Abstract—This work aims to develop a transformer and a converter, to be used in DFACTS, useful to control the impedance in the transmission lines, and consequently, the power that flows in it. The operating principle is the transformer use the line as primary, clamping the core around the line, and the AC/DC converter in the secondary, doesn’t use auxiliary power sources to create the negative impedance seen by the line.

Simulation results are presented and discussed.

Index Terms – Power line, Transformer, PWM converter, AC/DC converter, negative impedance.

I. INTRODUCTION

This paper describes one study in the less developed area of the power system, the transmission of electrical energy. This situation only exists because there was no need to improve it, until nowadays. It’s increasingly difficult to build new power lines, especially due to environmental issues. Thus arises the need to improve the performance of power lines that currently exist and also provide technology to implement in the future lines. As opposed to traditional strategies to vary the transmission line impedance, such as the phase shifting transformer or mechanical switched resistances and inductances, the DFACTS take advantage of the latest power electronics development and benefit from the IGBT which provide voltage and phase control, due to the PWM techniques, which consist in high frequency modulations, whose output signal has low amplitude harmonics.

There are several technologies to implement the DFACTS in a transmission line, such as Shunt-Devices, Series-Devices and Shunt-Series-Devices. It will be used the Series-Devices, which method of operation consists in adding a series voltage, that can be tuned to vary the impedance of the line, typically it’s used a current transformer with the core clamped around the line, a AC/DC converter and a capacitor at the DC source, Figure 1.

The project considers that the transformer and converter operates on power cables carrying currents less than 1000 A, if the current drops below a certain limit, the circuit continues to operate, but its reliability is not guaranteed. However, this device is to be implemented only in transmission lines, where the power flows hasn’t high variations.

II. TRANSFORMER

Essentially, a transformer consists in two or more windings coupled by mutual magnetic flux. In this case the primary is the power line made of aluminum, so the number of turns is unitary, the secondary has 50 turns and is made of copper. The core of the transformer is clamped to the primary, as shown in Figure 2, and this means that is impossible to avoid having an air gap. It consists of a steel alloy M-36, whose properties are well defined in the simulation program FEMM.
The relative magnetic permeability of the core of the transformer is \( \mu_R = 4416 \). It is needed to choose some real measurements of the transformer, to achieve a possible transformer that can be built, thus are chosen the inner and outer diameters in order to obtain the length.

\[
\text{inner diameter} = 5 \text{ cm}; \quad (1) \\
\text{outer diameter} = 9 \text{ cm}. \quad (2)
\]

The inner diameter is very important, since it’s necessary to fit there the power line, all the secondary turns and the isolator. The outer area of the transformer is only surrounded by air.

The simulation program FEMM determines the behavior of the magnetic field lines in the core, and the average value of the magnetic field, which is used to calculate the electrical and physical parameters of the transformer.

Like all metals have technical limits of operation, one of the more important in magnetic fields is the maximum magnetic field allowed in the core, in this case, is given by the FEMM that the hysteresis loop has,

\[
B_{\text{max}} = 1.5 \text{T}. \quad (3)
\]

So, by simulation, and considering 1000 A of current flowing in the power line and an average magnetic field of 1 T, it will be achieved the length of the transformer and the size of the air gap. However, is important to achieve a value to the air gap length, \( g \), which confirms that it is much smaller than the average distance, \( l_g \), done by the magnetic field lines, \( \Phi \), if it doesn’t, the magnetic flux will not follow the path defined by the core and the air gap, and the techniques of magnetic circuit analysis can’t be used, the flux will “leak out” of the sides of the air gap. The existence of an air gap increases the magnetic reluctance of the magnetic circuit, \( R_c \),

\[
R_c = \frac{\Phi}{i_l} = \frac{\Phi}{N_1}, \quad (5)
\]

with some algebraic manipulation it’s possible to determine the air gap length,

\[
g = \frac{i_l \mu_0 \mu_R N_1 - \Phi l_g}{R(\mu_R - 1)} \approx 1.2 \text{ mm}. \quad (6)
\]

Since \( g \ll l_g \), it’s possible to use this parameters and the transformer will work. It’s now necessary to determine the length of the transformer, using the equivalent model, and the complete simulation with the FEMM.

