A New Single Phase AC/AC-Multilevel Converter
For Traction Vehicles Operating On AC Line Voltage

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Abstract
A new converter concept for direct connection to the power line of AC-fed traction vehicles will be introduced. This concept contains a new single phase AC/AC-modular-multilevel-converter (M^2LC) and a concentrated medium-frequency transformer. A design for multi-system operation will be investigated that can operate on an AC15kV / 16½Hz as well as an AC25kV / 50Hz power line.

The new single phase M^2LC, enabling four quadrant operation, forms the core of this converter concept. The basic characteristics of this new converter will be introduced. Simulations and analytical investigations underline the attractiveness of this new M^2LC converter. This versatile traction converter concept stands out due to its modularity, its superior control characteristics as well as its good adaptability to various traction drives. Therefore, the single phase M^2LC has the potential to replace the conventional transformer of future AC-fed traction vehicles.

1. Introduction
Several different line-side-switched converter topologies have already been proposed. The possible advantages aimed at are the replacement of the bulky line-transformer, increased efficiency and other points. Most of these systems contain one or several medium-frequency (MF) transformers [2, 4]. With these transformers galvanic isolation is achieved and the high voltage of the power line can be transformed to a voltage level more suitable for conventional converters. Two other principally different concepts have also been proposed. On the one hand it is the high-temperature superconducting line-transformer [5] and on the other hand it is a line-side-switched converter with a high voltage insulation within the traction motors [3].
As the core of the introduced converter concept, a new single phase AC/AC- Modular-MultilevelConverter (M²LC) will be presented. This converter can also be extended in order to form an 1phase/3phase M²LC (Fig. 4) or any other type of multi phase converter. However, the focus of this paper lies on the application of the single phase M²LC as part of the multi-system traction converter. The characteristics of this single phase converter are similar to all other multi phase converters of the same structure. Next to this M²LC concept related DC/AC-M²LC converters have already been presented [1].

With the new converter concept (Fig. 1) a compact MF-transformer is fed directly by the single phase M²LC which is operating on the AC line voltage. The concept facilitates four-quadrant operation and superior line-side behaviour under steady state and transient conditions. Passive LC-filters at the line-side or resonant tank circuits tuned to the double line-frequency are eliminated.

![Fig. 1 Traction converter concept for the operation on the 15kV/16⅔Hz and 25kV/50Hz power line](image)

2. Structure of the converter concept

The core of the proposed converter concept forms the new single phase M²LC which operates directly on the AC power line. It connects a MF-transformer to the power line (Fig. 1). The structure of this new converter will be discussed in the following chapter. The Voltage $v_{tr}$ of about 15 kilovolts amplitude is transformed by the MF-transformer to about 3 kilovolts which can be handled by conventional four-quadrant converters. The frequency of the transformer voltage is typically in the range of 500Hz to a few kilohertz. In this case, the operation with a 2kHz transformer will be shown.

Due to the fact that the transformer frequency is around a few kilohertz, conventional traction converters using state-of-the art semiconductors can be used on the low voltage side of the transformer (Fig. 1).

An additional advantage is the fact that the traction converters of this new concept (Fig. 1) do not need passive resonant tank circuits tuned to the second harmonic of the power line voltage. This is due to the fact that the M²LC is able to compensate the severe power pulsation of the power line, directly. Neglecting the power pulsation with the double transformer-frequency, the M²LC transmits practically constant power.

The transmission of constant power via the transformer - as well as the fact that only one concentrated MF-transformer is needed - results in a very cost-efficient design with a high efficiency. Especially the good power to insulation-voltage ratio as well as the low demands concerning the transformer stray inductance are major aspects which enable a transformer-efficiency of above 99% together with a very good power to weight ratio and relatively low costs.
3. The new single phase AC/AC-modular-multilevel-converter

The M²LC converts the power line voltage \( v_{\text{line}} \) (15kV/16\( \frac{2}{3} \)Hz or 25kV/50Hz) into the MF-voltage \( v_{\text{tr}} \) and it also absorbs the second harmonic of the power line, as mentioned above. Therefore, practically constant power can be transmitted via the MF-transformer. Between power line and the M²LC only a small line choke \( L_{\text{line}} \) (Fig. 1) is necessary which causes a voltage drop below 5% of \( v_{\text{line}} \) at 16\( \frac{2}{3} \)Hz. This is due to the fact that the converter voltage \( v_{\text{M²LC}} \) is a pulsewidth modulated multilevel-voltage with adjustable fine voltage steps.

