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EFFECTS OF WAVEFORM DISTORTION DUE TO HARMONICS IN POWER SYSTEM PROTECTION

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ABSTRACT— Nowadays, electrical power system are subjected to waveform distortion caused by power electronics devices. This work analyses how overcurrent relays, installed in a typical industrial power system, respond to the harmonic waveform distortion caused by such devices.

KEYWORDS: Power Quality, harmonics, protection systems, computer simulation.

I. INTRODUCTION

The protection of power systems is an art. Its main goal is to protect the power system devices against the effects of the faults by the outage of the affected portion. We say that the design of the protection system is an art because it must combine speed and reliability at a minimum cost.
To avoid damage to persons and equipments the protection system must clear the fault at the first sign of abnormality by disconnecting the affected equipment from the system. To be considered reliable, a system must have all its components working well; the fail of one component will cause the fail of the whole system. In the protection system, the relay is the component that has two failure modes: they can fail by not operating when they are needed to or operate when they are not expected to [1].
On the other hand actual power systems are being subjected to many changes. These changes range from deregulation of the power markets to modifications in the characteristics of the loads supplied by them. Harmonics are included in these changes. In the past their influence in power system operation could be neglected, but today the growth of use of power electronic devices by consumers caused an increase in the harmonic content of the voltage and current waveforms [2].
As the components of the protection system are subjected to the waveforms that are distorted by the harmonics, we expect them to have troubles in their operation, for example: the electromechanical relays that make part of the protection system are designed to operate with perfect sine wave at the fundamental frequency (60 Hz) and they should respond to the true RMS value of voltage and current waveforms [3].
The harmonics alter the RMS value and the relays have to discriminate normal and abnormal situations of the parameters by the assumption that they are in the limits required by the good power quality, so poor power quality, as harmonics for example, has bad influence over the protection system reliability [4].
This work investigates the influence of power system harmonics in the protection system components. In section II we will describe how we model a CT installed on a feeder which has a non-linear load, in section III we will discuss the effects of harmonics in the protection systems, section IV describes the simulation and its results.

II. MODELLING A CT UNDER A NON LINEAR LOAD CONDITION

Non-linear loads that are present in distribution systems demand electrical power. This power has three components: active power measured in *kW*, reactive power measured in *var* and the distortion power, which is measured in *var* too. The active and reactive components are due to the generation system and the distortion power is produced by non-linear loads [5].
If one has a sinusoidal voltage source feeding a non-linear load there will be a current flowing from the load to the system, which will cause a distortion on the voltage waveform. Figure 1 shows a non-linear load being fed by a sinusoidal voltage source. In the figure we notice that a voltage will appear at load terminals, to this voltage we call *transmitted voltage* $v_t(t)$, We can split this voltage in two components: one called *incident voltage* $v_i(t)$ and the called *reflected voltage* $v_r(t)$. So we can express the *transmitted*

$$v_t(t) = v_i(t) + v_r(t) \tag{1}$$

voltage as shown in eq. (1).
where :

$$v_i(t) = \sqrt{2} \cdot V_1 \operatorname{sen}(\omega \cdot t + \alpha_1)$$

$$v_r(t) = \sum_{n=1}^{\infty} V_n \operatorname{sen}(n \cdot \omega \cdot t + \alpha_n)$$

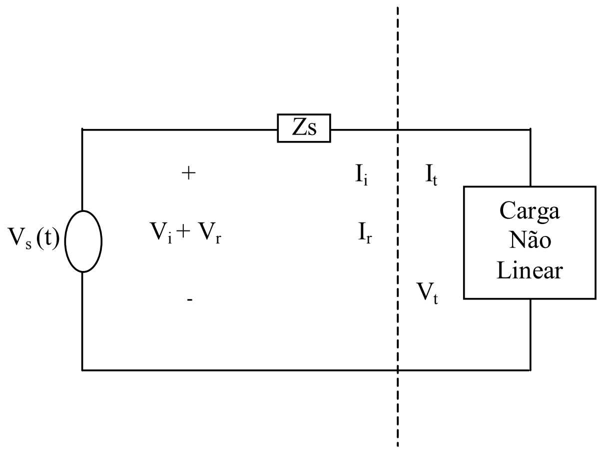

Fig 1. Sinusoidal voltage source and harmonic load

In the eq. 1 n represents the harmonic order, Vn represents the RMS value of nth harmonic voltage and α_n is the angle between the nth harmonic voltage and the nth harmonic current. Similarly the load current can be divided in two components as the voltage is. So we will have an incident current and a reflected current. We can express them as in eq.(2):

