A Novel Approach for Energy Balanced Operation of Submodules in Multilevel VSC HVDC Systems

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***Abstract*—The analysis of the characteristics of the operating behavior and functionality is essential to understand the MMC (modular multilevel converter) topology. Along with the basics of the operation mode the analysis of the stationary operation is the main interest. The operating performance is characterized by the switching events in order to balance the capacitor voltages. The balancing operations are based on the energy stored in the submodule capacitors. To reproduce the reference signal (sinusoidal signal) with a loss optimized switching frequency an adjustment of the balancing operations is necessary.**

In this paper different submodule drive methods were analyzed. Along with the classic drive methods (PWM) a new approach – the so called dynamic charge allocation (DCA) – was developed. In contrast to the PWM drive method the DCA drive method supplies a stable converter operation for low switching frequencies. As a result it is possible to calculate every capacitor voltage within the MMC converter. The DCA method allows a stable converter operation for low converter switching frequencies due to the developed predictive switching necessity function. Based on the capacitor voltages it is possible to define the necessity of energy balancing mechanisms which will be an indicator of the converter stability for each different drive method.

It is shown that for stationary operation no dynamic energy balancing mechanisms are necessary using PWM or DCA drive methods.

***Index Terms*— Balanced Capacitor Voltages, Energy Balanced Converter Operation, Modular Multilevel Converter, Submodule Drive Method, Voltage Source Converter.**

I. Introduction

Throughout the world multilevel converter technology gains more and more importance [1]. The technology is based on a series connection of capacitors, which are individually controlled by IBGTs which was introduced from Lesnicar and Marquardt in 2003 for HVDC applications [2]. Therefore MMC converters are able to generate any voltage waveform. The main characteristic of MMC converters is the independent control of active and reactive power. The series connection of controlled voltage sources (manifested in capacitors) enables a converter operation with low harmonic distortion and low switching frequency of each submodule [3, 4]. In comparison to classic HVDC technology self-commutated converters supply a low-loss operation with low need for filtering [4].

The reduced necessity of filtering and the ability to operate weak AC grids turns MMC converters into the key technology for the grid access of offshore wind farms [3].

Fig 1 a) shows the general setting of a MMC for HVDC applications. The converter consists of three phase units (so called phase modules). Each phase module is formed by two converter arms (upper and lower arm) containing a series connection of equally constructed submodules (SM) with a series inductor. The inductor suppresses circular currents within the converter and limits fault currents. The usual submodule topologies for HVDC applications are the half-bridge and the full-bridge circuit as shown in Fig 1 b) and c). This paper will concentrate on the use of half-bridge submodules only.

In stationary operation the current flowing through the phase modules of the converter (summation of all submodules in one phase) causes a periodic charge and discharge of the submodule capacitors. In every time cycle energy is consumed by the connected network and transferred to the DC side of the converter for rectifier operation and vice versa for inverter operation. For a stable stationary operation the consumed and the transferred energy in every time cycle has to be equal [3, 4].

To check the stability (balanced energy within the submodule capacitors) of the converter operation the capacitor voltages of every submodule has to be considered for the calculation.

$$E_{\mathrm{conv}}(t)=\frac{1}{2}\cdot C_{\mathrm{m}}\cdot v_{\mathrm{m}}(t)^2=\frac{1}{2}\cdot C_{\mathrm{SM}}\cdot N_{\mathrm{SM}}\cdot v_C(t)^2 \qquad (1)$$

E_{conv} = Energy within one converter arm
C_{m} = Capacitance of one converter arm
v_{m} = Desired module voltage
N_{SM} = Number of submodules within one converter arm
C_{SM} = Capacitance of the submodule capacitor
v_{C} = Capacitor voltage

The current flowing through the submodules defines the charge or discharge of every submodule respectively within the converter arms depending on the switching state (according to Fig 2). In the “ON” state of the submodule a positive current leads to a charge of the submodule capacitor whereas a negative current leads to a discharge of the capacitor. In the “OFF” state the submodule capacitor is bypassed and hence the capacitor will not be charged or discharged [3].

The switching state which is currently applied to the submodules is defined by the different submodule drive techniques in the next section.

