A FAULT PROTECTION SCHEME FOR SERIES ACTIVE POWER FILTERS

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ABSTRACT.- A protection scheme for series active power filters is presented and analyzed in this paper. The proposed scheme protects series active power filters when short-circuit faults occur in the power distribution system. The principal protection element is a varistor, which is connected in parallel to the secondary of each current transformer. The current transformers used to connect the active power filter present a low magnetic saturation characteristic increasing current ratio error when high currents circulate through the primary winding, thus generating lower secondary currents. In this way, the power dissipated by the varistors is significantly reduced. After few cycles of short-circuit currents flowing through the varistor the gating signals applied to the active power filter switches are removed and the PWM voltage-source inverter is short circuited through a couple of antiparallel thyristors.

I.- INTRODUCTION

Series active power filters have proved to be an interesting and viable solution for reactive power and current harmonic compensation [1]-[6]. With an appropriate control strategy they can compensate current harmonics and voltage unbalance in three wires and four wires power distribution systems [3]-[4]. The small power rating required by series active power filters allow their implementation with low cost PWM voltage-source inverters [4]-[6]. However, the main disadvantage of this type of compensation is that requires a special protection scheme since it cannot be protected with normal circuit breakers or power fuses. When a short-circuit occurs in the power distribution system, larger currents flow through the primary of the current transformers, generating dangerous voltages and currents in the secondary windings and damaging the PWM voltage-source inverter.

Although series active power filters have already been presented and analyzed in the technical literature [1]-[6], no information is available concerning their behavior when short-circuit currents flow through the power distribution system. Previously reported literature discusses series active power filters in terms of principles of operation and compensation characteristics. Control circuit design for normal operating conditions have also been discussed but no one has analyzed and proposed a protection scheme for this type of compensation system.

The protection scheme topology presented in this paper is shown in Figs. 1 and 2. It consists of a varistor connected in parallel to the secondary winding of each current transformer, and a couple of antiparallel thyristors. A special circuit detects the current flowing through the varistors and generates the gating signals of the antiparallel thyristors. The protection circuit of the series active power filter must protect only the PWM voltage-source inverter connected to the secondary of the current transformer and must not interfere with the protection scheme of the power distribution system. Since the primary of the active power filter transformers are connected in series to the power distribution system, they operate as current transformers, so that their secondary windings cannot operate in open circuit. For this reason, if a short-circuit is detected in the power distribution system, the PWM voltage-source inverter cannot be disconnected from the secondary of the current transformer. Therefore, the protection scheme must be able to limit the amplitude of the currents and voltages generated in the secondary circuits. This task is performed by the varistors and by the magnetic saturation characteristic of the transformers.

The main advantages of the series active power filter protection scheme proposed in this paper are the followings:

i) It is easy to implement and has a reduced cost.
ii) It offers full protection against power distribution short-circuit currents.

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iii) It does not interfere with the power distribution system.

Finally, the viability of the proposed protection scheme is verified by simulation with PSpice on a 10 kVA bread board model.

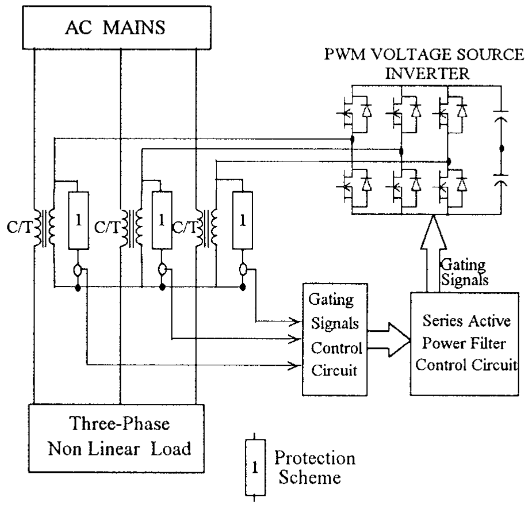

Fig. 1. The series active power filter and the proposed protection scheme.

II.- PRINCIPLES OF OPERATION

Short circuits in the power distribution system generate large currents that flow through the power lines until the circuit breaker operates clearing the fault. The total clearing time of a short circuit depends on the time delay imposed by the protection system. The clearing time cannot be instantaneous due to the operating time imposed by the overcurrent relay and by the total interruption time of the power circuit breaker. Although power system equipment, such us power transformers, cables, etc., are designed to withstand short circuit current during at least 30 cycles, the active power filter may suffer severe damage during this short time. The withstand capability of the series active power filter depends mainly on the inverter power semiconductor characteristics.

Since the most important feature of series active power filters is the small rated power required to compensate the power system, typically 10 to 15 % of the load rated apparent power, the inverter semiconductors are rated for low values of blocking voltages and continuous currents. This makes series active power filters more vulnerable to power system faults.

