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Electromagnetic compatibility analysis of a control strategy for a hybrid active filter

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ABSTRACT

In this paper a control strategy for a hybrid filter has been proposed. The hybrid filter consists of an active power filter connected in series with the source and a passive filter connected in parallel with the load. The proposed strategy is based on minimizing the effective value of the voltage at the point of common coupling to ensure the transfer of the power demanded by the load. By applying the Lagrange multipliers, the value of the equivalent resistance of the set load-compensator was determined in order to achieve unity power factor. An experimental prototype was designed to verify its behavior. The compensation equipment operation was analyzed from the point of view of the system stability and from their behavior regarding disturbances of the grid voltage. For this, the hybrid filter was subjected to six electromagnetic compatibility test as it is defined in IEC 61000 standard. In all tests, the equipment maintained its functionality before, during and after the perturbation in the supply voltage.

1. Introduction

Currently, a large number of loads make use of the power electronics for their operation. In the same way, the number of distributed generators that are connected to the network through inverters is increasing. These are only two clear examples of how the power electronics is increasing its presence in the equipment that connects to the grid. As a result, there is a worsening of the electric power quality which makes it an issue very important in electrical engineering. To mitigate this quality problem, in recent years, new compensation circuit topologies have been proposed. Most of these include active power filter (APF). Some of them are based on parallel topology, so that the active filter is connected in parallel with the load (PAF). This topology has been the most studied. However, it has some drawbacks: it is difficult to realize a large rated PWM inverter with rapid current response and low loss, the initial cost is high as compared with that of shunt passive filter and it only allows compensation of load called harmonic current source (HCS). In other topologies the active filter is connected in series with the source (SAF) what allow compensation of type load of harmonic voltage source (HVS). Others proposed configuration are constituted by two active filters, first one connected in series and the second one connected in parallel (SPAF). It is effective for all load types [1,2], in contrast they use two APFs which involves a high cost of equipment.

Besides these, other topologies have also been proposed [2–8]. Some of them combine the use of active and passive filters, called hybrid filters. The use of hybrid filters to improve the power quality was proposed in Ref. [9]. The aim is to improve the behavior of passive filter with an active filter lower power. Among them, the topology constituted by a series active filter with a passive filter parallel (SAPPF) has proved to be an effective topology for compensation of any load type, HCS or HVS. Different compensation strategies have been proposed for the SAPPF. The main aim is to improve the filtering features of the passive filter, eliminating the drawbacks that passive filters have when they are connected to the grid. Thus, the series APF can act as a device capable of isolating the passive filter of the power grid, which avoids possible resonances with the system or that the passive filter becomes a drain from close load harmonics [9–17].

Latest proposals include additional control target as compensation of reactive power, making the load compensator set have a resistive behavior. For it, compensation voltage is obtained from the determination of the resistance value that consumes the power demanded by the load. The power transferred is determined considering only the fundamental harmonic and direct sequence component of the current. In this case, the calculation algorithm is based on the formulation of the instantaneous reactive power [16] in order to achieve constant power at the source side when

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it is applied to a balanced three-phase and three-wire system. Similar compensation objectives are proposed in Ref. [17] where the control strategy is based on the dual vectorial formulation of the instantaneous reactive power. This strategy is applicable to unbalanced four-wire three-phase systems and it allows the compensation of reactive power and the mitigation of source current harmonics. The control strategy is based on considering an ideal resistive load which transfers active power corresponding to the positive sequence component of the fundamental harmonic. Thus, when the system voltage is unbalanced and non-sinusoidal, the currents are balanced and sinusoidal and the instantaneous power transferred by the source is constant.

This paper develops a new control strategy for SAPPF, which is based on minimizing the effective value of the voltage at the point of common coupling (PCC) to ensure the transference of the demanded power by the load. Thus, the determination of the reference signal is raised as a problem of constrained optimization for systems of three and four wires. As a result the set load-compensator works with unity power factor. The voltage and source current are collinear. This allows harmonic mitigation and compensation of reactive power. In contrast to the strategy presented in Ref. [17] the power transferred by the source is not constant.

The strategy proposed in Ref. [17] is suitable for those balanced nonlinear loads, where the current unbalance is due to the mains voltages. However, when the load is unbalanced and the voltage system is balanced, the series APF generates a voltage unbalanced system at the load side, in order to achieve a balance of currents. This may cause the voltage values are above or below nominal value in some phases, depending on the degree of load imbalance. For this situation the strategy presented in this paper would be more convenient since the voltage at the load side is similar to the network voltage although the load is unbalanced.