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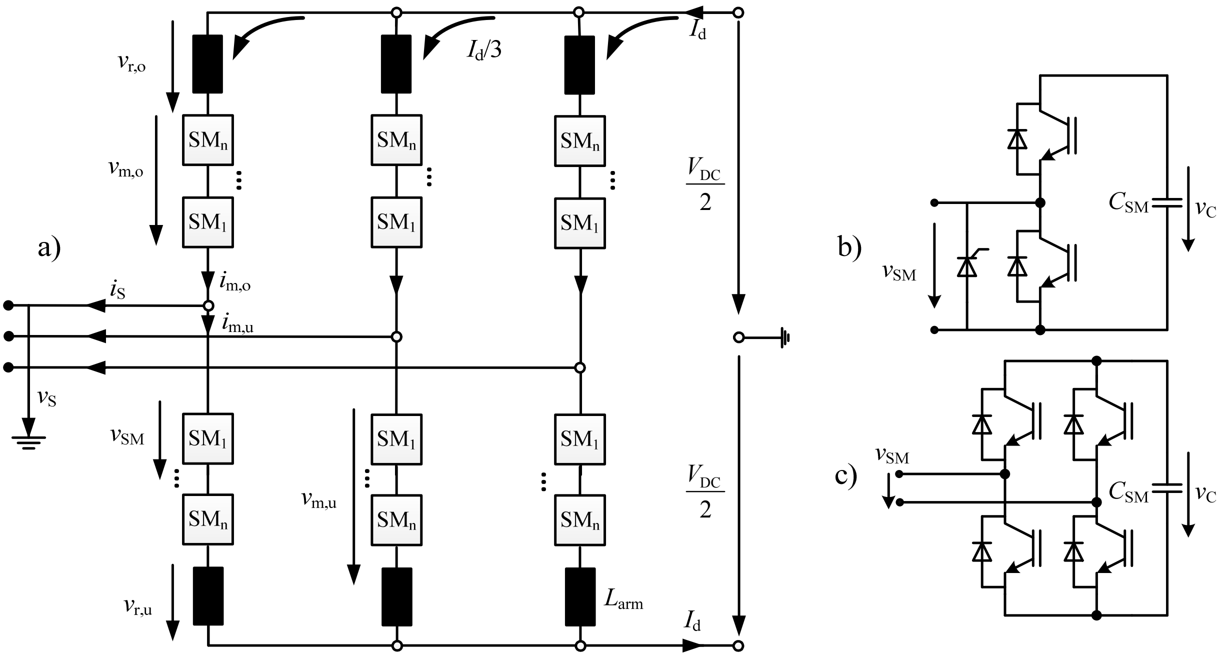

Fig 1: a) General MMC layout with b) half-bridge SM topology and c) full-bridge SM topology

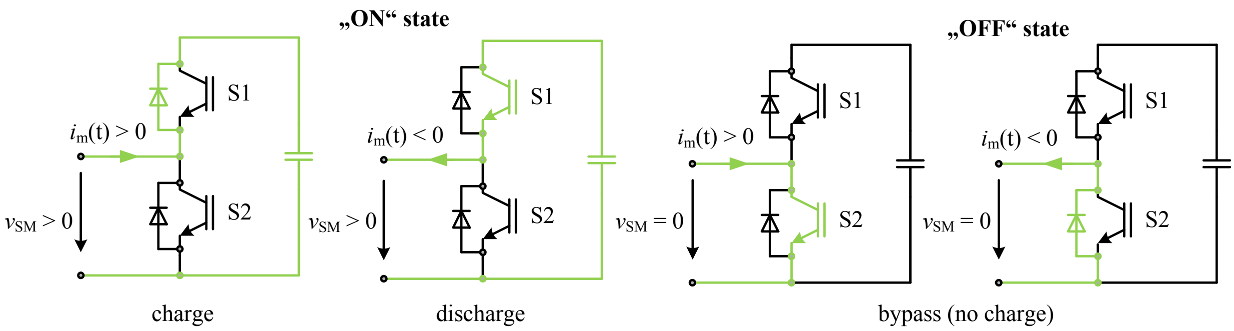

Fig 2: Operating states of the submodules dependent on the module current

Most papers regarding energy or voltage balancing in MMC converters are based on the PWM drive technique [5, 7, 8, 9, 10]. This paper introduces a new drive technique which doesn't use static reference signal comparison but a dynamic algorithm to identify the switching necessity. The dynamic of this algorithm allows a (energy) balanced operation of the MMC converter in stationary operation for high numbers of switching elements with a low switching frequency for an economic converter operation [6].

For the calculation it is assumed that the connected AC grid is symmetrical. With that assumption it is sufficient to calculate only one phase unit of the converter.

II. Analysis of Different Submodule Drive Methods

To drive the submodules there are currently two prevailing approaches: The classic PWM drive method or dynamic algorithm drive method. Due to the high number of submodules within the converter a separate controller for every submodule won't be economically realizable. To overcome this problem several quantities have to be measured during the operation of the converter to drive the submodules.

