Abstract.
Deregulation of the electric power industry is making power quality a topic of increasing importance. Suitable corrective actions for the reduction of total harmonic distortion introduced into the distribution network by industrial loads are more necessary than ever. For the design of these corrective actions simulation has been proved to be a very useful tool. In this paper, the simulation of an active filter for the reduction of the voltage total harmonic distortion created by a steel plant is presented.

Keywords
Harmonic distortion, active filter, simulation, steel plant, induction furnace

1. Introduction

One of the most economic ways of producing steel is made through the use of induction furnaces. The problem with this kind of furnaces, from an electrical point of view, is the creation of a considerable harmonic distortion. The cause of the distortion is within the induction furnace design and operation. An induction furnace works melting the scrap using a medium frequency magnetic field created by a coil. The coil is fed by the medium frequency AC current supplied by an inverter which is fed by a DC current converter connected to the AC distribution network supply.

As the created distortion is very high and affects the voltage supplied by the distribution network, it is highly possible that other loads supplied from the same network will be affected. In this case, it is necessary to have corrective actions in order to fulfill the legislation concerning voltage harmonic distortion.

Among these corrective actions, active filters are one of the most effective [1,2]. This solution presents many advantages over other alternatives:

- The steel plant is composed of loads that vary fast their consumption changing the harmonic composition. The connection and disconnection of power electronic components changes the harmonic composition too. The filter has to be fast.

- The active filter overcomes the resonance problems associated with the power factor correction capacitors. Moreover, the filter can work as a dynamic compensator of reactive power, depending on the instantaneous needs of reactive power of the steel plant.

- The active filters can perform a load compensation of the three phases, removing the neutral current in unbalanced systems.

Before taking any corrective action, it is necessary to evaluate the distortion introduced by the installation into the distribution network. In this stage, simulation has been proved to be a useful tool when evaluating the harmonic distortion. It allows to quantify the harmonic distortion created by a system and, when a corrective action is introduced, simulation shows the reduction in the distortion. Hence, simulation can be used as a tool for the design of the active filter.

In this paper, the simulation has been carried out using MATLAB/Simulink. To be exact, blocks of the SimPowerSystems blockset have been used. Moreover, blocks for the simulation of the induction furnace and for calculation and visualization of the harmonic content have been developed.

2. Modelling of the steel plant

A. Steel plant description

The steel plant substation is fed alternatively from two 30 kV lines switched by means of a disconnector. The electric load of the plant is composed of 6 induction furnaces, temper furnaces and general services.

The distribution transformer of the general services is composed of three standard transformers of 315, 630 and 1250 kVA with secondary voltages of 398-230 V, 575-332 V and 230-133 V respectively. These transformers feed general services such as shot suction conveyors, offices, lighting…

The distribution transformer of the temper furnaces consists of three transformers of 800, 1000 and 1000 kVA, with secondary voltages of 230-133 V, 230 and 230-133 V respectively. One of the 1000 kVA transformers feeds the furnaces resistors and the other two feed the furnaces auxiliary services.

The steel plant comprises 6 induction furnaces of two different types. Four furnaces are of type 1 and other two are of type 2.
Each furnace of type 1 is fed from a 4 MVA three-winding transformer whose configuration is Yy6d5. The voltage is reduced from 30 kV to $30 \pm 2 \times 30$ V using tap-changers. The secondary winding feeds a thyristor controlled rectifier and the tertiary feeds another identical rectifier. The rectification has a 12-pulse configuration. Both rectifiers are connected in parallel including filtering coils that improve the direct current obtained. The obtained DC voltage value is 1250 V. Three medium frequency inverters are fed with the DC voltage getting a 500 Hz one-phase alternating current of controllable amplitude. The outputs of the inverters are connected in parallel and a transformer is used to increase the voltage amplitude. A capacitor bank is connected in parallel with the induction furnace coil to achieve a controllable resonance of the coil. The voltage in the coils that melt the steel is 2200 V with a frequency of 500 Hz and an approximate consumption of 3300 kW.

Each furnace of type 2 is fed from a 5 MVA three-winding transformer whose configuration is Dy11d0. The voltage is reduced to 945 V. Similarly to the type 1 furnace configuration, the secondary winding feeds a thyristor controlled rectifier and the tertiary feeds another identical rectifier. The rectification has a 12-pulse configuration. Both rectifiers are connected in series including filtering coils. The obtained DC voltage value is 2800 V. A capacitor bank is connected in parallel with the induction furnace coil. The approximate consumption of the coil is 4000 kW.

The induction furnaces work in the resonant frequency with the capacitor banks connected in parallel. The coils have no core, as it is the scrap which takes its place. The resonant frequency value varies with the condition of the scrap as the self-inductance of the coil changes. Therefore this frequency value is controlled by the inverter control system so that capacitors and coil are always in resonance. When the furnace starts working the frequency is low (400 Hz) and its values increases as the scrap is melted.

The rectifiers used to get the DC voltage are the cause of the injection of current harmonics in the system and consequently the cause of the voltage distortion. The characteristic harmonics injected by a 12-pulse rectifier are harmonics of order 11th and 13th.

B. Simulink model of the steel plant

All the elements have been modelled using existing Simulink blocks contained in the SymPowerSystems blockset.

The distribution transformers of the general services and the temper furnaces consume 1800 kW with a $\cos \phi$ of 0.85. For simulation purposes they have been modelled as a lineload of these characteristics. This is acceptable as their consumption is only a little portion of the total power consumed in the plant and they do not produce any distortion.