It is studied two main cases, the no-load, Figure 3, and short-circuit, Figure 4, secondary. These simulations are worthy to verify the values of the magnetic field, and the behavior of it.

![Figure 3 – Behavior of the magnetic field lines in the no-load condition.](image)

The average value of the magnetic field, \( 1 \text{T} \), is the expected, and there aren’t many leaks. It’s also possible to see, that the region of the core that has more “interference” in the stability of the magnetic field, is the air gap.
In the short-circuit condition, the voltage in the secondary is null. In an ideal transformer the secondary current should be proportional to the power line current, affected by the ratio of transformation, $m$. It’s clear, that the magnetic field in the core is almost null, and it should be in an ideal transformer. In the simulation, this doesn’t happen because the circuit is not absolutely symmetric.

Using the equivalent model in $\pi$ of the transformer, using as an approximation, only the magnetic reluctance of the air gap, and assuming values for the leakage inductance of the primary, it’s possible to calculate the length of the transformer.

$$L_1 = 2 \mu H;$$  \hspace{1cm} (7)  

$$S = \frac{L_1 n^2}{\mu_0} = 1.91 \times 10^{-3} m^2$$  \hspace{1cm} (8)

$$length \approx 10 \text{ cm}$$  \hspace{1cm} (9)

The dimensions and simulations obtained make possible the application and production of this transformer. A short resume of the physical and electrical parameters of the transformer are in Table 1 and Table 2, respectively.

### Table 1 – Physical parameters of the transformer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter of the core</td>
<td>9 cm</td>
</tr>
<tr>
<td>Inner diameter of the core</td>
<td>5 cm</td>
</tr>
<tr>
<td>Air gap length</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Core length</td>
<td>10 cm</td>
</tr>
</tbody>
</table>

### Table 2 – Electrical parameters of the transformer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>2 $\mu$H</td>
</tr>
<tr>
<td>$R_1$</td>
<td>0.1 m$\Omega$</td>
</tr>
<tr>
<td>$L_m$</td>
<td>1 m$\Omega$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>100 k$\Omega$</td>
</tr>
<tr>
<td>$L_2$</td>
<td>95 $\mu$H</td>
</tr>
<tr>
<td>$R_2$</td>
<td>5 m$\Omega$</td>
</tr>
</tbody>
</table>

### III. AC/DC CONVERTER

Is now important, to know how to act in order to guarantee a negative impedance seen by the power line.

Figure 5 shows the design of the proposed system, the transformer, the AC/DC converter and the DC power supply. The power of the transformer (5kVA) is much lower than the high voltage line transmitted power. It means that the current in the power line, can be assumed to be a current source, $i_L$. The transformer and the DC source capacitor, feeds a power IGBT full-bridge inverter.

The IGBT bridge is operated as a pulse width modulation (PWM) converter and controlled to initially charge the DC source capacitor, unsure 400 V in the DC source, and to create a AC voltage in the secondary of the transformer, in order to guarantee the 5 V amplitude voltage in the primary. The PWM is devised to obtain a $V_{PWM}$ voltage proportional to the power line current so that the power converter and DC source are seen as impedance [4].

#### A. Control of the Full-Bridge Inverter

As the main goal is to obtain a sinusoidal voltage in the secondary, which is an image of the power line current, it’s necessary that

$$v_s = m \left( -L_1 \frac{dL}{dt} \right),$$  \hspace{1cm} (10)

this condition, with the negative signal, is the most important condition, since it gives the negative impedance.

