$i = I\left[\cos \omega t - e^{-\frac{t}{T}}\right] \tag{7}$$

This value becomes maximum after about half a period, and for t = π ω it has a value of

$$i = -I\left(1 + e^{-\pi\frac{R}{\omega L}}\right) \tag{8}$$

In a three-phase system, in case of a short circuit (3-phase), only one phase can satisfy condition (7), the other two phases have smaller aperiodic components [2] (Fig. 5).

The degree of distortion depends on the initial phase angle φ of stationary current. If this angle is 0° or 180°, the il component of the current equals the stationary current amplitude.

Due to the high value of the total current, TCL current transformer can get saturated and its errors increase significantly. From this perspective, two regions can be defined:

-unsaturated core and the errors are included in the manufacturer data;

-saturated core, and errors can not be predicted, errors exceeding design conditions accepted by the CT's design conditions.

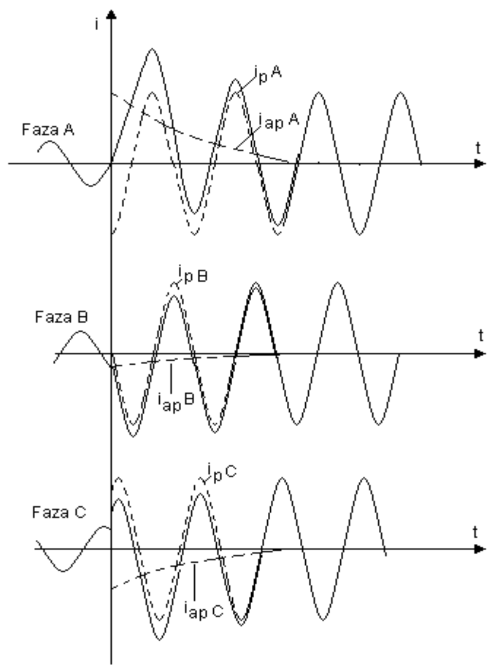


Fig 5: The three phase currents under short circuit conditions

The core saturates once the current exceeds the maximum value of saturation knee point. This regime can be achieved regardless of this non-symmetrical component, but usually the aperiodic component increases the saturation. Under saturation conditions, the secondary current is correctly reproduced until the phenomenon of saturation appears, and the wave distortion is even greater as the saturation is more pronounced.

Fig 6 is an overview of the symmetrical component without the aperiodic, but with a lower saturation regime (Fig. 6a) and a more pronounced saturation regime (Fig 6b).

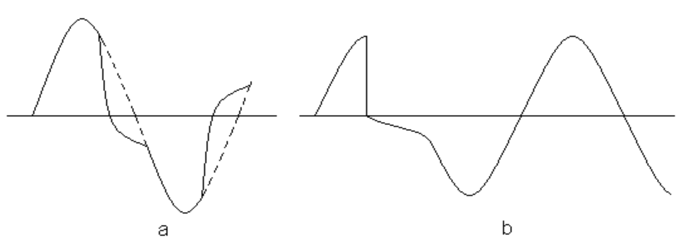


Fig 6: Modes of saturation of current transformers

As mentioned, the aperiodic component, especially when it has maximum value, leads to an increase of saturation (Fig 7). It should be mentioned that besides aperiodic component, in one sense or another, the residual flux remaining in the TC core is involved. The most unfavorable situation occurs when the residual flux and the aperiodic component have the same direction. As a result of some analysis, this flux might be possible in 50% of the cases.

No matter how the saturation is reached, the occurrence of this regime seriously affects secondary fault current values on the secondary side by large errors that result. These errors can not be appreciated and they have an important influence on the behaviour of the protective equipment.