As there is no induction furnace electrical model in Simulink, new blocks have been created for the two types of induction furnaces (Figures 1 and 2).
3. Modelling of the active filter

The active filter is basically an inverter that works as a current source. The injected current follows a reference value calculated by a control strategy. This value is calculated as the difference between the main component of the current and the total value of the load. This difference, that is equal to the harmonic components but with a phase lag of 180°, is injected so that the supply current becomes a pure sinusoidal wave.

The inverter of the active filter is a GTO bridge with 6 legs that is connected to a storage capacitor on the DC side. The injected currents are measured to control the inverter properly. The inverter control strategy is based on the p-q theory [3-6]. Some lineal loads such as reactors, capacitors and resistors are used to reduce the harmonics introduced by the commutation of the GTOs. Finally, a transformer increases the voltage level.

In Fig. 3, it is shown the model used for the simulation of the active filter.
The filter has been inserted in parallel with the furnace loads and it is located in the point of common coupling with the distribution network, as can be seen in Fig. 4.

![Fig. 4. Model of the steel plant including the active filter](image)

4. Harmonic analysis

In order to perform the harmonic analysis of the voltage and current signals present in the steel plant, a Simulink block has been developed. This block calls an M-file that makes the required calculations and shows graphically the harmonic spectrum of the analysed signal (Fig. 5). The 1st harmonic is out of scale so that the rest of the harmonics can be visualized properly. The calculated values correspond to peak values.

![Fig. 5. Harmonic analyser result](image)

A real time harmonic analyser that show the peak values of the first 20 harmonic components as the circuit is being simulated has been developed too. This block has been developed using Simulink blocks. The results format is shown in Fig. 6.

![Fig. 6. Real time spectrum analyser](image)

5. Simulation and results

The steel plant has been simulated considering different levels of load: one, three and six furnaces working. Firstly, the voltage harmonic distortion created by the plant has been measured. Secondly, after the active filter has been added, the distortion has been measured again.

A. One furnace working

The results obtained in the harmonic distortion analysis of voltage and current at the connection point of the plant are shown in Figures 7 and 8. The THD value corresponding to the current is 4.47% while the voltage THD is 1.04%.

![Table 1](image)

The highest harmonics are the 11th (550 Hz) and the 13th (650 Hz) and they are repeated at the 23rd (1150 Hz) and the 25th (1250 Hz). These values are typical in the system analysed, as the 12-pulse rectification is designed to remove the 5th, 7th, 11th, 13th harmonics. As any standard rectifier, the triplen harmonics are also removed.
If the harmonic analysis is performed including the active filter the results change (Figures 9 and 10). The THD of the current is reduced from 4.47% to 1.87% and the voltage THD from 1.04% to 0.66%. The values of the highest harmonics have been reduced considerably. But some new components of low value (even harmonics due to the injection of the filter) can be observed.

B. Three furnaces working

The results obtained in the harmonic distortion analysis of voltage and current are shown in Figures 11 and 12. The THD value corresponding to the current is 6.91% while the voltage THD is 3.23%.

It is observed that the 9th harmonics takes a considerable value as it is not being absorbed correctly by the rectifier due to the high non-linear load of the inverters.

If the harmonic analysis is performed including the active filter the results improve (Figures 13 and 14). The THD of the current is reduced from 6.91% to 3.85% and the voltage THD from 3.23% to 2.06%.
This is the most common working situation of the steel plant as it usually has all the furnaces working in order to get the maximum profitability. This is the worst case from the point of view of the harmonic distortion and the filter should be able to correct it properly.

The results obtained in the harmonic distortion analysis are shown in Figures 15 and 16.

The current THD value is 7.41% while the voltage THD is 6.38%. The voltage distortion is too high as it is above the limit imposed by the regulations (5% for 30 kV).

The highest harmonics are the 11th and the 13th. The 9th harmonic also increases its value from the previous cases.

The results obtained including the active filter are shown in Figures 17 and 18.
The THD of the current is reduced from 7.41% to 3.33% and the voltage THD from 6.38% to 3.61%. The new value of the voltage distortion is below the limit of 5%. Therefore the filter is adequate for the steel plant to fulfil the voltage quality requirements.

The 11th and 13th harmonics are still the highest harmonics and the 9th is nearly removed. But there are many new components of low value introduced by the filter spread over the spectrum.

D. Results summary

A summary of the results obtained is shown in Tables I and II.

<table>
<thead>
<tr>
<th>No. of furnaces working</th>
<th>Voltage THD (%)</th>
<th>THD with active filter (%)</th>
<th>Reduction of THD (%)</th>
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<tr>
<td>1</td>
<td>1.04</td>
<td>0.66</td>
<td>36.5</td>
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<tr>
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</tr>
<tr>
<td>6</td>
<td>6.38</td>
<td>3.61</td>
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</table>

<table>
<thead>
<tr>
<th>No. of furnaces working</th>
<th>Current THD (%)</th>
<th>THD with active filter (%)</th>
<th>Reduction of THD (%)</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td>4.47</td>
<td>1.87</td>
<td>58.1</td>
</tr>
<tr>
<td>3</td>
<td>6.91</td>
<td>3.85</td>
<td>44.2</td>
</tr>
<tr>
<td>6</td>
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<td>3.33</td>
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</tr>
</tbody>
</table>

6. Conclusions

By means of the simulation carried out, the voltage harmonic distortion created by a steel plant has been evaluated. Moreover, the reduction of the distortion by an active filter has been simulated. The simulation tool allows designing the filter so that the required level of harmonic distortion is obtained.

References