$$
\begin{aligned}
i_t(t) &= i_i(t) + i_r(t) \\
i_i(t) &= \sqrt{2} \cdot I_1 \operatorname{sen}(\omega \cdot t + \beta_1) \\
i_r(t) &= \sqrt{2} \cdot \sum_{n=1}^{\infty} I_n \operatorname{sen}(n \cdot \omega \cdot t + \beta_n)
\end{aligned}
\tag{2}
$$

Suppose now that the circuit in figure 1 represents a distribution feeder coming out of an industrial substation and feeding the non-linear load. This feeder will have a protection net composed of a circuit breaker, the current transformer and the relay. The current transformer equivalent circuit is shown in figure 2.

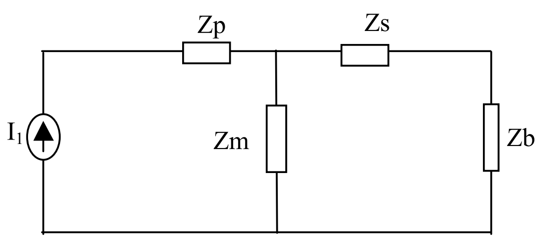

Fig. 2 – Current transformer equivalent circuit

We can model a current transformer as a constant current source in parallel with the burden and magnetizing impedances [7]. So if this CT is installed in a feeder with a non-linear load on it, we can model it as many current sources as the harmonic currents present in the system. Figure 3 shows how the CT equivalent circuit will be.

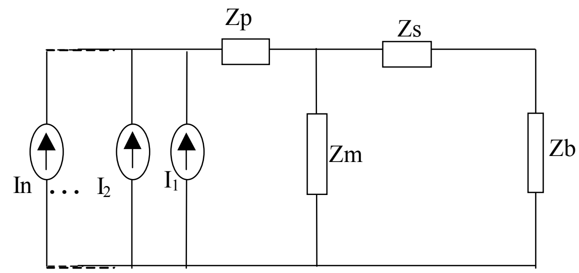

Fig 3 – CT equivalent circuit under non-linear load conditions.

III. HARMONIC DISTORTIONS EFFECTS IN POWER SYSTEM PROTECTION

According to C.F. Henville in [8] the power system protection is intimately close to power quality. The author justifies his statement by saying that the power system protection eliminates the faulty circuits from the system while the power quality deals with the reliable delivering of the electrical energy within certain established limits. He also states that the short circuits degrade the voltage waveform causing sags and that the relays must distinguish between normal and abnormal parameters and the problems in power quality such as harmonic distortions in current waveform can influence in their decision, because the set up of the relays are based on parameters that lie inside the good quality (no harmonic distortion) boundaries of the energy supply.

The protection devices will respond to harmonic distortion in several ways. In some cases the harmonic distortion is inherent to the values being measured, as in the rectifying bridge present in many electrical devices. These loads generate 3rd harmonic currents and in a commercial building one can find a lot of these loads (faxes machines, copiers, computers, etc) that together will generate a significant 3rd harmonic current. We know that 3rd harmonic currents have characteristics of zero sequence currents [9] and they will sum in the neutral conductor, if there is a 51N relay installed it could operate due to the third harmonic current, since it is normally adjusted to operate with fundamental currents that are lower than the third harmonic currents. This situation is good if we consider that the relay is protecting the neutral conductor against overload, but if we remember that the 51N relay is expected to operate for short circuits, this situation may cause some problems for the maintenance crew, that will be looking for a short circuit that doesn't exist. The down time could be grater then it should be if the relay hasn't operated or simply alarmed an overload caused by 3rd harmonic currents.

