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**Index Terms**

Multilevel converters, adjustable speed drive, converter control, high voltage power converters

**Abstract**

The suitability of the direct modular multi-level converter for high power, low speed, gear- and transformerless drives is investigated. Control methods which optimize the capacitor voltage ripple are presented, analyzed and verified in simulation.

## I. Introduction

Gears are unwelcome in high power low speed electric drive applications such as marine propulsion, SAG mills, hydro power, mine hoists, conveyors, wind turbines etc. [1]–[3]. Instead, high torque motors/generators which directly drive the load are employed. Soft starting and speed control for process optimization can provide significant operational benefits for such high power plants, thus there is a big interest in using electric frequency converter based variable speed drives. Cycloconverters are very robust and compact but are difficult to integrate into the supply network. Medium voltage source converters are more grid friendly. Series connected H-bridge based converters are also available at six to eleven kV. Due to the many secondary windings they are tightly integrated with the supply transformer however which can make siting difficult.

Motors for such applications typically have low electrical nominal frequencies for mechanical reasons and to permit the use of cycloconverters. Indirect modular multilevel converters (indirect MMC) are thus not well suited because of their limitations at low output frequencies [4], [5]. The use of direct MMC, which shares most of the benefits of the indirect MMC, has thus been investigated.

Direct modular multi-level converters as shown in fig. 1 consists of branches, each connecting one phase of one system (RST) to one phase of the other (UVW). The branches are a series connection of a choke and a number of identical power-electronic building blocks (PEBBs) as appropriate for the desired system voltages. No transformers are required. Each PEBB contains a capacitor, an IGBT full-bridge and the associated gate drive-, communication-, control- and protection electronics [6]–[8]. The current commutation loops are encapsulated in the PEBBs and the branch currents are continuous in MMC, which distinguishes them from conventional voltage source and matrix converters [9], [10]. The number of voltage levels and the apparent switching frequency of the branch voltages is proportional to the number of PEBBs. This leads to a very low THD and small voltage steps which render sine

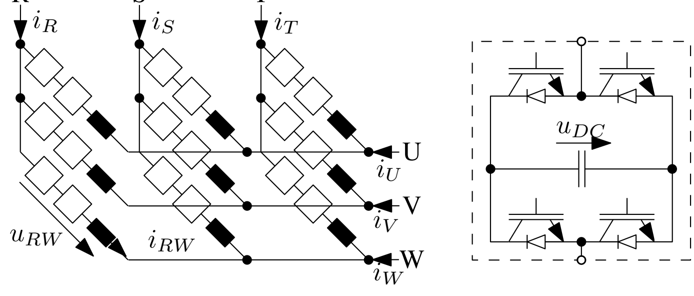


Fig. 1. The AC-AC Modular Multi-Level Converter (direct MMC) topology.

or $\partial u/\partial t$ filters or reinforced machine insulation dispensable. On the other hand, a relatively large amount of energy has to be stored in the PEBB capacitors as the PEBBs are essentially single phase converters. The control of the voltage in all those capacitors also poses a formidable challange. Thus MMCs typically use at least six PEBBs per branch as VSC are more attractive when fewer PEBBs would be needed.

## II. Capacitor voltage ripple and control

A low frequency ripple exists on the voltage of the PEBB capacitor in MMC converters. The magnitude of this ripple must be kept within acceptable bounds at all times. This implies limitations on the output current of indirect MMC at low output frequencies [5], [11]. Subsequently the capacitor voltage ripple in the direct MMC is analyzed in analogy to the analysis performed for the indirect MMC in [5].