![Fig. 2 AC/AC single phase modular multilevel converter topology](image1)

![Fig. 3 Scheme of a multilevel converter arm](image2)

Structure of the M²LC

This M²LC consists of four identical multilevel converter arms (Fig. 2 and 3). Each converter arm consists of \( N \) identical submodules. The submodules (Fig. 3) contain H-bridges and associated DC-storage capacitors. Full four-quadrant-operation of the converter is achieved without any additional connections or energy transfer to the DC-storage capacitors of the submodules. In a first step, the arms may be considered as controlled voltage sources.

It shall be pointed out that all submodules are physically equal. They do have the same semiconductor-ratings as well as the same capacitance. For this reason all submodules are identical 2-terminal devices. The power supply for the IGBT-drivers of each submodule is taken out of the associated, local capacitors. Therefore, only one bi-directional fibre optic per submodule represents the interface on the control side.

With these identical 2-terminal submodules, a very versatile and compact converter construction can be realized. No other additional converter-units are needed. The fact that all submodules can be connected with each other without the need for any additional low inductive busbars at high voltage-levels facilitates a robust and fault tolerant converter design.

The converter basically consists of 4\( N \) identical submodules. This is not only a strong advantage concerning maintenance aspects. This feature also facilitates a very consistent redundancy concept. Even though different submodules might have different tasks during the operation, they can easily be replaced by each other. This results in a converter structure which enables improved availability.

The central control-unit of the converter communicates with all submodules and the current transducers via bi-directional fibre optical interfaces. Such a control-unit is being realized as part of a
M$^2$LC-prototype converter which is under construction at our institute. How the voltages of all storage capacitors can be controlled, will be explained further on.

**Basic operation**

With the single phase M$^2$LC two bipolar voltages $v_0$ and $v_1$ can be impressed, independently (Fig. 2). Concerning the traction converter, the voltages $v_0$ and $v_1$ of the M$^2$LC (Fig. 2) do correspond to $v_{M^2LC}$ and $v_{tr}$ (Fig. 1). Since the topology of the M$^2$LC is absolutely symmetric, it does not make any difference if $v_0$ corresponds to $v_{M^2LC}$ and $v_1$ to $v_{tr}$ or vice versa.

The M$^2$LC can impress both voltages $v_0$ and $v_1$ by appropriate control fully independent from each other. The following equations describe the relationship between the voltages $v_{ax}$ of the arms and the output voltages $v_0$ and $v_1$:

\[
\begin{align*}
    v_{a1} &= \frac{v_0 - v_1}{2} \quad (1) \\
    v_{a2} &= \frac{v_0 + v_1}{2} \quad (2) \\
    \hat{v}_{ax} &\geq \frac{\hat{v}_0 + \hat{v}_1}{2} \quad (3)
\end{align*}
\]

With the equations (1) and (2), the needed arm voltages can be derived. By controlling the submodules of each arm appropriately, the arm voltages $v_{a1} \ldots v_{a4}$ will be impressed. Several different PWM-methods can be chosen for this task. When each desired arm voltage is impressed, consequently the desired voltages $v_0$ and $v_1$ are impressed on the output terminals.

In order to be able to impress two fully independent voltages $v_0$ and $v_1$ with different frequencies and amplitudes, each arm has always to be able to impress the voltage amplitude $\hat{v}_{ax}$. Equation (3) describes the relationship between the needed minimum voltage amplitude $\hat{v}_{ax}$ of each arm and the maximum amplitudes of the output voltages $v_0$ and $v_1$.

**Control of the DC-storage capacitor voltages**

In the above chapter it has been described how the output voltages can be impressed by the converter - based on the assumption that all the submodules can be regarded as ideal 3-level voltage sources. In the following, it will be described how the DC-storage capacitors of the submodules can be controlled in practice so that they can be used as reliable voltage sources.

By impressing $v_0$ and $v_1$, the equivalent input and output currents can be controlled. Consequently, the input and output power of the converter can be controlled this way. Nevertheless, two more tasks have to be fulfilled in order to control all DC-storage capacitor voltages:

1. the stored energy within the whole converter shall be kept at a certain set point value - this is equivalent with an identical set point value for all submodule storage capacitor voltages
2. the voltage-levels of all DC-storage capacitors have to be balanced within a reasonably tight tolerance band

The first task is relatively simple. By monitoring all storage capacitor voltages at a central control unit, the overall stored energy can easily be derived. By adapting the input and output power of the converter, the overall stored energy can be adjusted to its set point value. Instead of using the stored energy as a control parameter, the average voltage of all storage capacitors can also be used as an equivalent parameter. This parameter can easily be derived from the monitored capacitor voltages and for small variations around this voltage-average, a negligible error will be made.
In the case that the first task is fulfilled and all storage capacitors are balanced as well, they have reached their set point value. To keep all storage capacitors balanced the following method can be used:

- all four converter arms have to be controlled in such a way that the stored energy in all arms is about equal
- the voltage balancing within one converter arm can be realized in the following way:
  - when the converter arm will absorb power the submodules with the lowest storage capacitor voltages will be used in order to impress the desired arm voltage
  - when the converter arm will supply power it is vice versa and the submodules with the highest storage capacitor voltages will be used in order to impress the desired arm voltage

**Other multiphase M²LCs**

The modular multilevel converter topology of the single phase converter can be extended to a 1phase/3phase M²LC (Fig. 4). As one can see, just one extra phase module has to be added in order to derive this converter topology from the single phase M²LC. In analogy, any other multi phase M²LC can be realized. The static and dynamic performance of all multi phase converter topologies is similar to the one of the single phase M²LC.