The block diagram of the proposed protection scheme is shown in Fig. 2.

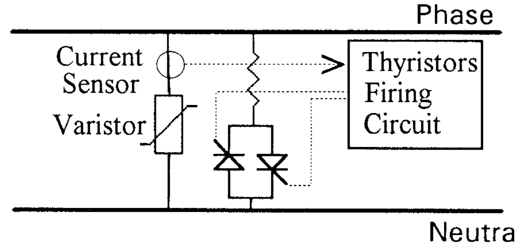

Fig. 2. The proposed series active power filter protection scheme.

When short-circuit currents circulate through the power distribution system, the low saturation characteristic of the transformers increases the current ratio error and reduces the amplitude of the secondary currents. The larger secondary voltages induced by the primary short-circuit currents are clamped by the varistors, reducing the amplitude of the PWM voltage-source inverter currents. After few cycles of duration of the short-circuit, the PWM voltage-source inverter is by-passed through a couple of antiparallel thyristors, and at the same time the gating signals applied to the PWM voltage-source inverter are removed. In this way, the PWM voltage-source inverter can be turned-off. The secondary short-circuit current will circulate through the antiparallel thyristors and the varistors until the fault is cleared by the protection equipment of the power distribution system.

The principles of operation and the effectiveness of the protection scheme are shown in Fig. 3.

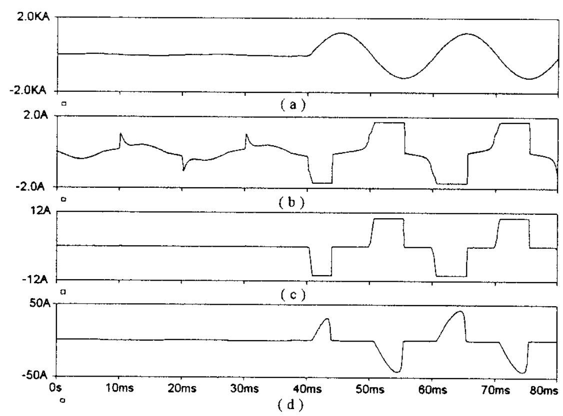

Fig. 3. Simulated waveforms of the series active power filter during a three-phase short-circuit in the power distribution system set at 40 ms. (a) Current flowing in the power distribution system. (b) Current through the secondary of the current transformer. (c) Current flowing through the varistor. (d) Current through the thyristors.

III.- DESIGN CRITERIA

3.1.- Current Transformers

Normally, current transformers (CTs) are specified for applications in protection systems or in instrumentation. The main difference between these two types of current transformers is related with the turn ratio accuracy at fault current levels. The accuracy at high overcurrent depends on the saturation characteristic of the magnetic core. Saturation results in a rapid increase of the current ratio error. Current transformers used in protection system present a ratio error below 10% at any current value from 1 to 20 times the rated current at standard burden. For current transformer used in instrumentation, saturation occurs at 5 times the rated current.

The protection scheme implemented for the series active power filter requires a current transformer with a low saturation point in order to provide an effective protection of the voltage-source inverter. For this reason, CTs used for protection or instrumentation cannot be used, unless they had been specified to operate with a low rated burden. However, since the equivalent impedance of the inverter depends on the compensation characteristics (i.e. the inverter ac output voltages and ac currents are changing continuously) it is preferable to specify a current transformer with a low saturation characteristic, that means the saturation should start at 2 to 3 times the rated current.

The hysteresis curves of the iron core used for the construction of the current transformer are shown in Figs. 4 and 5. Figure 4 shows the hysteresis curve for rated operating conditions and Fig. 5 illustrates how the magnetic characteristic of the same CT changes due to the saturation effect.

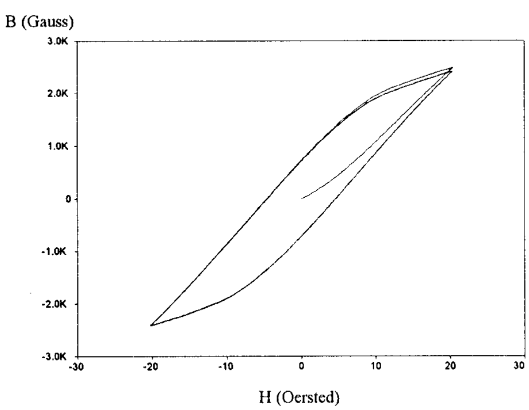

Fig. 4. Hysteresis curve for rated operating conditions.