Another situation is that caused by harmonics that are present in phase currents is that they tend to be absorbed by capacitors and cause overloads, if these capacitors are protected by overcurrent relays that are insensible to harmonics there is a great risk of damage, but if the relays are capable of detecting these currents they can avoid it by disconnecting the capacitors as soon as harmonic currents are detected.

The CT saturation is another item to be considered. When subjected to high currents, such as those present at short circuits, the CT tends to saturate and their response to the primary current does not reflect the reality. This is showed in figure 4.

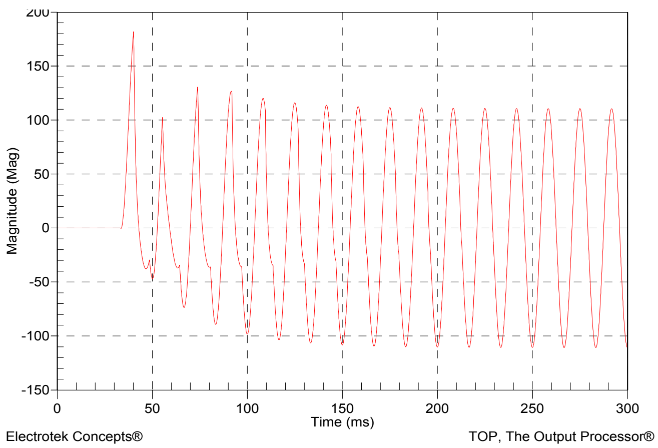

Fig. 4 – Saturation of the secondary current of a CT.

In this figure we can see that in the first three cycles the current waveform is distorted by the CT saturation.

IV. TESTS AND RESULTS

The simulation was conducted over CT and relays models extracted from bibliography. The models were applied in the industrial system showed in figure 5.

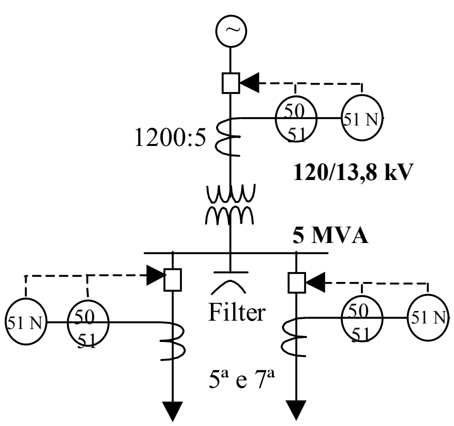

Fig. 5 – One line diagram of the test system

The objective of the simulations was to observe how the secondary current of the CT develops under harmonic distortion and their influence on the relays.

The one line diagram in figure 5 shows a typical industrial system. It has a main substation that receives the energy from the utility in 44 kV and distributes it in 13.8 kV to be used by the industrial processes. The substation feeds two loads: a linear load, composed by an aggregate of induction motors and a rectifying station that feeds a process that uses direct current. The system has a 5th and 7th harmonic filter to mitigate the influence of these harmonic components. The protection system is composed by three circuit breakers each of which has its CT and relays. The relays are one 50/51 overcurrent and one 51N to protect the neutral against overcurrents.

The CT was modeled using the procedure proposed in [6] and was simulated in the ATP program using the saturable transformer component shown in figure 6.

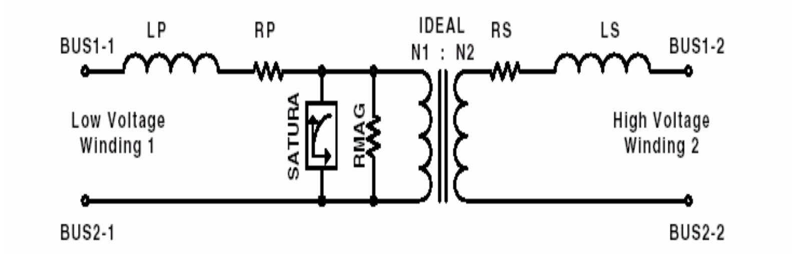

Fig. 6 – ATP saturable transformer component

The simulation circuit in ATP has seven components: One type 14 voltage source simulating the fundamental (U), one HFS source to simulate the 5th harmonic (HFS) voltage according to the model proposed in section II, the current probe, the saturable transformer, an RLC circuit simulating the power system impedance and other for burden impedance.