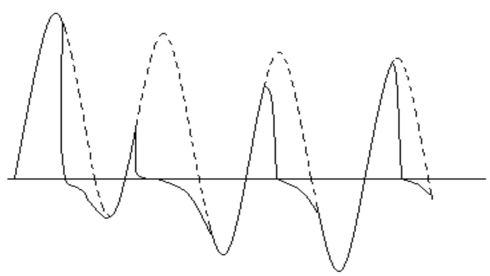


Fig 7: Current Transformer with a strong saturation

In order to avoid such a situation, it is mandatory that the saturation to be not reached at the peak value of the current given by adding the two components. This can be achieved through the oversizing of the current transformer and other constructive measures or by adapting the burdens and secondary time constants. In case of an external fault, the busbar differential protection must not operate, and under these conditions, the coefficient of stability for the differential protection can be calculated as follows [8]

$$K_V = \frac{I_{dez.} - I_0}{I_{fr.}} = \frac{I_\Delta - I_0}{I_\Sigma} \quad (9)$$

Where

-I_0 is the current in the absence of restraint action

-$I_{dez} = I_\Delta$ is the differential current;

-$I_{fr} = I_\Sigma$ is the restraint current.

In relation (10), the terms are R.M.S. values calculated from two similar currents. The first, a sine-wave current (i_2) that represents the total short circuit current from all sources connected to the same busbar as sum of the currents originated from current transformers not saturating and the second, a non-sinusoidal (i_{2L}), which represents the total current short-circuit of the faulty line, but obtained through a current transformer that saturates. In Fig 8 are represented these trends.

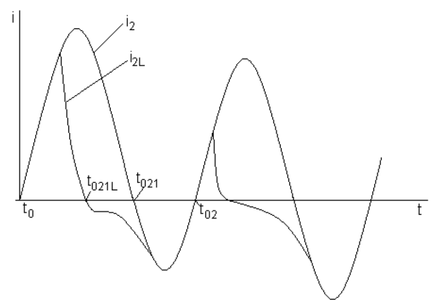


Fig 8: Currents "used" by differential protection

The terms of stability coefficient have the following form:

$$I_{dez.} = I_{\Delta} = \left[\int_{t_0}^{t_{021}} i_2.dt + \left|\int_{t_{021}}^{t_{02}} i_2.dt\right|\right] - \left[\int_{t_0}^{t_{021L}} i_{2L}.dt + \left|\int_{t_{021L}}^{t_{02}} i_{2L}.dt\right|\right] \quad (10)$$

$$I_{fr.} = I_{\Sigma} = \left[\int_{t_0}^{t_{021}} i_2.dt + \left|\int_{t_{021}}^{t_{02}} i_2.dt\right|\right] + \left[\int_{t_0}^{t_{021L}} i_{2L}.dt + \left|\int_{t_{021L}}^{t_{02}} i_{2L}.dt\right|\right] \quad (11)$$

and correspond to transient short-circuit current shown in Fig. 7.
We can write (Fig.9)

$$I_{dez.} = I_{\Delta} = \left[A_{1n}^{+} + A_{1n}^{-}\right] - \left[A_{2n}^{+} + A_{2n}^{-}\right] \quad (12)$$

and similar

$$I_{fr} = I_{\Sigma} = \left[A_{1n}^{+} + A_{1n}^{-}\right] + \left[A_{2n}^{+} + A_{2n}^{-}\right] \quad (13)$$

Relation (10) can be approximated by

$$K_V = \frac{\left\lfloor A_{1n}^{+} + A_{1n}^{-} \right\rfloor - \left\lfloor A_{2n}^{+} + A_{2n}^{-} \right\rfloor}{\left\lfloor A_{1n}^{+} + A_{1n}^{-} \right\rfloor + \left\lfloor A_{2n}^{+} + A_{2n}^{-} \right\rfloor} \quad (14)$$

An analysis of relations (12), (13) and (14) leads to the following conclusions:

-unbalance current is the differential current, based on which the protection operates, and it has high values, higher than the ones when the saturation does not occur;

-restraint current, which counteracts the protection operating, has lower values than the case where no saturation occurs;

-under these conditions, the factor of stability can have higher values than the tripping characteristic. It can be estimated that for an error of 50%, the operating slope is almost 0.3 (for tripping the operating has to be higher than the setting value for the slope). In case the current transformer TCL doesn't get saturated, the coefficient of stability has small values due to the normal errors.