A. PWM Drive Method

The classic approach uses pulse width modulation (PWM) with triangular carrier signals to drive the submodules. The basis of every PWM gate control function is the assignment of one carrier signal for each submodule.

The switching event in the submodule is triggered once the reference signal (here: module voltage of the upper and lower converter arm) is greater than the carrier signal [5].

For this paper the classic PWM carrier signal techniques have been compared and checked whether a stable converter operation is possible using this drive method for multilevel converters.

The following PWM techniques have been analyzed: carrier disposition (CD), phase disposition (PD), phase

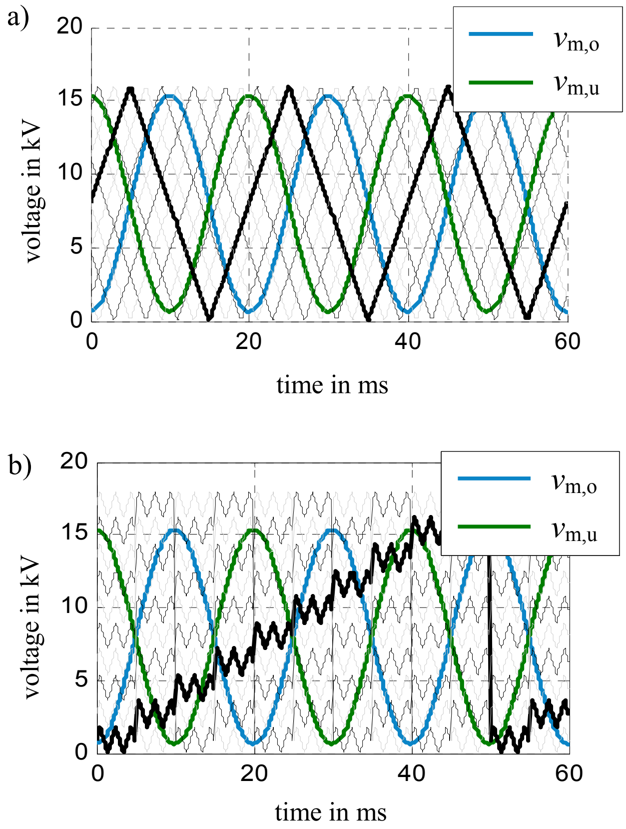

Fig 3: Schematic illustration of a) PWM-PSC and b) PWM-HPSC drive method

opposite disposition (POD), phase alternating opposite disposition (APOD) and phase shifted carrier (PSC). The PSC drive method represents the method usually used for multilevel converters. This technique only provides an adaptation of the carrier signal frequency in order to vary the switching frequency of the submodules since the phase shift of the signals is defined by the number of submodules in each converter arm (Fig 3 a) and Equation 2).

$$\varphi_D = \frac{360°}{N_{SM}} \tag{2}$$

To achieve more variance in adapting the switching pattern the HPSC (Hybrid PSC)-PWM method is introduced. With this method it is possible to vary the stacking of the single carrier signals of each submodule and the frequency of the carrier signal (Fig 3 b)).

To operate multilevel converters it is necessary to distribute the charge and discharge evenly along all submodules. Since the carrier signals of the CD, PD, POD and APOD method are stationary a dynamic carrier signal adaption in order to balance the charge distribution evenly is necessary. A thorough analysis of the CD, PD, POD and APOD drive method can be found in [5, 7, 8].

Fig 4 to Fig 6 show the time characteristics of the submodule capacitor voltages within one converter arm of the multilevel converter for different drive methods of the submodules. The illustrations show the voltage for the CD, HPSC and PSC drive method.

