# The Universal Power Electronics Based Distribution Transformer, An Unified Approach

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***Abstract-* A high frequency switched, power electronics based distribution transformer is introduced and described. Besides the definition of appropriate voltage- and power ratings also several preferred topologies are discussed, favorable to replace the typical power frequency distribution transformer by a high frequency switched one with low number of variants.**

**Special attention is paid on modularity and on automated production capability of all individual components, very low first and operating costs e.g. low maintenance costs, long operation intervals and high efficiency especially at partial load.**

## I. INTRODUCTION

Classical reasons for Power Quality (=PQ) problems like lightning and switching operations by utilities together with a growing share of power generated by renewable energy sources have a negative impact on the PQ in the Medium Voltage (=MV) and the Low Voltage (=LV) power distribution network. To provide a high PQ for at least consumers with sensitive processes a wide range of products for the improvement of PQ for both, the MV- and the LV grid are available. These products are based either on improved traditional technology or on Power Electronics (= PE) conversion technique, see [1].

PE based PQ solutions are usually on the LV-side and a huge market for these systems is established e.g. Uninterruptible Power Supply (=UPS)-systems and active filters, see [2] and [3] as examples. PE based PQ-systems installed on the MV-side - see [4] - represent today only a small fraction of the PQ equipment installed within the MV-distribution network (mainly by cost-performance reasons). But with the rapid decline in cost and the availability of highly reliable, low loss semiconductors with high frequency switching capability, it can be expected that the penetration of PE based PQ-systems in the MV-distribution network will increase within the next years, see [5][6] and [7]. Moreover, PE conversion technique will also enter MV power distribution market segments, which today are dominated by mature electromechanical and electromagnetic technology. Therefore, also the economical replacement of a typical power frequency MV/LV distribution transformer in the lower power range with a high frequency switched "electronic transformer" and *extended functionality* seems to be feasible. Such a PE based distribution transformer can operate - for instance - either on AC MV input (three phases or one phase) or DC MV input. The system enables load balancing and guarantees a low harmonic current distortion. Voltage dips or even complete short time outages on the MV-side can be bridged with DC-link capacitors (similar to an UPS-system). For longer outages local controllable resources can be connected directly to a DC-link.

The decision to invest in a PQ-system is always based on an economic evaluation. The value of a PQ-system has to be considerable higher compared to the life cycle costs. Hence, utilities and product manufacturers have to find optimal solutions to end up with the best possible cost-performance ratio. In future, standardized modular building blocks with smart integrated primary & secondary technology, embedded value added features and economy-of-scale manufacturing are requested. This will result in direct cost savings and in reduced life cycle costs for the total power delivery system. Since the number of consumers with a high degree of process automation is increasing, a new market in the medium power range (100kW-1MW) is developing for such PQ-systems.

A PE based high frequency switched MV/LV transformer will start as a niche product, where a higher functionality (as described above) is of value. But the market share of those PE based solutions will grow with the same rate of change as the costs and power losses for PE equipment will go down. Fig. 1 shows such a future MV distribution grid.

Today, the structure of MV/LV distribution system, the ratings of the voltages (both, on the MV- and the LV side) and the power frequency varies from region to region. Thus, to end up with low number of variants of a PE based distribution transformer only a well defined concept will be successful within the high competitive market environment. Therefore, in this paper besides the definition of appropriate voltage- and power ratings also several preferred topologies will be discussed, favorable to replace the typical power frequency distribution transformer by a high frequency switched one. Special attention will be paid on modularity and on automated production capability of all individual components, very low first and operating costs (e.g. low maintenance costs and long operation intervals), high efficiency especially at partial load and availability of energy (redundant concept).