The peak-to-peak ripple magnitude of the PEBB capacitor voltage $U_{cap,pp}$ can be derived from the PEBB power as it is proportional to the variation of the stored energy in the PEBB $E_{cap,pp}$: With the mean of the PEBB capacitor voltage being $U_{cap,avg}$ and the PEBB capacitance $C$ it is

$$E_{cap,pp} = C U_{cap,avg} U_{cap,pp}.$$

The stored energy in a PEBB is the integral of the PEBB power at its terminals neglecting internal losses. Analogously, the energy variation of an entire branch consisting of $N_{PEBB}$ PEBBs with a branch capacitance of $C_{branch} = C/N_{PEBB}$, a sum of PEBB capacitor voltages $U_{\Sigma cap}$ and equal PEBB capacitor voltages is also proportional to the capacitor voltage ripple magnitudes:

$$E_{\Sigma cap,pp} = C_{branch} U_{\Sigma cap,avg} U_{\Sigma cap,pp}.$$

Therefore the cell capacitor voltage ripple can be determined via the branch power spectrum. The branch power in turn is the product of the branch voltage and the branch current $p_{xy} = u_{xy} i_{xy}$. The branch power must be zero mean to maintain stable PEBB capacitor voltages. The branch voltages in a direct MMC equal the difference of the phase voltages of the phases connected by the respective branch and an optional common mode voltage.

$$u_{xy} = u_x - u_y + u_{cm},\ x \in \{R, S, T\},\ y \in \{U, V, W\} \tag{1}$$

The phase currents $i_x$ and $i_y$ given by the motor and grid control must also be met, the branch currents $i_{xy}$ have to be chosen accordingly. The straightforward solution is to evenly divide the phase current among all branches connected to the respective phase [7], [8].

$$i_{xy} = \frac{1}{3} i_x - \frac{1}{3} i_y \tag{2}$$

The analysis of the resulting branch power reveals that it is nonzero mean (i.e. the cell capacitor voltages are unstable) when the mean phase powers $p_x = u_x i_x, p_y = u_y i_y$ of the phases which are connected by a branch do not sum to zero, either of the system frequencies is zero or the system frequencies are equal:

$$\begin{aligned} p_{xy} &= u_{xy} i_{xy} \overset{eqs.1,2}{=} \frac{1}{3}\left(p_x + p_y - i_x u_y - u_x i_y\right) \\ &\Big\downarrow \begin{array}{lcl} i_z & \sim & \sin(\omega_z t + \phi_z) \\ u_z & \sim & \sin(\omega_z t + \phi_z) \end{array} \\ &\sim P_x + P_y + A\cos(2\omega_x t + \cdots) + B\cos(2\omega_y t + \cdots) + C\cos(\omega_x t \pm \omega_y t + \cdots) \end{aligned} \tag{3}$$

Workarounds which stabilize the cell capacitor voltages at those operating points are presented in the following sections.

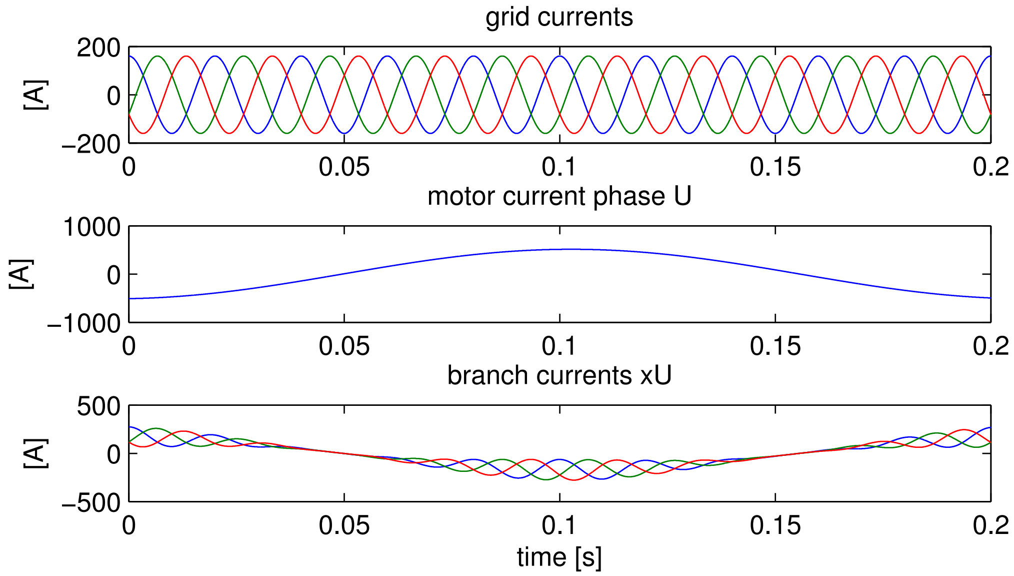


Fig. 2. Grid currents, a motor phase current and the respective branch currents in a direct MMC converter in instantaneous power mode (IPM, eq. 6). The motor is operating at 5 Hz, one-third of its nominal frequency.