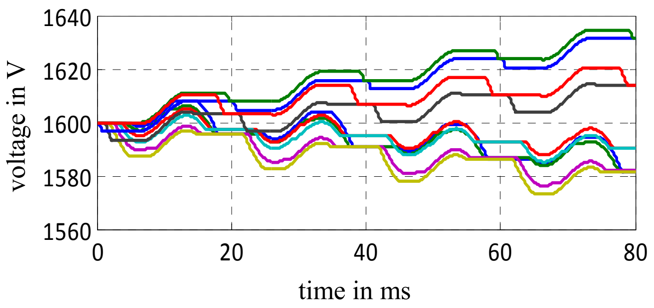

Fig 4: Capacitor voltages with CD drive method

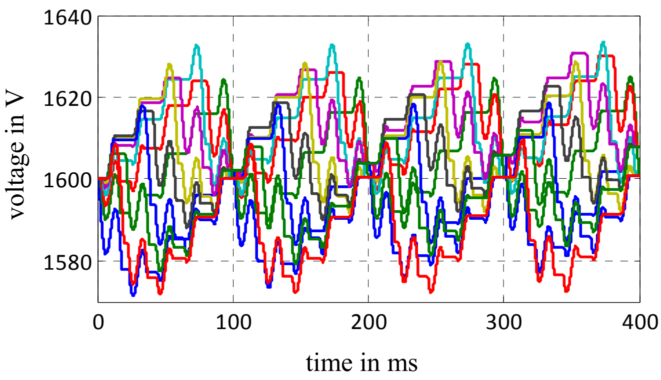

Fig 5: Capacitor voltages with HPSC drive method

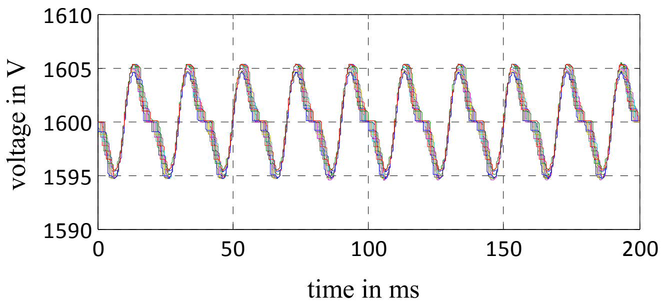

Fig 6: Capacitor voltages with PSC drive method

By reference to the spreading of the capacitor voltages of converters with CD (respectively PD, POD and APOD) drive method it can be stated that these drive methods lead to an uneven charge distribution along all submodules. Due to this unbalance these drive methods are not the preferred solution for multilevel converters.

With PSC and HPSC it is possible to receive a balanced charge distribution without a dynamic carrier signal adaption (no spreading of the capacitor voltages).

The main disadvantage of PWM drive techniques is the high switching frequency which is necessary to receive a balanced operation of the converter. For low switching frequencies a dynamic carrier signal adaption control is necessary to receive a balanced operation (refer to [5, 7, 8, 9, 10]).

B. DCA DRIVE METHOD

The second prevailing submodule drive method uses an algorithm in order to control the submodule switching once a switching event becomes necessary. According to [6] a switching algorithm for multilevel converters should consist of two switching criteria. The first switching criterion should determine a switching necessity in dependence of the desired voltage and the second switching criterion should select the best submodule to maintain a balanced operation.

Fig 8 shows the functionality of the developed DCA algorithm. The first switching criterion determines whether there is the necessity for a switching event. A switching event is triggered if the error between the provided voltage from the converter and the desired voltage becomes too big. The necessity of a switching event isn't set by a constant value but by a necessity function (predictive) within the algorithm. In this function the current error between the provided and the desired voltage is compared to the error of the resulting voltages after a switching event is performed. If it is possible to decrease the error by the next switching event the algorithm will trigger the switching event or won't give the switching command in case of an increase of the error respectively. Thereby it is guaranteed that the desired voltage gets reproduced properly by the converter.

The second switching criterion is a balancing function. For positive module currents (resulting charge of the submodules) the submodules with the lowest voltage and for negative module currents (resulting discharge of the submodule) the submodules with the highest voltage are selected to perform a switching event. This strategy makes sure that the charge distribution along all submodules is symmetrical. This method is called dynamic charge allocation (DCA).

Analyzing the time characteristic of the capacitor voltages of converters using the DCA drive method it can be stated that a stable converter operation is achieved for very small switching frequencies.

Using the DCA algorithm two ripples in the capacitor voltages occur (which can also be found at PWM drive method generated capacitor voltages). The first ripple is the amplitude of the capacitor voltage which is dependent on the submodule capacitance and the energy consumed by the connected AC grid (refer to Fig 7 ②). The second ripple is a result of the switching events in the converter which causes a deviation between the capacitor voltages of the submodules in the respective converter arm (this effect can be seen in Fig 7 ①).

For lower switching frequencies the voltage deviation between the capacitor voltages of the submodules increases. For stationary operation a greater ripple between each capacitor voltages of the submodules won't have a negative impact. For dynamic operations a large voltage ripple between the single capacitor voltages can cause a violation of the submodule voltage limits.