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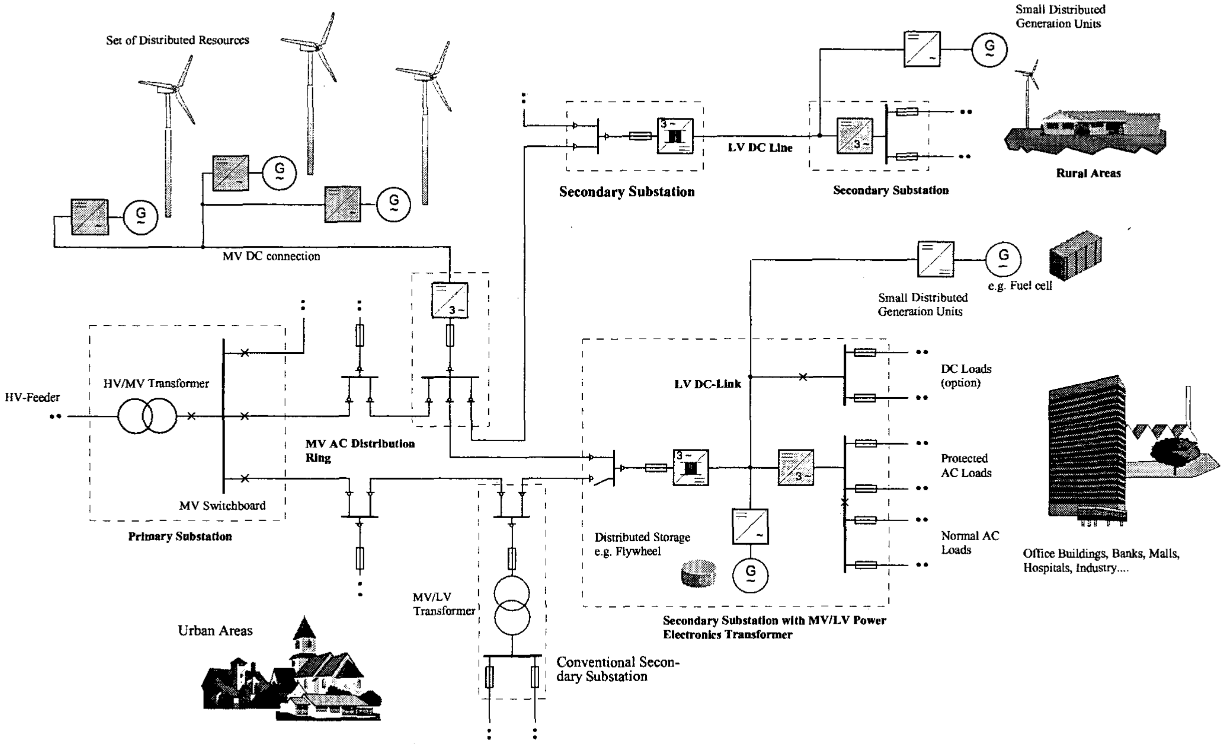



Fig.1. MV AC distribution grid with DC subsystems (LV and MV grid) and a high level of distributed resources. High frequency switched AC-to-AC converters with DC-link provide a high power quality for selected customers.

## II. TYPICAL RATINGS & BASIC REQUIREMENTS

Although a complete DC power distribution system will be feasible in future, in the next decade a PE based distribution transformer will operate in the already existing AC-MV distribution grid only. Therefore, a PE based distribution transformer has to meet at least all known standard regulations and should be adaptable easily to meet the different MV- and LV levels worldwide. Hence, the typical power level of a PE based distribution transformer will be in the range of today's power frequency MV/LV distribution transformers. An overview of the most relevant ratings is given in table 1 (more ratings can be found e.g. in [8]):

TABLE 1
SELECTION OF TYPICAL POWER FREQUENCY MV/LV DISTRIBUTION TRANSFORMER RATINGS

| Typical Transformer Ratings (kVA) | | | | | |
|---|---|---|---|---|---|
| 105 | 315 | 630 | 1250 | 1600 | 2000 |

The voltage level on the MV- and the LV-side is set by worldwide AC grid voltages (including AC railway voltages). An overview of the most important MV- and LV-voltage levels is given in table 2 and table 3 (based on e.g. IEC standards, explicit specified for Europe and North America, but also Asia, Japan and Australia are included).

TABLE 2
SELECTION OF RELEVANT MV VOLTAGE RATINGS

| | MV voltages (kV) | | | | |
|---|---|---|---|---|---|
| Europe | 3.6 1) | 7.2 1) | 12 1) | 17.5 1) | 24 1) |
| North America | 4.75 2) | 8.25 2) | 15 2) | 25.8 2) | |
| Railway | 17.2 3) | 27.5 4) | | | |

1) 3 phases, 50 Hz, 2) 3 phases, 60 Hz, 3) 1 Phase, 16 2/3 Hz, 4) 1 Phase, 50 or 60 Hz