### A. *Operation with asymmetric grid or load*

Nonzero mean branch powers will arise from asymmetric grid voltages or currents with the current sharing according to equation 2 because then the mean phase powers $P_z$ are not necessarily equal for all phases of a system and in turn the mean powers of the two phases connected by a branch will not necessarily sum up to zero. This can be corrected by dividing the phase current among branches according to the mean phase power at the opposite side of the branch („mean power mode" MPM):

$$i_{xy,MPM} = i_x \frac{P_y}{P_U + P_V + P_W} - i_y \frac{P_x}{P_R + P_S + P_T} \tag{4}$$

These branch currents lead to the correct phase currents provided that the phase currents are common mode free:

$$i_x = \sum_{y\in\{U,V,W\}} i_{xy,MPM} \overset{eq.4}{=} i_x \underbrace{\sum_{y\in\{U,V,W\}} \frac{P_y}{P_U + P_V + P_W}}_{\equiv 1} - \frac{P_x}{P_R + P_S + P_T} \underbrace{(i_U + i_V + i_W)}_{\equiv 0}$$

The branch power balance is not conditional on symmetric grid conditions anymore:

$$\begin{aligned} 0 &= P_U + P_V + P_W + P_R + P_S + P_T \text{ overall power balance} \\ p_{xy} &= u_{xy} i_{xy,MPM} \overset{eqs.1,4}{\sim} \underbrace{p_x P_y - p_y P_x}_{\text{zero mean}} - u_y i_x P_y + u_x i_y P_x \end{aligned} \tag{5}$$

### B. *Operation at large fundamental frequency ratios*

The nonzero mean branch powers that occur when the fundamental frequency of one of the connected systems is zero can be avoided by adjusting the distribution of the higher frequency phase currents $i_y$ among the connected branches with respect to the relative instantaneous phase powers of the zero frequency system:

$$i_{xy,IPM} = i_x \frac{p_y}{p_U + p_V + p_W} - i_y \frac{P_x}{P_R + P_S + P_T} \tag{6}$$

This will subsequently be referred to as „instantaneous power mode" (IPM). Figure 2 illustrates the phase and branch currents in IPM. IPM can also be used to reduce the capacitor voltage ripple magnitude when one system frequency is very low but not quite zero. The branch currents in IPM (eq. 6) lead to the correct phase currents provided that the phase currents are common mode free:

$$i_x = \sum_{y\in\{U,V,W\}} i_{xy,IPM} \overset{eq.6}{=} i_x \underbrace{\sum_{y\in\{U,V,W\}} \frac{p_y}{p_U+p_V+p_W}}_{\equiv 1} - \frac{P_x}{P_R+P_S+P_T} \underbrace{(i_U+i_V+i_W)}_{\equiv 0}$$

The resulting branch power has to be zero mean:

$$\begin{aligned}
p_{xy} &= u_{xy} i_{xy,IPM} \overset{eqs.1,6}{\sim} (p_x - P_x)p_y - i_x u_y p_y + u_x i_y P_x \\
&\quad \left\downarrow \begin{array}{lcl} i_z & \sim & \sin(\omega_z t + \phi_z) \\ u_z & \sim & \sin(\omega_z t + \phi_z) \end{array} \right. \\
&\sim A\cos(2\omega_x t + \cdots) + B\cos(2\omega_x t \pm 2\omega_y t + \cdots) \\
&\quad - C\cos(\omega_x t \pm \omega_y t + \cdots) + D\cos(\omega_x t \pm 3\omega_y t + \cdots) \\
&\quad + E\cos(\omega_x t \pm \omega_y t + \cdots)
\end{aligned}$$

The branch power is therefore nonzero-mean when $\omega_x = 0$, $\omega_x = \omega_y$ or $\omega_x = 3\omega_y$. Therefore IPM cannot be used at a frequency ratio of 3:1, MPM can be used however as shown in figure 3.

