Realisation of the galvanic isolation in customer-end DC to AC inverters for the LVDC distribution

Background:

The electric distribution network in Finland has normally voltage levels of 20 kV and 400 V. The electric power is transferred near the customers with the higher voltage and then transformed down to the lower voltage. The problem in this case is that the 20 kV power network consisting of overhead lines malfunctions very easily. If one branch is malfunctioning could this mean that many other branches are left without electricity. Also the amount of large and expensive distribution transformers is great. An alternative for this could be DC distribution, where the RMS value of the low voltage would be bigger than 400 V. In this case electrical power could be transferred for longer distances without the need of 20 kV lines for one or a few customers. This demands that the power inversion must be executed at the consumer end.

There are two possible techniques for direct current electricity distribution: Unipolar and bipolar. The difference between these two is the voltage levels used. In unipolar system there's only one voltage level in addition to neutral. In the bipolar system there are three voltage levels: positive DC-voltage, negative DC-voltage and neutral. In both systems the grid can be realized as a ground lifted IT-network.

In unipolar system the customer connections must always be done in the same way. In bipolar system there are four ways to realize these connections. As a two conductor connection can be made: between positive and neutral, between negative and neutral and between both positive and negative voltage. In a three conductor connection all of these voltage levels are in use. Both systems use the highest voltage level that is possible according to the EU low-voltage directive 73/23/EEC. In bipolar system the highest allowed distribution voltage is ±750 V_{DC} and in unipolar system voltage is 1500 V_{DC}.

Using DC-voltage it is possible to increase power when compared to AC electric distribution. As an alternative, when the power is kept as same, electricity can be transferred longer distances. The reason for this is that the EU has determined the directives concerning AC- and DC-distribution separately, specifically with the peak value. With DC-voltage the peak value equals the effective value of the DC-voltage. This allows higher voltages to be used. Also with DC-voltage, lower amount of dissipated power can be achieved because inductance has no effect in continuous operation and the skin effect does not raise the resistance of the cable. Other advantage is that due to its structure, the DC-link does not transfer short circuit currents thus the safety design for the grid is simpler.

Thesis definition

With DC-distribution the transformation of DC-voltage to mains AC-voltage (230 V_{rms}, 50 Hz) is done close to the customer. Thus the customer end device must be compact and modular designs in order to connect many of these in parallel. Also the converter must realize galvanic isolation between the input and output. Without galvanic isolation network protection would be more complex. In to the customer end and additional isolation control device should be installed. When earth fault and an isolation fault in a customer device take place simultaneously, there would be a dangerous contact voltage between the case of customer device and ground.

In a galvanically isolated system the grid earth fault and customer device isolation fault do not cause a mutual circuit through ground. During an earth fault there would not be need to shut down distribution thus removing the need for isolation control device in customer end. The contact voltage of faulty device in a galvanically isolated system is 0 V because there is no ground contact with supplying grid.

The galvanic isolation offers a possibility to implement the customer's grid as a grounded TN-system. Without isolation the customer grid and supply grid could form a short circuit through grounding. Also the DC-voltage cannot occur in the output of the device.

Problem setting and aim of the thesis

The converter presented in the thesis is designed to convert a power of 1 kVA from 750 V_{DC} to mains voltage (230 V_{RMS}, 50 Hz). The device is optimized to have a good efficiency and to separate the output galvanically from the input. Designing the high frequency transformer is a difficult task because both the resonant converter attached to the primary side and the cycloconverter on the secondary side lay demands to the transformer. It is most necessary to find an optimal design between the efficiency of the transformer and costs and processibility.

When realizing the DC-distribution a very high demand is laid upon the efficiency. Usually the efficiency levels of power electronic devices are lower than traditional distribution transformers, which is the reason why it is important to find a end device topology operating with very high efficiency. The aim of the thesis is to design a high-frequency transformer which operates at very high efficiency. Galvanic isolation is realized with the transformer. The efficiency of the transformer has to be as good as possible so that it will affect as little as possible to the total efficiency of the converter. Also the thesis regards possibilities for optimizing the efficiency with different core materials and designs. In the thesis there is also a brief overview of the designed power converter and functions of other parts of the converter, which are: resonance converter on the primary side of the transformer, cycloconverter in secondary side of the transformer and filter. Also the used Pulse-density-modulation (PDM) is presented in the thesis.

Results and conclusions

Designing a high-frequency transformer in to the DC/AC converter presented in the thesis is a task with great number of challenges. The supplying resonance converter and the cycloconverter on the secondary side lay their own requirements for the transformer. The input voltage has to be kept as low as possible. In this case it would require changing the topology used on the primary side or the resonance converter should be operated below its resonance frequency. The firs options will make the use of high frequencies more complicated and then might increase the size of the transformer. The latter option will make the control of resonance converter more difficult because the magnetizing inductance of the transformer takes part in the resonance. Decreasing the switching frequency does not increase the amplitude of the noise in the range of 0.1 f_{HF} - 1.9 f_{HF}, but the noise will move to lower frequencies in respect to the high-frequency. This will complicate the optimization of the output filter of the converter.

The problem is not to design an optimized transformer but to manufacture one. Even the best optimization methods do not take account the manufacturability. For this reason the design and optimization of a transformer is done by optimizing the transformer in the beginning. After that the parameters of the transformer are changed and fixed in respect to the efficiency in order to achieve a solution that is manufacturable and still has the highest efficiency possible. Practically this means a slight over scaling of the transformer core. This also means that the efficiency will decrease a bit because the core losses dominate with over scaled core. In an application like the converter presented in the thesis the guiding principle for transformer design is manufacturability with respect of the efficiency. The key idea is to design a transformer which operates at highest possible efficiency and still is manufacturable.