TABLE 3
SELECTION OF RELEVANT LV VOLTAGE RATINGS

| Rated LV voltages (V) [1] | | | | |
|---|---|---|---|---|
| 100/200 | 120/208 | 110/220 | 127/220 | 120/240 |
| 230/400 | 277/480 | 400/690 | | |

1) 2 or 3 phases + Neutral, 50 or 60 Hz

## III. BASIC SYSTEM APPROACH

To handle the different voltage and power levels with today's available PE-components in principle two different approaches on the converter side are visible:

- Application of multilevel converters, each sub-converter equipped with standard components (no series connection of semiconductors) and one high frequency transformer per sub-converter with the full insulation capability, resulting in a high number of series connected sub-converters on the high voltage level side (e.g. 20 series connected converters at a primary AC voltage of 24kV, 3 phases)
- Usage of series connected semiconductor switches in series connected sub-converters (e.g. two or three converters instead of 15-20 converters with the multilevel approach), thus low amount of high frequency transformers with full insulation capability

Today, the market tends to semiconductor switches with higher blocking capability, lower on state losses, higher switching speed and with smart integrated gate drivers. In the near future semiconductor switches will become more and more standardized and as a consequence a further significant reduction of costs of semiconductors can be expected. Unfortunately the market prognoses for magnetic components are not so optimistic as in case of the semiconductors. It can be expected that high frequency magnetic components will be still expensive in the future, especially when they have to fulfill a high insulation requirement. Consequently "the less the better" strategy is maybe the better choice, when talking about low cost PE equipment for power distribution of the future.

Following this approach in principle a three stage power conversion with MV and LV DC-link, a two stage power conversion with LV DC-link only, a two stage power conversion with MV DC-Link only and finally a direct three phase AC-to-AC converter without any DC-link are possible, see figure 2. These different design approaches comprises different conversion sections (1 = MV AC-to-DC converter, 2 = MV/LV DC-to-DC converter, 3 = LV DC-to-AC converter, 4 = MV/LV AC-to-DC converter, 5 = MV/LV DC-to-AC converter, 6 = MV/LV AC-to-AC converter and 2, 4, 5 and 6 including HF-transformer).

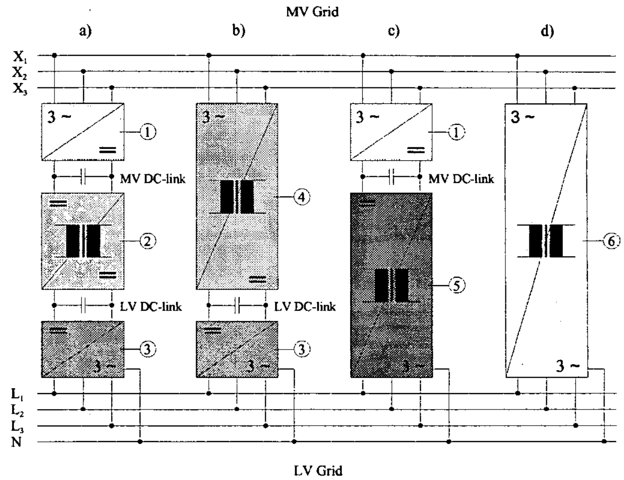



Fig. 2. Different design approaches to realize a PE based distribution transformer

## IV. COMPARATIVE ANALYSIS

To pre-select the best suited approach a comprehensive comparative analysis of these different conversion sections was performed. For the analysis more than 100 papers and patents on soft and hard switched topologies were studied and the results obtained were summarized. Furthermore, an analysis of the switching behavior of existing semiconductor devices (e.g. GTO, IGCT, IGBT, MOS) and of new semiconductor devices like SiC, an analysis of different magnetic core materials (e.g. amorphous core material or ferrite) and different insulation materials was performed. For the comparison the following assumptions were made:

- Power levels according to table 1, voltage levels according to table 2 and table 3
- Three phase MV-input voltage and three phase LV-output voltage with neutral conductor
- Balanced sinusoidal MV input current independent on the load characteristic on the LV-side
- 100% unbalanced one phase load of the LV-side against the neutral conductor as special load condition, the other two phases run idle
- Energy storage capability to support an UPS-system and an integrated interface for small distributed resources (< 500 kW power rating)
- Short circuit breaking capacity, solid insulation and natural cooling only
- Power flow control, unidirectional (first priority) or bidirectional (second priority) power flow
- Modularity and multi-system compatibility
- High efficiency (as high as possible) especially at partial load