### *C. Operation with equal input and output fundamental frequencies*

Phasor notation can be used to analyze the branch power when the fundamental frequencies of both systems are identical. The sum of the first two terms of equation 5 remains zero mean, the last two terms of that equation can be written in phasor notation as:

$$\begin{aligned}
P &= \Re\{IU^*\}, U^* \text{ is the complex conjugate of } U \\
P_{xy} &\sim \cdots + \Re\{I_y U_x^* P_x - I_x U_y^* P_y\} \\
&\quad \left\downarrow \begin{array}{lcl} U_x & = & 1 \\ I_x & = & 1 + jQ_x \\ U_y & \in & \mathbb{C} \setminus \{0\} \\ I_y & = & (-1 + jQ_y)/U_y^* \end{array} \right. \\
&\sim \cdots + \Re\left\{\frac{-1 + jQ_y}{U_y^*} + (1 + jQ_x)U_y^*\right\} \\
&\sim \cdots + \cos(\angle U_y)\left(|U_y| - \frac{1}{|U_y|}\right) + \sin(\angle U_y)\left(Q_x|U_y| - \frac{Q_y}{|U_y|}\right)
\end{aligned} \tag{7}$$

The mean branch power $P_{xy}$ is therefore zero if both systems have identical voltages (in phase and magnitude, $U_y = 1$), which cannot be achieved for all branches in a converter at the same time. $P_{xy}$ also disappears if both the voltage magnitude and the reactive power are equal in both systems ($|U_y| = 1$ and $Q_x = Q_y$), the power converter would thus typically provide capacitive reactive power to both the motor and the grid in the case of a motor drive.

Further, common mode voltage and currents circulating in the MMC may be used to compensate for the nonzero mean branch power analogous to the low frequency operation for indirect MMC [5]. The converter must be designed to accommodate the extra currents and voltage in synchronous operation however, which would significantly increase the built-in switch power as synchronous operation is typically the dimensioning operating point anyway. This method is therefore not considered to be practical for direct MMC.