![Fig. 4](image)

**4. Operation characteristics of the converter**

The following chapter presents the steady state as well as the transient operation characteristics of the converter. Therefore, detailed simulations of a 5MW-2-system-converter will be used.

Looking at the performance of the M²LC, one has to keep in mind that it must transmit line-side power which pulsates with the 2nd harmonic of the line-voltage. However, the transmitted power on the transformer-side is practically constant. Therefore, the power pulsation has to be absorbed by the converter itself. This can be done by absorbing the pulsating power with all submodule capacitances. This results in a pulsating DC voltage $v_{dc}$ (Fig. 5 and 8) which can be allowed for the new converter concept. Without restrictions, a high voltage ripple around the nominal value of $\Delta v_d (\geq +/-20\%)$ can be realized.
For the investigated design of a 5MW converter, the submodules are realized with 3.3kV IGBTs and 640µF/1900V storage capacitors. Each converter arm consists of N=18 submodules. This includes 2 submodules per arm for redundant operation.

For the voltage range of the converter with a maximum voltage amplitude of \( V_{\text{M2LC}} > 42\text{kV} \) on the 25kV/50Hz power line, other IGBT blocking voltages could well be the optimal choice, depending on several aspects. The modularity of the M\(^2\)LC gives the freedom to choose from a wide range of switches.

Due to the fact that a very high voltage ripple of the storage capacitors can be allowed (Fig. 5 and 8), the energy storage requirements can be limited to a level equal or less than needed for conventional systems.

The nominal stored energy of the 5MW M\(^2\)LC is 83kWs in total. The stored energy in the related traction converters can be reduced considerably when they are fed from a M\(^2\)LC. This results in an energy storage requirement of about 18kWs per 1MW nominal converter power, in total. For conventional state-of-the art traction converters which operate on the 15kV/16\(\frac{2}{3}\)Hz power line, the nominal stored energy in the related DC-capacitors as well as the resonant tank circuits is also in this range. Therefore, the new converter concept has equal energy storage requirements compared with state-of-the art systems and does not suffer from excessive energy storage requirements.

**Operation on the 15kV / 16\(\frac{2}{3}\)Hz power line**

In this chapter, the basic operation characteristics of the converter topology will be presented. Therefore, simulation results have been applied in order to show the characteristics of the line-side and transformer currents and voltages (Fig. 5, 6 and 7).

![Simulation of the operation at nominal power of 5MW on the 15kV/16\(\frac{2}{3}\)Hz power line](image-url)

Fig. 5 Simulation of the operation at nominal power of 5MW on the 15kV/16\(\frac{2}{3}\)Hz power line
In Fig. 5, the line current $i_{\text{line}}$ as well as the line voltage and the associated converter input voltage $v_{M^2\text{LC}}$ are shown for a steady state operation point of 5MW power-level. It can be seen that the converter does impress an extremely smooth line current. Line voltage and line current are in phase with each other.

In order to be able to transfer a constant power of 5MW via the MF-transformer, the $M^2\text{LC}$ has to store a considerable amount of energy. This requirement is caused by the unavoidable power pulsation of the single phase line-side. The energy is equally stored in all DC-storage capacitors of the $M^2\text{LC}$. This energy storage results in the pulsation of the voltage-average $v_{\text{dav}}$ of all DC-storage capacitors (Fig. 5).

Although, $v_{\text{dav}}$ pulsates with up to +/- 20% around its nominal value, there is no noticeable impact on the line current or the transformer currents. The reason for this is that the control can adapt the pulse control factor of the related submodules with each PWM-period.

The current and voltage waveforms of the 2kHz-transformer are shown in Fig. 6. The transformer has a turn ratio of 5:1. Therefore, the amplitude of the output voltage $v_{\text{tr, sec}}$ is 1/5 of the input voltage $v_{\text{tr, pri}}$. By adjusting the phase shift between primary and secondary side, the transferred power can be changed easily and very fast. The transformer-ratio has primarily been chosen to realize an optimum with respect to the $M^2\text{LC}$-efficiency as well as semiconductor costs. By choosing an optimum transformer-ratio, the required total silicon area can be kept at a level equal or less than comparable 5MW-converters. In the presented simulations all four-quadrant converters which would be connected to the secondary side of the MF-transformer are combined to a single 2-level four-quadrant converter.