The results obtained can be summarized as follow:

- A significant benefit regarding cost and size is visible, when the switching frequency is high enough to allow to use amorphous core material effectively (close to saturation level without overheating problems, even if the price is high compared to ferrite)
- Usage of fast switching semiconductors with lower voltage blocking capability is more favorable and more future oriented compared to low speed high voltage blocking semiconductors (e.g. HV-IGBT, IGCT), because the symmetry of series connected switches is easier to handle with fast switching semiconductors
- Efficient integration of small distributed resources (e.g. fuel cell, small gas turbine) and UPS support (integration of e.g. a flywheel or Ultra-Caps) are economically attractive if the power conversion section No. **a** and No. **b** are applied. The other two possibilities are of less interest from the performance and component point of view.
- Conversion section No. **b** is favorable for lower power levels (e.g. 100-250 kW) when requirements are not very high and an unidirectional power flow is sufficient
- Conversion section No. **a** allows the highest flexibility and is favorable if requirements are high and if bi-directional power flow is of importance

Although also for conversion section No. **b** different topologies were selected and designed in the following conversion section No. **a** will be discussed more in detail.

To guarantee a sinusoidal input current and a stabilized MV DC-link voltage for the MV AC-to-DC converter a topology with a voltage boost characteristic is assumed. Thus, a low number of MV DC-link levels is sufficient to handle nearly all MV-levels worldwide, see table 4.

Following this approach it can be seen, that all MV AC voltages can be stabilized to e.g. multiples of 14 kV, whereby 14 kV is favorable for low MV AC-voltages and 42 kV (3 x 14 kV) for all other MV-levels (the second column shows the rectified DC-voltage obtained with a standard 3 phase rectifier). As shown later this selection will on one hand help to reduce the number of variants drastically. On the other hand especially in Europe a better utilization of the already existing cable MV grid can be guaranteed if, for instance, embedded small MV DC-grids will be realized in future, see fig.1.

The same procedure can now be applied on the LV-side. Here multiples of 350V are favorable to meet all standard LV-levels Table 5 shows as examples some relevant LV-DC voltage ratings.

It is obviously, that modules with a power level of 105 kVA, 210 kVA and 420 kVA and 630 kVA are favorable to meet all typical power ratings of today's power frequency transformers. A higher power level is achievable by parallel connections of converter modules. Table 6 gives an overview for the most interesting ratings (selection only).

TABLE 4
DETERMINATION OF MV DC-LINK VOLTAGES

| | RMS-value of AC-voltage (kV) | Rectified MV-voltage (kV) | MV DC-voltage (kV) Level 1 | MV DC-voltage (kV) Level 2 | MV DC-voltage (kV) Level 3 |
|---|---|---|---|---|---|
| Europe | 3.6 | 5 | 14 | (28) | n.e. |
| | 7.2 | 10 | 14 | (28) | n.e. |
| | 12 | 17 | - | 28 | 42 |
| | 17.5 | 25 | - | 28 | 42 |
| | 24 | 34 | - | - | 42 |
| North America | 4.75 | 7 | 14 | (28) | n.e. |
| | 8.25 | 12 | 14 | (28) | n.e. |
| | 15 | 21 | - | 28 | 42 |
| | 25.8 | 36 | - | - | 42 |
| Railway | 17.2 | 24 | - | 28 | 42 |
| | 27.5 | 39 | - | - | 42 |

n.e. = not economically

TABLE 5
DETERMINATION OF LV DC-LINK VOLTAGES

| RMS-value, AC-voltage (V) | 127/220 | 230/400 | 277/480 | 400/690 |
|---|---|---|---|---|
| LV DC-voltage (V), Level 1 | 350 | - | - | - |
| LV DC-voltage (V), Level 2 | (700) | 700 | 700 | - |
| LV DC-voltage (V), Level 3 | | (1050) | (1050) | 1050 |

TABLE 6
DETERMINATION OF POWER RATINGS

| Power frequency rating (kVA) | 315 | 630 | 1250 |
|---|---|---|---|
| Sections with multiples of 105 kVA | 3 x 105 | 6 x 105 | n.e. |
| Sections with multiples of 210 kVA | 2 x 210 | 3 x 210 | 6 x 210 |
| Sections with multiples of 315 kVA | 1 x 315 | 2 x 315 | 4 x 315 |
| Sections with multiples of 420 kVA | - | - | 3 x 420 |
| Sections with multiples of 630 kVA | - | 1 x 630 | 2 x 630 |

## V. SELECTION OF TOPOLOGIES

For the MV AC-to-DC converter (No. 1) in principle several three-phase converter topologies can be applied (depending on requirements). Most favorable are converters with low amount of switches, low blocking requirements and low switching stress (e.g. the VIENNA rectifier to serve for unidirectional power flow, stabilized output power and sinusoidal input current), see [9] and fig.3. Redundancy can be achieved by paralleling of converter sections.