Without the low pass filter, the secondary voltage is the PWM output of the full-bridge inverter. Therefore, the PWM is devised to obtain an average voltage, within a period, $T_{SW}$, proportional to the power line current.

$$\frac{1}{T_{SW}} \int_0^{T_{SW}} v_s dt = \frac{1}{T_{SW}} \int_0^{T_{SW}} (V_{PWM}) dt,$$  \hspace{1cm} (11)

$$T_{SW} \to 0.$$  \hspace{1cm} (12)

It is considered that, in each switching period, $T_{SW}$, the desired secondary voltage is constant, and the $V_{PWM}$ mean value must be equal.

$$\frac{1}{T_{SW}} \int_0^{T_{SW}} \left[ m \left( -L_1 \frac{dL}{dt} \right) - V_{PWM} \right] dt = 0$$  \hspace{1cm} (13)
However, (13) is not completely true, since it is necessary to consider the error of the difference, $\epsilon$. This error is expected to be null

$$\frac{1}{T_{SW}} \left[ -mL_i I_k + \int_0^{T_{SW}} (V_{PWM}) dt \right] = \epsilon.$$  \quad \text{(14)}

By analysis of the system, it is possible to know the behavior of the circuit, depending on the secondary current, the DC source current, and the active IGBT, Table 3.

<table>
<thead>
<tr>
<th>$i_s &gt; 0$</th>
<th>$i_s &lt; 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_1Q_2$ ON</td>
<td>$Q_3Q_4$ ON</td>
</tr>
<tr>
<td>$I_0 &gt; 0$</td>
<td>$I_0 &lt; 0$</td>
</tr>
<tr>
<td>$Q_3Q_4$ ON or $Q_2Q_4$ ON</td>
<td>$I_0 = 0$</td>
</tr>
<tr>
<td>$Q_1Q_2$ ON</td>
<td>$Q_3Q_4$ ON</td>
</tr>
<tr>
<td>$I_0 &lt; 0$</td>
<td>$I_0 &gt; 0$</td>
</tr>
<tr>
<td>$Q_3Q_4$ ON or $Q_2Q_4$ ON</td>
<td>$I_0 = 0$</td>
</tr>
</tbody>
</table>

To ensure a better functioning of the circuit, it is necessary to consider the losses, which will give stability to the control system and a DC voltage with less ripple. These losses consist of a fictitious time variable resistance, which depends on the power of the converter in each period, meaning that (14) must be rewritten

$$\frac{1}{T_{SW}} \left[ -mL_i I_k + \int_0^{T_{SW}} (r_{12}(V_{base} - V_0) - V_{PWM}) dt \right] = \epsilon.$$  \quad \text{(15)}

Considering all this, the full-bridge PWM modulator, Figure 6, where the gain before the integrator is $1/T_{SW}$, and helps to define the switching frequency in addition to the $\epsilon$ value. It’s used two hysteretic comparators with different hysteresis values, 1 and 0.5. It’s important to implement in the control system, a time to load the DC source capacitor.

The secondary voltage has a fundamental component at the frequency of 50 Hz and other high frequencies components, which exist due to the action of the switching of the semiconductor, however, these components are small compared to the 50 Hz, so the instantaneous power injected in the converter equals the instantaneous DC power [5]:

$$2\eta V_{PWM} I_s \sin(\omega t)^2 = I_0 V_0$$  \quad \text{(16)}

the value of the instantaneous current of the DC source is given by

$$I_0 = \frac{\eta V_{PWM} I_s}{v_0} (1 - \cos(2\omega t))$$  \quad \text{(17)}

the voltage on the capacitor is given by integrating the AC component of the current on it:

$$v_c = \frac{1}{C_0} \int_0^t \left( \frac{\eta V_{PWM}}{v_0} \cos(2\omega t) \right) dt = \frac{\eta V_{PWM} I_s}{2C_0 v_0} \sin(2\omega t)$$  \quad \text{(18)}

the value of the capacitor is

$$C_0 = \frac{\eta V_{PWM} I_s}{2\pi v_0 V_0}.$$  \quad \text{(19)}

This gives $C_0$ around 1.9 mF.

C. AC Input Low Pass Filter

The input low pass filter, Figure 7, is designed assuming typical 2nd order filter. Assuming a Thévenin equivalent network $Z_{of}$ seen from the transformer ($Z_{of} \approx v_o/i_o$) [5].