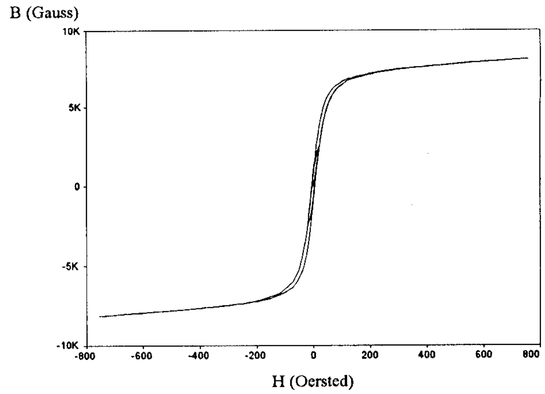

Fig. 5. Hysteresis curve for short circuits.

Due to the saturation of the CTs the secondary currents are significantly distorted. This affects the compensation characteristic of the active power filter. However, since the system is operating under fault operating conditions, compensation is not required. The effect of the saturation in the waveform distortion of the secondary current is shown in Figs. 6 and 7. In Fig. 6 the primary and secondary currents under short circuit operating condition are shown, for CTs with a high saturation point. In Fig. 7 the same waveforms are shown but in this case the CTs have a low saturation point.

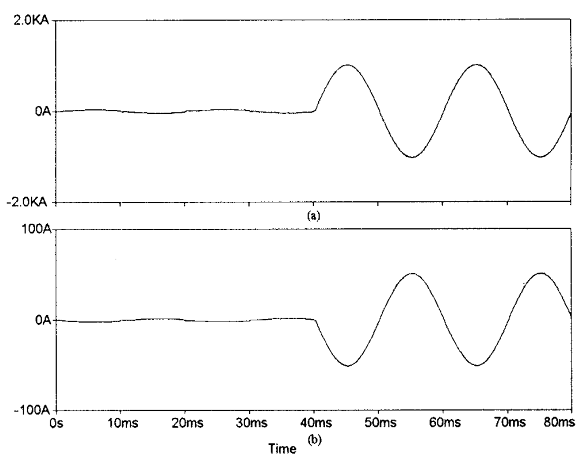

Fig. 6. Primary and secondary currents for a CT with a high saturation point. (a) Primary current. (b) Secondary current.

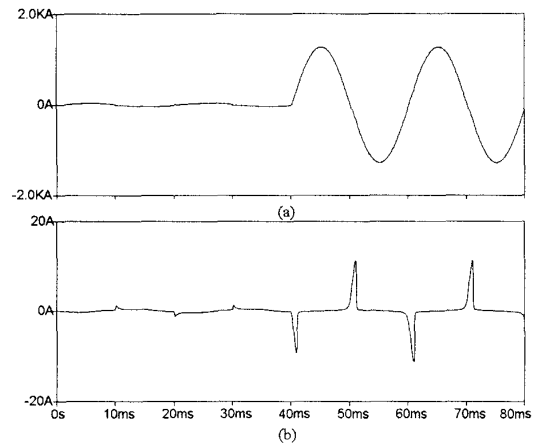

Fig. 7. Primary and secondary currents for a CT with a low saturation point. (a) Primary current. (b) Secondary current.

The turn ratio of the current transformer is 1:20. For a CT with a high saturation point, if the amplitude of the primary current is 1300 [A], the reflected current in the secondary reaches 65 [A] (Fig. 6), that means that the CT is operating in the linear region. For a current transformer with a low saturation point, the reflected secondary current reaches only 11 [A], for the same primary current, eventhough the current waveform is more distorted. The reduction in the amplitude of the secondary current due to the saturation is very convenient for the proposed protection scheme.

3.2.- Varistor

For most of the applications, the selection and specification of a varistor must follow the following five step process.

i) Determine the necessary steady state voltage rating.
ii) Establish the transient energy absorbed by the varistor.
iii) Calculate the peak transient current through the varistor.
iv) Determine the power dissipation requirements.
v) Select a model to provide the required voltage-clamping characteristic.

The most important data required for the correct specification of a voltage suppressor or varistor is the maximum transient energy absorbed by the device and the related power dissipation requirements. These two characteristics are difficult to evaluate, since they depend on the type of failure or transient that generates the overvoltage. For this reason, and in order to increase the reliability of the protection scheme, a couple of antiparallel thyristor are connected in parallel to the varistor. In this way, a current divider is provided decreasing the amount of energy dissipated in the varistor. The control circuit that generates the gating signals to the thyristors is simple and is shown is Fig. 8.

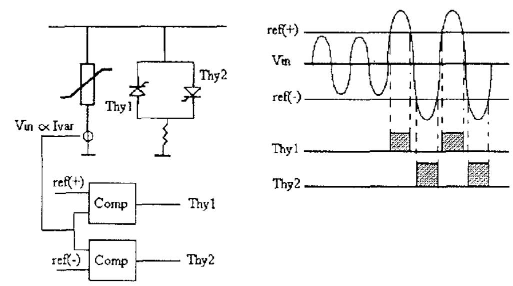

Fig. 8. The control circuit that generates the gating signals to the thyristors.