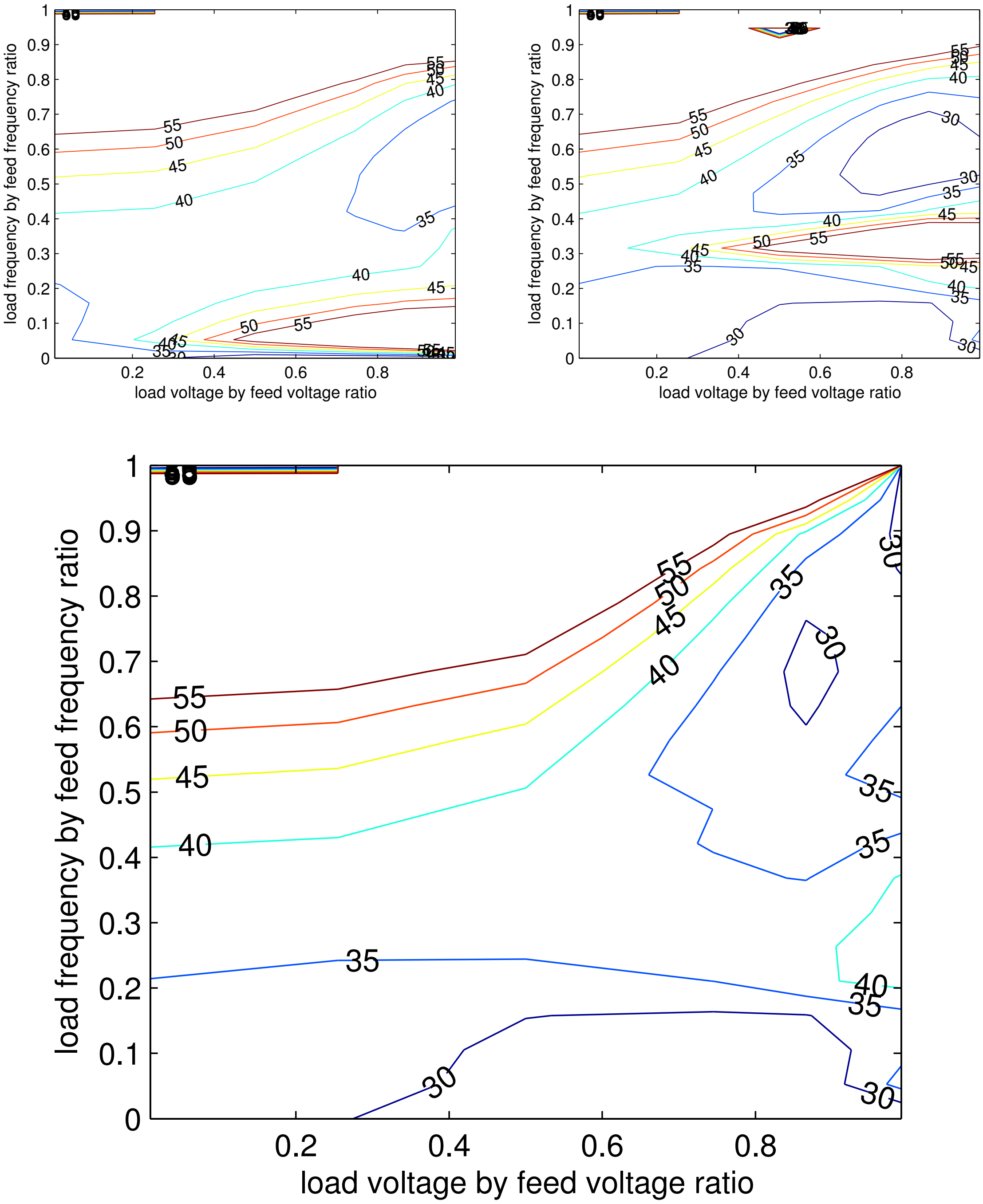


Fig. 3. Overall energy storage in J/kVA required to achieve a $\pm 10\%$ PEBB capacitor voltage ripple with a direct MMC in dependence of the load voltage and the load frequency. The plots are based on simulation results. The load current magnitude is constant and the inductive load has a $\cos(\varphi) = 0.95$. The supply frequency is 50 Hz. In the top left graph the current is shared among the branches according to the mean phase powers (MPM) and the grid $\cos(\varphi) = 1$. Operating points in the lower right corner of the graph are not economically reachable in MPM. In the top right graph current sharing is done with the instantaneous phase powers (IPM) and a grid $\cos(\varphi) = 1$. Branch energy instability occurs at a frequency ratio of 1:3 but the operating points in the lower right corner are now feasible. In the bottom graph IPM is used at load frequencies below 0.25 p.u., otherwise MPM is used. The reactive power of the load is mirrored to the grid side if both the frequency and voltage ratios are $> 0.5$ (i.e. in the top right quarter of the graph). The energy storage requirement is moderate below the diagonal from (0,0) to (1,1). The operating points of a VSD will be located below a line connecting the origin to the nominal point, which will typically be located on the right axis of the graph where the motor voltage equals the grid voltage.

## III. BUILT-IN POWER SEMICONDUCTOR SWITCH POWER

The built-in switch power $S_{IGBT} = \sum_{IGBT} I_{peak} U$ is a measure of power semiconductor silicon area and cost. It can be calculated from the peak branch current $I_{branch,peak}$ and the total capacitor voltage per branch $U_{\Sigma cap}$ and is subsequently used to compare different MMC variants.

$$\frac{S_{IGBT}}{S} = \frac{N_{branches} N_{IGBTperPEBB} U_{\Sigma cap} I_{xy,peak}}{\sqrt{3} U_{ll} I_{x,rms}}$$

### A. Direct MMC

The branch current of the direct MMC in MPM under symmetric grid conditions is descibed by equation 2. With equal RMS phase currents in phases X and Y $I_{x,rms} = I_{y,rms}$ but at distinct frequencies the branch peak current is

$$I_{xy,peak,MPM} = \frac{2\sqrt{2}}{3} I_{x,rms}$$

The total capacitor voltage per branch equals the peak line to line voltage if both systems have the same maximum voltage and third harmonic common mode voltages are injected.