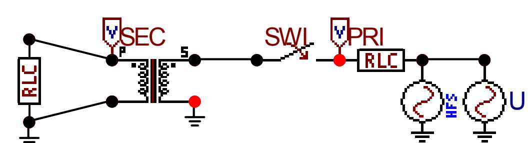

Fig. 7 – ATP simulation circuit

The relays are simulated using a MATHCAD™ algorithm as showed in [6]. There two types of relays: one using the RMS algorithm and the other is using the DFT algorithm. The RMS algorithm can be used to simulate the eletromechanical relay because these relays respond to the RMS value of the measured quantity [6].

The simulated CT is at the protection network of the main circuit breaker of the industrial system shown in fig . 5. At instant t=0.0333s a short circuit occurs and at t=0.05 the system looses the 5th harmonic filter. In the simulations the harmonic voltage ranges from 10 to 40% of the fundamental. The simulation results are showed in figures

8-10. We can see that the CT saturates and causes distortion on current waveform that appears on the secondary. In figure 4, we have the simulation result of a short circuit in the same CT without the harmonic sources and we see that although a saturation occurs it vanishes after approximately three cycles and as the harmonic content increases the saturation continues as sown in figures 8 to 10. This fact can affect the operation of the relay that receives the information from the CT. Figures 11 to 13 show the overcurrent relay response using the RMS algorithm.

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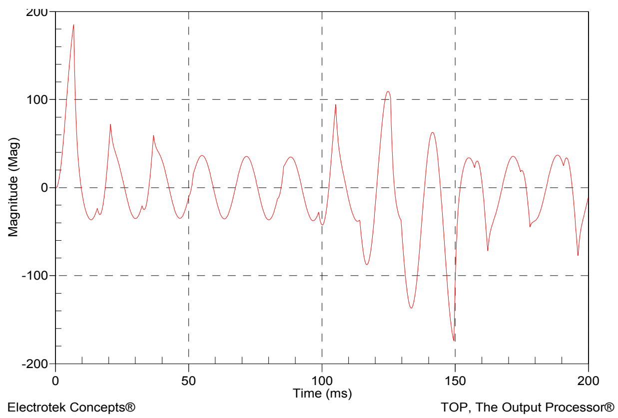

Fig. 8 – Harmonic voltage of 10% of the fundamental.

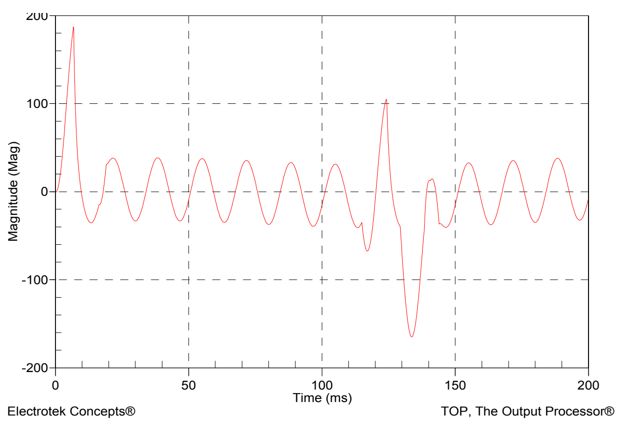

Fig. 9 – Harmonic voltage of 20% of the fundamental

In figures 11 to 13 we see the response of the overcurrent element to the distortion caused by the 5th harmonic voltage. The blue line is the real secondary current, the black line is relay set up and the red line is the current calculated by the RMS algorithm. The saturation of the CT really influences the response of the relay. In the first cycle, the calculated current passes the pick up current, but it holds just for one cycle and keeps under the pick up current for six cycles and then passes again the pick up current for one cycle and then again goes under the pick up.