The largest problem with the manufacturability is the size of the winding. If optimal numbers of turns are large (in other words several dozen) it is quite clear that three windings do not fit on to same core. In this case the number of turns must be decreased. This means that the flux density in the core increases which eventually means higher core losses. This then means that a larger core has to be used in order to limit the flux density. The size of the core cannot be over scaled as much one desires because the mass of the core will increase relatively more than the cross section of the core. This means that a larger core operating with the same flux density than a smaller one, will produce higher losses.

Also the completely filled winding window if using large currents. The cross section of the conductor has to be small in order to place the windings on to the same coil former. This increases current density. The current density can exceed practical cooling limit of 4.5 A/mm^2. This depends on surroundings of the transformer. With enough space the free convection can cool the transformer even with current density of 6 A/mm^2. Usually with current densities this large an extra blower is required. With the transformer designed in the thesis, this problem did not occur since the curren density in primary winding is around 4.3 A/mm^2 and in secondary 3.2 A/mm^2. In addition the effective current density in secondary windings is lower than that because the both secondary winding are loaded one at a time.

By using ETD54 core instead of ETD49, lower current densities we're achieved. In addition the increase in mass was still relatively low in comparison with the increase in the cross section of the core. In that case the core losses were even smaller than with smaller core. Also the current densities remained relatively small. If even larger core (ETD59) was used, the core losses would have been over 10 W. With core losses of this scale the desired minimum efficiency of 98 % could not have been achieved.

In practice the efficiency of the transformer can be increased a bit. With another type of ferrite as a core material the change in the efficiency would be just in scale of few hundredths of a per cent because the used N97 Ferrite by Epcos is already one of the best low-loss material in the markets. As an alternative to ferrite core could be amorphous materials. With amorphous materials the core losses would be smaller, which makes the use higher flux density possible. Also the number of turns in windings would be smaller.

The problem with this is that amorphous materials are more expensive than ferrites and there is not very many different shapes available for the core. Most of the amorphous cores are toroidal and with this shape the space in the winding window would be even smaller than with ETD core. This would mean higher flux densities which negates the advantage gained with the material. Also with toroidal core the area of core cross section increases less in respect to the mass than in ETD cores. This will mean larger increase in core losses than in the case of ETD core.

The efficiency of the transformer could be increase possibly with few tenths of per cent. Therefore I don't consider increasing the efficiency suitable if it is not a must. If the efficiency increases only by few tenths of a per cent, it is not sensible to pay many-fold price of the core. Even the nanochrystal cores which resemble amorphous materials cost too much to be a sensible option. In addition to this the minimum order quantity of Vacuumschmelze (amorphous transformer core manufacturer) is 1000 pieces. With the recent prices and order quantities the use of amorphous or nanochrystal cores is not sensible, especially when a ferrite core produces practically the same results.

If the efficiency of the transformer has to be increased, the focus should be on decreasing the input voltage of the transformer instead of changing the materials. As the flux density is directly proportional to the input voltage and inverse proportional to the number of winding turns, smaller number of winding turns can be achieved with the use of lower voltage without a dramatic increase in flux density. Then with increase of required current can a larger conductor be fitted to the transformer.

With the frequency used in the application (100 kHz) the windings of the transformers have to be done with Litz-wire. Theoretically using foil in the secondary windings works, but the capacitance between primary and secondary, along with other parasitic components, will disturb the function of the resonance converter. In this case the resonance frequency can be totally different than the desired one. Also at this operating point the resonance converter cannot supply enough current or high enough voltage.

By changing the secondary winding conductor from foil to Litz-wire, the resonance converter will be able to function according to theory. However, the voltage is not sinusoidal like theory would suggest. There is a disturbance of about 1 MHz in the waveform. This disturbance is caused by the parasitic capacitance between primary and secondary and the parasitic inductances and capacitances between components and circuit card. Even though the capacitance between primary and secondary can be decreased by setting a faraday guard between primary and secondary, using foil is not a practical solution for a transformer. The price of foil is many-fold compared to Litz-wire. Also an extra layer between the windings will always serve as additional heat isolator between the core and cooling fluid (in this case air). Also with foil there is no space in the winding window for extra turns in case of increase in desired secondary voltage.

Practically there should be as much as possible of isolation material between primary and secondary. This will reduce the capacitance between primary and secondary. However, this will increase the heat isolation in the transformer, which means that a proper design of transformer isolation would require a thorough analysis. Of course the material chosen affects to the thickness.

By changing the type of conductor in the secondary, better results were achieved. The output voltage of the resonance converter was better with secondary winding made of Litz-wire. The measurements show keep up with simulations and the transformer wad fed with approximately little bit over 1/3 of the nominal voltage. Unfortunately efficiency measurement could not have been done because there was problems with both the resonance converter and the cycloconverter. This meant that the load of the transformer was at the best around 1/3 of the nominal. The results would not have been very accurate and any further conclusion of the efficiency of the nominal operating point could not have been done of them.

As a need of further study with the transformer is minimizing the parasitic inductances and capacitances. Also their affect to the function of the resonance converter has to be studied. Also with the design of the whole system it is necessary to produce the prototype in such manner that measuring in any point of the prototype is possible.