Typically, the operation of the compensator is checked with nominal supply voltage; however, this equipment must operate correctly when a disturbance appears in the supply voltage. So, it is interesting to know the compensator behavior in these situations. The IEC 61000 standard [18–21] for electromagnetic compatibility (EMC) establishes test conditions to apply to any electrical equipment. Thus, the compensation equipment should be checked so that it can operate in environments polluted since the electromagnetic point of view. Here, hybrid filter behavior has been analyzed in six tests for electromagnetic compatibility: voltage dips, voltage unbalance, frequency variations, voltage fluctuations, slow voltage variations and voltage harmonics.

2. Compensation reference voltages

This section presents a compensation method based on the average value. The aim is to determine the minimum rms value of the voltage at the PCC so that the system transfers the active power to the load. To develop this strategy, a three-phase system is considered as a special case of multiconductor system [23]. Fig. 1 shows a system of four wires compensated by means of a series active power filter. This is represented by four controlled voltage sources with values u_{C1}, u_{C2}, u_{C3} and u_{C4}.

The currents i_1, i_2, i_3 and i_4 are the components of the instantaneous line current vector, which is defined by

$$\mathbf{i} = \begin{bmatrix} i_1 & i_2 & i_3 & i_4 \end{bmatrix}^T \quad (1)$$

where T means matrix transpose.

The system voltages may be defined with respect to a virtual neutral point. This corresponds to the neutral of a star formed by four linear elements of the same value, as it is shown in Fig. 1.

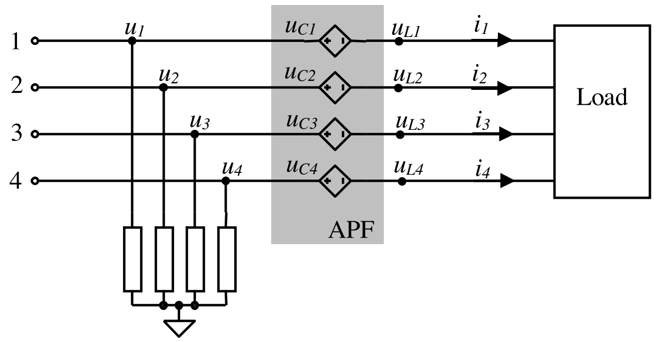

Fig. 1. Four wire system with series compensation equipment.

In this way, it is possible to define the instantaneous voltages, u_1, u_2, u_3 and u_4 of each of the conductors with respect to this common point. These voltages are the components of the voltage vector, **u**, which is defined by means of

$$\mathbf{u} = \begin{bmatrix} u_1 & u_2 & u_3 & u_4 \end{bmatrix}^T \quad (2)$$

The voltage system can be unbalanced and distorted.

In what follows, the subscript $\sum$ is used to refer to these "collective" values, including the fourth wire.

For a four-wire system the instantaneous power is obtained by the scalar product of the voltage vector by the current vector which is expressed by the equation

$$p_{\sum} = \mathbf{u} \cdot \mathbf{i}^T \quad (3)$$

The active power is obtained when the average value of the instantaneous power given in Eq. (3) is determined. Thus, for the fundamental period T, the active power is given by

$$P_{\sum} = \frac{1}{T} \int_t^{t+T} p_{\sum} dt \quad (4)$$

On the other hand, the voltage vector, **u**, can be determined such that it transfers the power demanded by the load with minimum rms. To solve this optimization problem the technique of Lagrange multipliers is used. So, objective function is defined by

$$F = \frac{1}{T} \int_t^{t+T} \mathbf{u} \cdot \mathbf{u}\, dt \quad (5)$$

Subject to the constraint

$$G = \frac{1}{T} \int_t^{t+T} \mathbf{u} \cdot \mathbf{i}\, dt = P_{\sum} \quad (6)$$

With F and G functions defined in Eqs. (5) and (6), Lagrangian equation is expressed as

$$L = F + \lambda G \quad (7)$$

Applying

$$\begin{aligned} \frac{\partial L}{\partial \mathbf{u}} &= 0 \\ \frac{\partial L}{\partial \lambda} &= 0 \end{aligned} \quad (8)$$

The result is an equation system whose solution is

$$\mathbf{u} = R \cdot \mathbf{i} \quad (9)$$

These voltages applied to a symmetrical resistive load of resistance R transfers the same average power that the nonlinear load. In this way, it is achieved that from the point of common coupling the system presents a unity power factor.