![Transformer Waveforms](image)

Fig. 6 Simulation of the transformer operation at nominal power of 5MW

In the following Fig. 7, the line current harmonics are presented. They have been derived by a FFT of the current $i_{\text{line}}$ (Fig. 5). This graph also contains the current limits of the German 15kV/16/3Hz power line over the relevant spectrum.

It can be seen that the converter spectrum fulfils well this very demanding task. The 4kHz PWM-frequency on the line-side can also be seen clearly (Fig. 7). Although, 4kHz is a very high PWM-frequency at this power-level, the average switching frequency of all 3.3kV-IGBTs is only around 350Hz. This relatively low IGBT-switching frequency contributes to the good efficiency of the $M^2\text{LC}$. 
In contrast to the operation on the 15kV/16\(\sqrt{2}\)/Hz power line, the operation on the 25kV/50Hz power line is not as demanding concerning the power pulsation on the line-side. Just 1/3 of the energy pulsation has to be absorbed by the M\(^2\)LC in this case. This results in a far lower voltage pulsation of all DC-storage capacitors as the waveform of \(v_{\text{dav}}\) in Fig. 8 shows.

**Operation on the 25kV/50Hz power line**

In contrast to the operation on the 15kV/16\(\sqrt{2}\)/Hz power line, the operation on the 25kV/50Hz power line is not as demanding concerning the power pulsation on the line-side. Just 1/3 of the energy pulsation has to be absorbed by the M\(^2\)LC in this case. This results in a far lower voltage pulsation of all DC-storage capacitors as the waveform of \(v_{\text{dav}}\) in Fig. 8 shows.
The lower voltage pulsation gives the freedom to increase the set point value for the controlled average voltage of all DC-storage capacitors. This advantageous measure enables operation of the M²LC on the 15kV or 25kV power line with the same hardware and no mechanical switches. The maximum voltage amplitude of the DC-storage capacitors with the M²LC operating on the 25kV power line is 5% lower than for the operation on the 15kV/16²/₃Hz power line. The waveform of $i_{\text{line}}$ (Fig. 8) demonstrates once more the very good steady state line-side behaviour. In the following chapter, a demonstration of the very good transient behaviour of this traction converter will be presented, too.

**Operation under harsh transient conditions on the 15kV/16²/₃Hz power line**

The simulation shown in Fig. 9 demonstrates the very good dynamic behaviour of the M²LC under extreme operation conditions. A sudden interruption of the bow contact of the traction vehicle is assumed. These frequent interruptions typically take place for less than 15ms. The bow contact interruption takes place at a maximum power line voltage level of 18.5kVrms. After several hundred microseconds, the converter control recognises the current interruption and steadily reduces the transferred power on the transformer-side ($P_{\text{tr}}$) from the nominal value of 5MW down to 500kW auxiliary power level.

Despite of this cut from the power-line it can be seen that the DC voltages $v_{\text{dxx}}$ of all submodules can be controlled well. This is clearly demonstrated by the waveforms of all DC-storage capacitors $v_{\text{d11}}..v_{\text{d4N}}$ which are shown in the third graph of Fig. 9. Although, extreme transients have to be realized by the converter, all DC-storage capacitor voltages are kept within a tight tolerance band.

In comparison to the M²LC, conventional converters with resonant tank circuits are often unable to cope with such extreme transients without interruption of power transfer and a subsequent restarting procedure. This is due to the fact that the resonant tank circuits of these converters cannot be damped, adequately. For the fact that the M²LC does not need these filters, it can be controlled a lot better under such working conditions. As mentioned above, this superior performance can be achieved with about the same total stored energy than needed for conventional systems.

![Fig. 9 Simulation of the traction converter topology at a bow contact interruption](image-url)

(Nominal power level and maximum line-voltage)
5. Conclusions

A new converter family has been introduced which stands out by a wide variety of characteristics. The superior dynamic behaviour as well as the steady state behaviour of this converter have been demonstrated with simulation results. Negligible harmonic distortion of the line-side current and a very high efficiency are achieved, too.

In addition to the excellent electrical performance of the converter, the new system stands out due to its modularity and the single concentrated transformer which results in an extremely versatile and cost-efficient design with a high redundancy and availability.

Owing to these reasons the single phase M²LC offers new degrees of freedom for the design of future AC-fed traction vehicles. It is also a very promising converter topology for many other high power applications. A 17-level prototype M²LC in the 2MW power range is under construction at present in order to further investigate this concept.

6. References

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