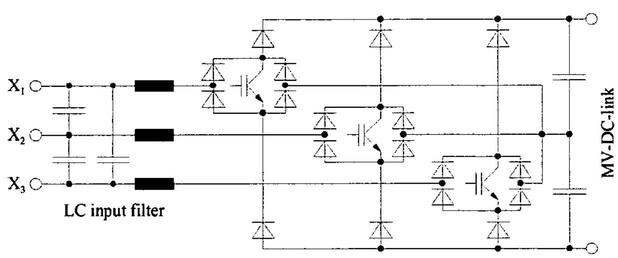



Fig. 3. MV voltage inverter with input filter to allow a sinusoidal MV input current and a stabilized MV DC-link voltage

To generate an own LV-grid in principle the well-known UPS converter topologies can serve (e.g. hard or soft-switched 3-leg voltage source inverter with DY-transformer or 4-leg voltage source inverter to generate a three-phase system with neutral conductor). Redundancy can be achieved by paralleling of converter sections (similar to the MV AC-to-DC converter section). Fig. 4 shows as an example a 4-leg voltage inverter with output filter.

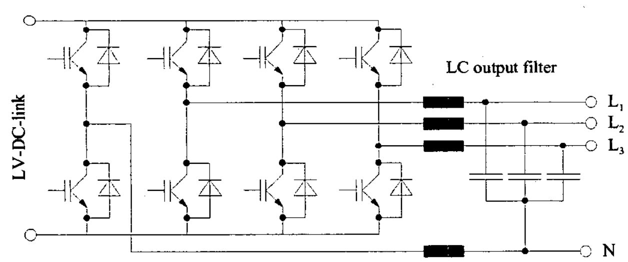



Fig. 4. LV 4-leg voltage inverter with output filter to generate a LV-grid

The MV/LV DC-to-DC converter will be a special one, because it contains the HF-transformer section, must be able to handle the high voltage insulation stress and should be easy adaptable to different MV and LV DC-link levels.
This problem can be solved if a modular converter is selected consisting exactly of 3 sub-converter sections, which can be connected in parallel (to serve for the low MV DC-link levels) or in series (to serve for the high MV DC-link levels). Also here in principle different converter types (e.g. based on a forward or bridge topology) are suitable, see [10]. A converter section that fulfils most of the requirements in an excellent way is shown in fig. 5.