The control circuit is implemented with two comparators. A reference voltage and a voltage coming from the current sensor are the input signals of each comparator. If the signal coming from the current sensor is greater than the reference signal a pulse is applied to the gate of the respective thyristor. The amplitude of the current that will circulate through the thyristor will depend on the impedance values of the varistor and thyristors respectively (current divider).

Varistors initially fail in a short circuit mode when subjected to surges beyond their peak current/energy ratings. They also fail in a short circuit when are operated at steady state voltages well beyond their voltage ratings. However, this latter mode of stress may result in the eventual open circuiting of the device due to the melting of the lead solder joint. If the varistor fails as an open circuit, large overvoltages will be apply to the PWM voltage source inverter. These overvoltages are limited by the thyristors.

The current/voltage characteristics of the varistor is shown in Fig. 9.

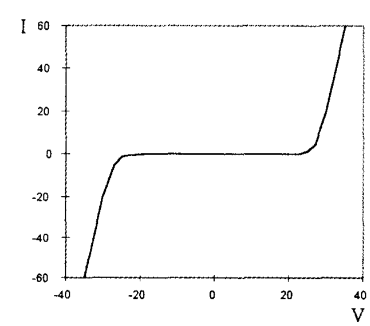

Fig. 9. The voltage/current characteristic of a varistor.

The combined effect of the low magnetic saturation of the CTs plus the connection of antiparallel thyristor reduces significantly the energy dissipate in the varistor during the power system fault, thus increasing the reliability of the proposed protection scheme at minimum cost. The use of a CT with high saturation point increases the amount of energy dissipates in the varistor, as shown in Fig. 10. By using a CT with low saturation characteristics the energy dissipated in the varistor is significantly reduced, as it is illustrated in Fig. 11, although the secondary current waveform is more distorted.

The energy dissipated by the varistor in two cycles after the power system short circuit started is 106 Joules, if no thyristors are used and a CTs with high saturation characteristics are connected. The dissipated energy is reduced to 16 Joules if a CT with low saturation point is used. If the thyristor are implemented, the energy dissipated by each varistor is reduced to 6 Joules in two cycles.

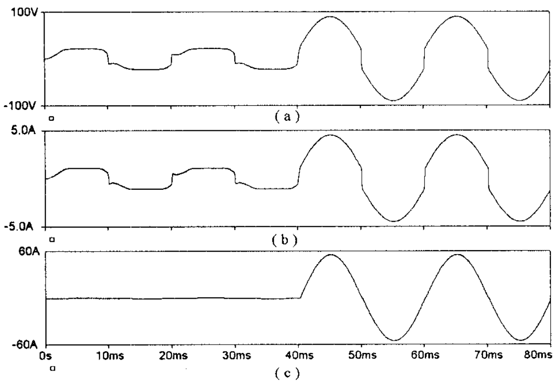

Fig. 10. Current waveforms for a CT with high saturation characteristics. (a) Current through the primary. (b) Current through the secondary. (c) Current through the varistor.

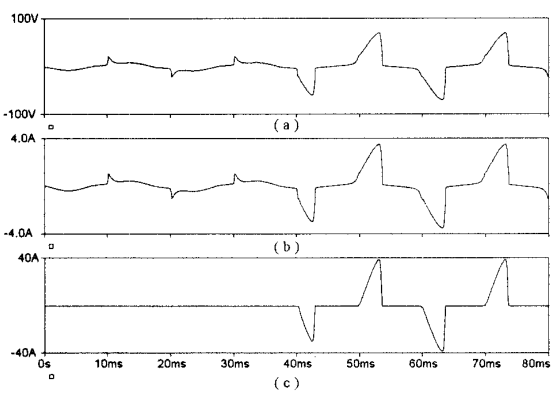

Fig. 10. Current waveforms for a CT with low saturation characteristics. (a) Current through the primary. (b) Current through the secondary. (c) Current through the varistor.

IV.- CONCLUSION

A protection scheme for series active power filters has been presented and analyzed in this paper. The proposed scheme protects series active power filters when short-circuit faults occur in the power distribution system. The principal protection element is a varistor. The combination of low saturation magnetic characteristic of the current transformers with the use of antiparallel thyristors helps to reduce the power dissipated by the varistors. The technical viability of the proposed scheme was proved by simulation using PSpice.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support from Fondecyt, for the financial support given through the projects 1940997 and 1960572. Also, the authors would like to thanks the "Dirección de Investigación" of Universidad de Concepción for the assistance gave through the project # 20.92.11.

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