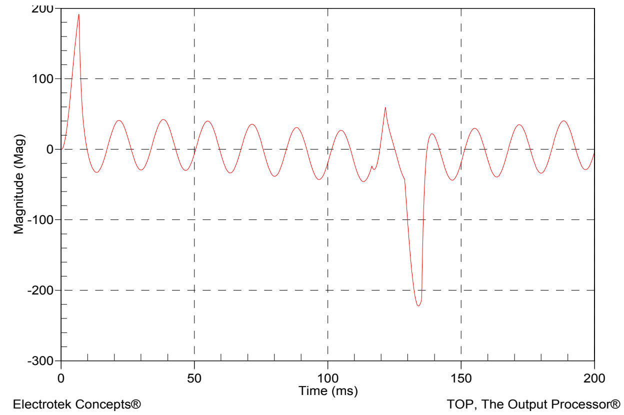

Fig. 10 – Harmonic voltage of 40% of the fundamental.

If the 50 element has a high set it could pick up and then drop out and then just after six cycles we would have a high current again that would pick up the relay and make it operate. As the circuit breakers have a time to open of about three cycles, the protection system would take nine cycles to eliminate the fault. This can be very dangerous because the equipments being protected would be carrying the fault current for a longer time period. For the 51 unit the situation is worse because it won't operate until the time delay is reached. In the figures above we see that the current keeps under the pick up current for six cycles and then picks up and drops out again, this can cause a fail in the coordination due to the operation of the back up protection. This is an unwanted situation because it leads to an outage of parts of system that are out of the faulty area.

To overcome this problem we can use a digital relay with an algorithm based on Fourier transform such as the DFT. Figures 14 to 16 show the response of the overcurrent element to the same defect.

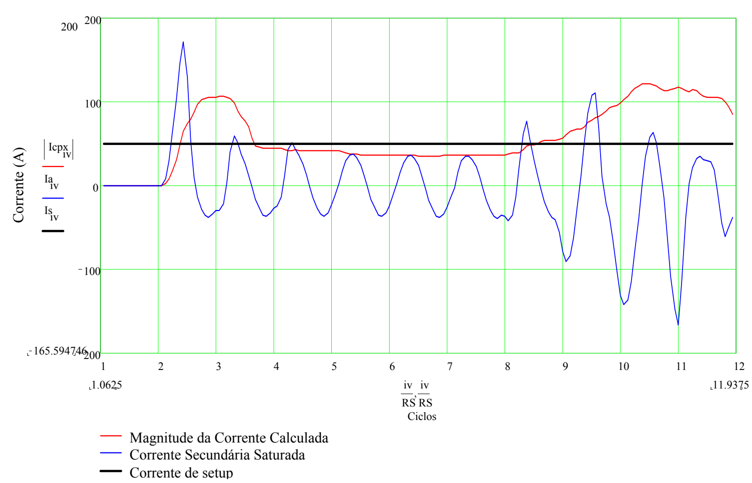

Fig. 11 – Response of an overcurrent relay to a 10% harmonic distortion using the RMS algorithm.

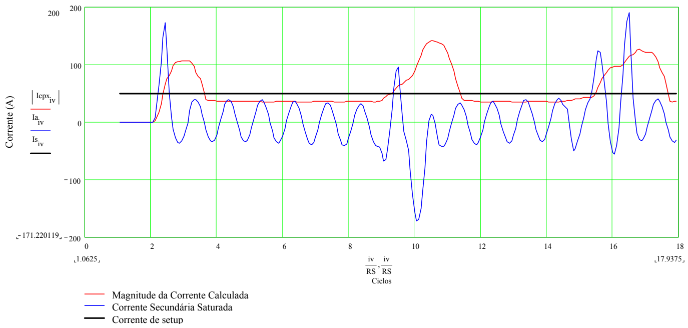

Fig. 12 – Response of an overcurrent relay to a 20% harmonic distortion using the RMS algorithm.