![Figure 6 – Full-bridge inverter generator.](image)

Figure 6 – Full-bridge inverter generator.

B. DC Source Capacitor

To the correct functioning of the converter, it is essential that the DC voltage is always bigger than 250 V, since with the low pass filter, this is the value of the maximum amplitude, so it is chosen a DC capacitor voltage of 400 V. In steady state this voltage should have an error of 5%. This error is due to the voltage ripple of the capacitor.

The value of the DC source capacitor, can be calculated in the DC side or in the AC side, however as current in the DC side is not uniform, it will be used the AC values.

The output of the filter is the secondary of the transformer. The transfer function is given by:

$$\frac{V_{of}}{V_{fi}} = \frac{1}{s^2 + \frac{R_f}{L_f} + \frac{1}{L_f C_f}}.$$  \quad \text{(20)}

Using the generic second order transfer function

$$H(s) = K \frac{\omega_n^2}{s^2 + \omega_n^2}$$  \quad \text{(21)}

and considering a 900 Hz cut off frequency and a damping factor near the unit, is possible to determine all parameters of the low pass filter.
IV. SIMULATIONS

The transformer magnetic circuit has been modeled and simulated with FEMM. The electric circuit with the electric model of the transformer and the converter has been modeled and simulated with MATLAB/Simulink. The simulation values were obtained for a power line current of 1000A, however were also tested other values.

Simulation results show that the losses in the magnetic circuit of the transformer are low; that the magnetic field lines are concentrated in the core and the average value is within the limits. It gives values to calculate the physical measurements of the transformer.

The full bridge PWM voltage is visible in Figure 8, the voltage obtained in the primary of the transformer has a 5 V amplitude. In Figure 9, is possible to verify the effect of the low pass filter, as well as the phase shift between the power line current and the primary voltage. This is the condition that ensures that the impedance is negative.

The DC voltage behavior is shown in Figure 10, which confirms that after the transient, the 400 V value is maintained constant with a small ripple.

By comparing the system with or without 100 DFACTS, it’s possible to quantify the parameters change for the power line with 220 kV

\[
\Delta V_c \approx 0.1\% \times V_c; \quad (23)
\]

\[
\Delta \theta_{vc} \approx 0.18^\circ. \quad (24)
\]

The use of more DFACTS causes a linear change of the parameters.

V. CONCLUSIONS

In this work was tested a transformer and a converter to be used in the DFACTS.

The transformer supplies a 2nd order low pass filter, which interfaces a full bridge IGBT inverter.

\[
R_f = \frac{Z_{df}^2 \omega_n}{\omega_n} \left( \frac{1}{1 - \frac{\omega_n^2}{\omega_n^2}} \right)
\]

\[
C_f = \frac{1}{\omega_n Z_{df} \sqrt{\frac{R_f}{\omega_n Z_{df}}}}
\]

\[
L_f = Z_{df}^2 C_f \quad (22)
\]

Table 4 – Low pass filter values.

<table>
<thead>
<tr>
<th>L_f</th>
<th>2.1 mH</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_f</td>
<td>13.4 µF</td>
</tr>
<tr>
<td>R_f</td>
<td>2.1 mΩ</td>
</tr>
<tr>
<td>Z_{df}</td>
<td>12.5 Ω</td>
</tr>
</tbody>
</table>

Figure 8 – Primary and secondary voltage without low pass filter.

Figure 9 – Primary and secondary voltage with the low pass filter.
One of the main objectives was the design of the transformer, especially the physical dimensions. With the simulations, it was possible to determine the electric model parameters and the physical characteristics of it. Thereby obtaining a transformer possible to produce and easy to apply.

The simulation results of the converter have some limitations, especially with the value of the primary voltage and the low pass filter. However, the control system fulfills the main objective of the converter, which consists in obtaining a negative impedance seen by the line, which affects the power that flows in the line.

The DC voltage is well regulated, and the system works without losing stability for values lower than 1000 A.

REFERENCES