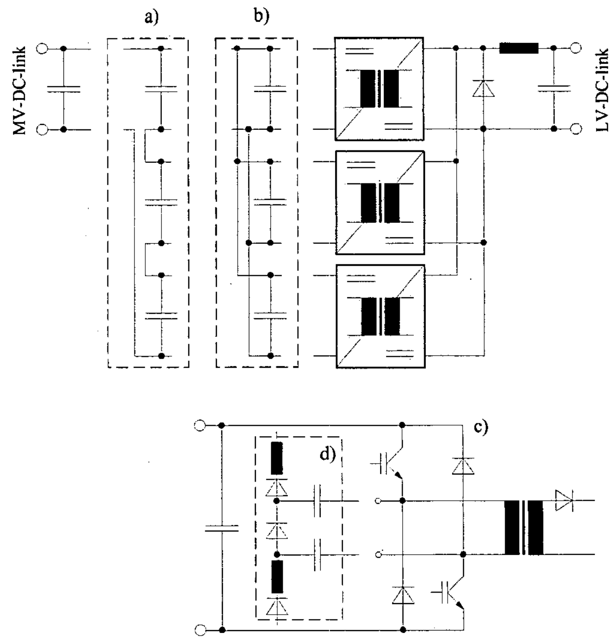


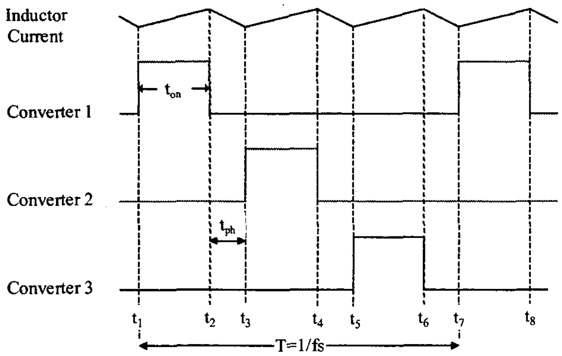

Fig. 5. MV/LV DC-to-DC converter section (based on a forward topology) with individual cells connected a) in series to serve for the high MV DC-link and b) in parallel to serve for the low MV DC-link, c) hard switched converter cell and d) regenerative snubber network to provide zero voltage switching

Generally, the converter illustrated in fig. 5 is capable for operations in two modes, namely, pulse-mode and overlap-mode. In addition, a simple, small and low loss snubber circuitry can be added easily to reduce the turn-off and turn on loss of the switches and therefore to improve the efficiency of the converter furthermore, see [11]. Figure 6 shows the differences between the pulse-mode and the overlap-mode respectively. In addition, the ideal voltage transfer ratio is given ($U_0$ = primary sided input voltage, $U_D$ = secondary sided output voltage, $N_P$ = number of turns of primary sided winding, $N_s$ = number of turns of secondary sided winding).

The pulse-mode is characterized by the fact that the turn-on times of the individual converter components are phase shifted from each other (duty cycle D<0.33). In the overlap-mode, however, the switch-on times of adjacent converter cells overlap each other (D>0.33). One very important advantage in the overlap-mode is that the load current is ripple free. The output filter inductor and the free-

wheeling diode (diode does not conduct at all) are theoretically of no relevance in this mode. For this reason, the output filter elements can be as small as possible thus reducing cost of the overall system.
In case of a parallel connection on the primary side one converter can fail or can be switched off during a low load period. The remaining two converters take over the supply of the total system power (D set to 0.45 instead of 0.33). Hence, the converter presented therefore provides a redundancy of n-1.

Pulse-mode with $U_0 = 3\,D\dfrac{N_s}{N_p}U_D$ (D < 0.33)




Overlap mode with $U_0 = \dfrac{N_s}{N_p}U_d$ (D > 0.33)

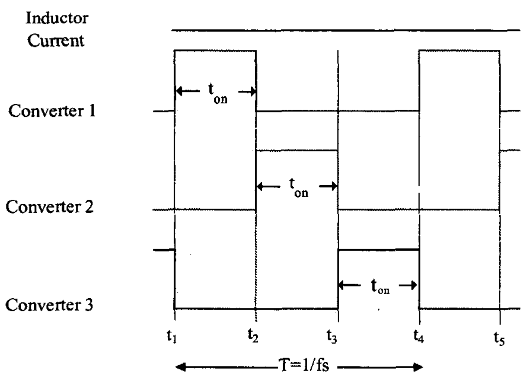



Fig. 6. Modes of operation of the novel converter section (gate signal of the individual switches)

To verify the theoretical investigations performed the modular converter shown in figure 5 was designed in detail and finally a prototype with a power level of 105 kW, a MV input voltage of 14 kV (converter sections connected in parallel) and a LV output voltage of 700V was constructed. The converter section operates as expected and if the low loss snubber is applied an overall efficiency of more than 97% was achieved.

## VI. CONCLUSION

Due to rapid decline in cost and the availability of highly reliable, low loss semiconductors with high frequency switching capability, it can be expected that power electronics products and solutions will play an important role in the future of the MV-Distribution. Power Electronics solutions will serve to improve the Power Quality and to interface distributed power resources to the grid in a very efficient way.
Moreover, it can be expected that PE conversion technique will also enter MV power distribution market segments, which today are dominated by mature electromechanical and electromagnetic technology. Therefore, also the economical replacement of a typical power frequency MV/LV distribution transformer in the lower power range with a high frequency switched "electronic transformer" and extended functionality seems to be feasible.

Within this paper besides the definition of appropriate voltage- and power ratings also several preferred topologies were discussed, favorable to replace the typical power frequency distribution transformer by a high frequency switched one. Special attention was paid on modularity and on automated production capability of all individual components, very low first and operating costs as well as high efficiency especially at partial load.

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