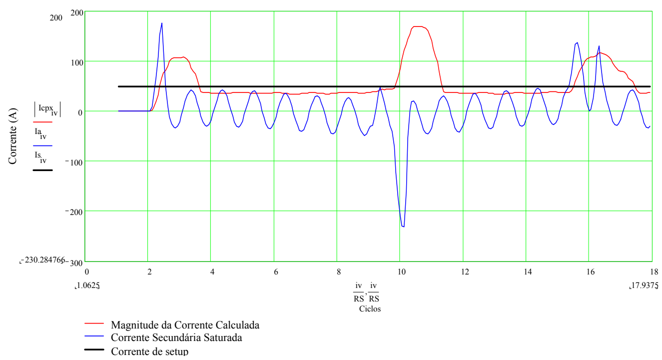

Fig. 13– Response of an overcurrent relay to a 40% harmonic distortion using the RMS algorithm.

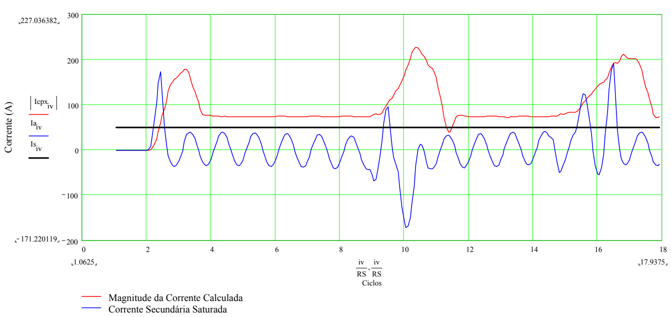

Fig. 14 - Response of an overcurrent relay to a 10% harmonic distortion using the DFT algorithm.

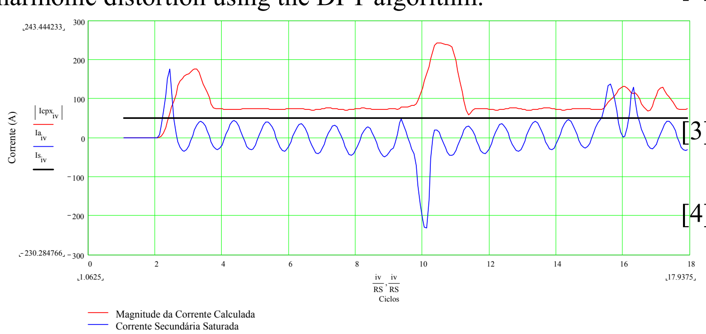

Fig. 15 - Response of an overcurrent relay to a 20% harmonic distortion using the DFT algorithm.

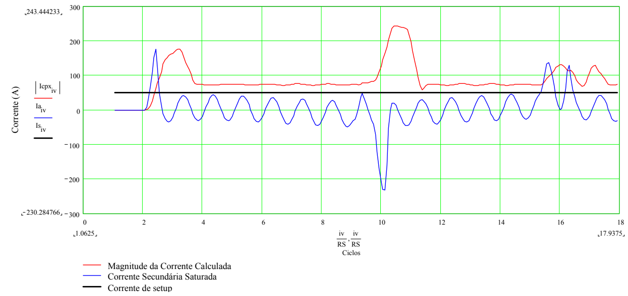

Fig. 16 - Response of an overcurrent relay to a 40% harmonic distortion using the DFT algorithm.

In the figures 14-16 we notice that the calculated current passes the pick up current and stays over it until the end of the simulation. This occurs because the DFT algorithm extracts the fundamental component from the signal supplied by the TC and then compares this value to the one adjusted on the relay. Even the 51 or the 50 units will operate without problems. We can use a subroutine in the relay algorithm to calculate the other frequency currents present in the system and generate an alarm to the operator or trip the circuit if wanted, but informing what harmonic component is responsible for the trip.

V. CONCLUSION

The paper presents a study about the influence of harmonic distortion in protection systems. The simulation results showed that there is link between power quality and good protection operation. The DFT algorithm showed to be better than the RMS algorithm when harmonic distortion is present in the power system. Another conclusion is that the simulation of the relays and CT can be used to validate the traditional protection study.

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