In IPM the higher frequency current is modulated according to equation 6. The peak value of the weighting term $\frac{p_y}{p_U + p_V + p_W}$ is two-thirds as opposed to one-third as with the term used in MPM, accordingly the peak branch current becomes

$$I_{xy,peak,IPM} = \sqrt{2} I_{x,rms}$$

### B. Indirect MMC

The operating mode of the indirect MMC that corresponds to the MPM of the direct MMC uses branch currents equal to one-half the phase current and one-third the DC link current. The maximum DC-link current is $\sqrt{3/2} I_{x,rms}$. Thus the peak branch current is

$$I_{xy,peak,indirect} = I_{x,rms} \left( \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{6}} \right)$$

Circulating currents can be introduced in the converter to reduce the required PEBB capacity and the current stress on the capacitors [5, eq. 1]. The resulting branch current can also be written as $i_{xy} = i_x(1 + \cos(\omega t))/2$. The peak branch current is equal to the peak phase current

$$I_{xy,peak,icxcm} = \sqrt{2} I_{x,rms}$$

Further circulating currents must be introduced in the indirect MMC to limit the capacitor voltage ripple when operating with full current at low frequencies [5, $i_{cx,dm}$].

$$i_{cx,dm} = \sin(\omega_{cm} t) \sqrt{(2)} i_x \frac{u_x^2/u_P - u_P}{2U_{cm,rms}}$$

In the special case where the phase voltage is zero the entire voltage range can be used for the common mode voltage $U_{cm,rms}$ and the resulting $i_{cx,dm}$ will have the same magnitude as the phase current. The resulting peak branch current is the highest of all considered cases:

$$I_{xy,peak,LFM} = 2\sqrt{2} I_{x,rms}$$

If the load voltage is not zero, up to twice this switching power has to be installed if the common mode voltage magnitude is to be maintained. If the common mode voltage magnitude is reduced, higher circulating currents are needed. The former case is considered as an upper bound for the installed switch power needed for an indirect MMC for applications with low nominal frequencies.

TABLE I

COMPARISON OF TOTAL BUILT-IN SWITCHING POWER NORMALIZED TO RATED CONVERTER POWER.

| topology | branches | IGBT per PEBB | $\frac{U_{\Sigma cap}}{U_{ll}}$ | $\frac{I_{xy,peak}}{I_{x,rms}}$ | $\frac{S_{IGBT}}{S}$ |
|---|---|---|---|---|---|
| direct MMC MPM | 9 | 4 | 1 | 0.9428 | 19.60 |
| direct MMC IPM | 9 | 4 | 1 | 1.414 | 29.39 |
| indirect MMC | 12 | 2 | 1 | 1.115 | 15.45 |
| indirect MMC with $i_{cx,cm}$ | 12 | 2 | 1 | 1.414 | 19.60 |
| indirect MMC LFM | 12 | 2 | 1...2 | 2.828 | 39.19...78.38 |

### C. Summary

The built-in switch power $S_{IGBT}$ of direct MMC and indirect MMC are summarized in table I. The direct MMC operated in MPM has the same built-in switch power as the indirect MMC operated with $i_{cx,cm}$ as per [5, eq. 1]. This is possible even though the direct MMC needs 50% more switches because of the current sharing among the continuously conducting branches which also leads to a higher power rating of the direct MMC if compared to an indirect MMC built with the same IGBTs. The built-in switch power of the direct MMC rises by 50% when using IPM instead of MPM. This is the price to pay for the lower capacitance requirement at very low output frequencies and is still far lower than what indirect MMC would need when nominal current and voltage is required at all frequencies.

## IV. CONCLUSION

It has been shown that direct MMC are better suited than indirect MMC to variable speed drive applications with low nominal frequencies. Control methods have been developed which maintain stable capacitor voltages in the direct MMC while operateing with low output frequencies or with identical input and output frequencies. This opens high power low speed electric drive applications for MMC such as marine propulsion, SAG mills, hydro power, mine hoists, conveyors, wind turbines and soft motor starters.

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