A correct evaluation of the coefficient of stability requires accurate assessment of i_{2L} current with actual errors introduced by TCL saturation.

In the first periods, when the I_{2L} current is saturated, errors are big and the stability coefficient has no the initial value, but is varying over time.

Modern busbar differential protections based on microprocessors technology use the same principle, the comparison of the differential and restraint current.

Unlike traditional protections, these protections achieve this criteria and additional features that give them a safer operation, of which we mention [9]:
-besides follow-on stabilization coefficient, fault location (inside or outside the protected area) is also achieved by measuring the phase of all currents: a fault inside the protected area will indicate the sense of all currents, so their phases relative to a reference , towards the bar, while an external fault for one of the currents indicates a phase shift of 180°;
- information processing after filtering and numerical analog conversion;
- recovery of the signal affected by saturation. Taking into account that on the first part, the CT reproduces the right form of the signal, the most widely used principle is based on measuring of the current slope, and then by extrapolation, the maximum value of defect size could be approximated.

Although numerical protective equipments use as their principle of operation, methods for increasing the security of differential protection, wrong operations were recorded for this category of equipments. The causes are related to the system consisting of current transformers and protective equipment.

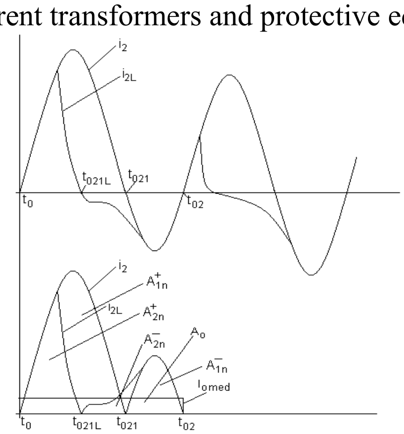


Fig 9: R.M.S. values of the short-circuit currents

Considering these aspects, some measures are necessary in order to optimize the behavior of the busbars protections during transients. These measures have two aspects [10], [11]:
-measures related to the algorithm embedded in the principle of protection;
-measures related to the improving behavior of current transformers during transients.

Modern digital relays use innovative algorithms to fulfill busbar protection requirements of fast operating times for all busbar faults, security for external faults with heavy current-transformer (CT) saturation, and minimum delay for evolving faults.

The differential characteristic can correctly restrain for many external faults when CT saturation occurs. However, the differential element itself is not enough to ensure correct restraint to external faults when severe CT saturation occurs. The differential protection is always supervised by a directional element. The directional element compares the angle of the measured fault currents. If at least one current is away from the sum of the remaining currents by an angle greater than 90°, the fault is considered an external fault. If all fault currents are within 90° of each other, the fault is considered internal.

All performances achieved in the new protective equipment can not be used if the transformers do not provide the right measured values.

The measures for improving the response of the current transformers refer to the oversizing of the magnetic circuit, secondary burden and time constant adaptation in order to achieve lower secondary errors, etc.

A solution for the future could be also the changing of the conventional current transformers with current transducers (sensors) that work on different principles (Rogowski coil, optical sensors, etc.) [12]. These transducers provide the signal, usually as a digital signal, transmitted by optical fiber. In this way, the security of busbar differential protection is increased.

3. Conclusion

In this paper the author demonstrated that the busbar differential protection can be influenced by the transient regimes, because, taking into account that the high level of currents, current transformers may be affected by the phenomenon of saturation.

The transient performance of a transformer was studied by the author using the modeling technique and therefore, based on the result of this study, the right transformer can be chosen in order to have acceptable errors.

No matter how the saturation is reached, the occurrence of this regime seriously affects secondary fault current values on the secondary side by large errors that result. These errors can not be appreciated and they have an important influence on the behaviour of the protective equipment.

In this paper the author made an original presentation of the main aspects related to the busbar protection in connection with the behaviour of the current transformer under transient conditions. This paper consists also of a part of the results from an analysis performed by the author regarding the behaviour of the CTs and the busbar protection during transient regimes.

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