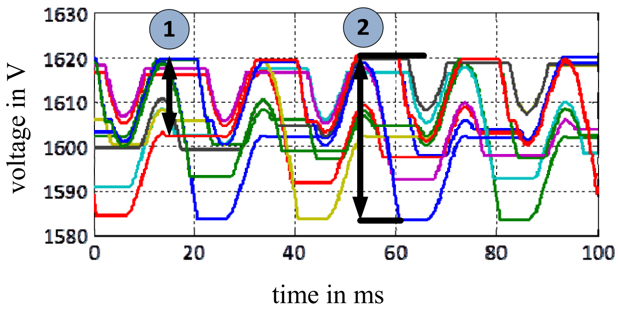

Fig 7: Capacitor voltages with DCA drive method

For high switching frequencies the deviation within the capacitor voltages of the converter reaches its minimum value i.e. every submodule obtains the same voltage. With decreasing switching frequency the deviation within the capacitor voltages increases. Since the switching frequency of the converter is dependent on many factors (operating point, voltages, size of the capacitor, etc.) it is necessary to introduce the factor *Korr* to control the switching frequency in order to maintain the same switching frequency for changing operating point conditions. This factor manipulates the actual value of the error E to generate a switching necessity at an earlier stage (by minimizing the actual error) or to delay a switching event (by enhancing the actual value of the error).

The resulting switching necessity function for the converter can be described as follows:

$$S_{\mathrm{N}} = \begin{cases} 1 \;\; \text{if } i_{\mathrm{m}} > 0 \wedge \left| v_{\mathrm{m}} - v_{\mathrm{provided}} + v_{\mathrm{C,min}} \right| < \left| E \right| + Korr \\ -1 \;\; \text{if } i_{\mathrm{m}} > 0 \wedge \left| v_{\mathrm{m}} - v_{\mathrm{provided}} - v_{\mathrm{SM,max}} \right| < \left| E \right| + Korr \\ 1 \;\; \text{if } i_{\mathrm{m}} < 0 \wedge \left| v_{\mathrm{m}} - v_{\mathrm{provided}} + v_{\mathrm{C,max}} \right| < \left| E \right| + Korr \\ -1 \;\; \text{if } i_{\mathrm{m}} < 0 \wedge \left| v_{\mathrm{m}} - v_{\mathrm{provided}} - v_{\mathrm{SM,min}} \right| < \left| E \right| + Korr \\ 0 \;\; \text{else} \end{cases}, \quad (3)$$

where:

1 corresponds to a switch on necessity of the submodule,
-1 corresponds to a switch off necessity of the submodule,
0 corresponds to no switching necessity of the submodule.

III. CONCLUSION AND COMPARISON OF THE DRIVE METHODS

TABLE I shows an overall comparison of the analyzed PWM drive methods and the DCA drive method. The exemplary input variables being used for the analysis of the different drive methods are listed in TABLE II.

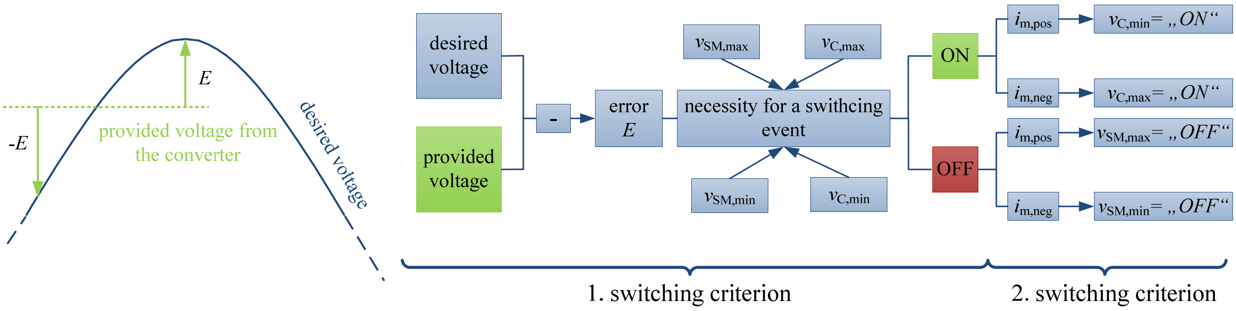

Fig 8: Schematic representation of the DCA algorithm

TABLE I
COMPARISON OF THE ANALYZED DRIVE METHODS

	CD-PWM[1]	**PSC-PWM**	**HPSC-PWM**	**DCA**
Switching criterion	$V_{Ref} > v_C$[2]	$V_{Ref} > v_C$	$V_{Ref} > v_C$	algorithm
Realizable number of voltage steps	2	no limit	no limit	no limit
Phase disposition of the. carrier signal	0°-180°	defined[3]	0°-180°	n.a.
Dynamic of the submodule drive method	n.a.	n.a.	n.a.	high
Adaption of the switching frequency	f_D and φ_D[4]	f_D	f_D and *Stap*	*Korr*
Switching frequency (stable stationary operation)	very high (kHz)	high	high	low
Effort of implementation	simple	complex	complex	medium

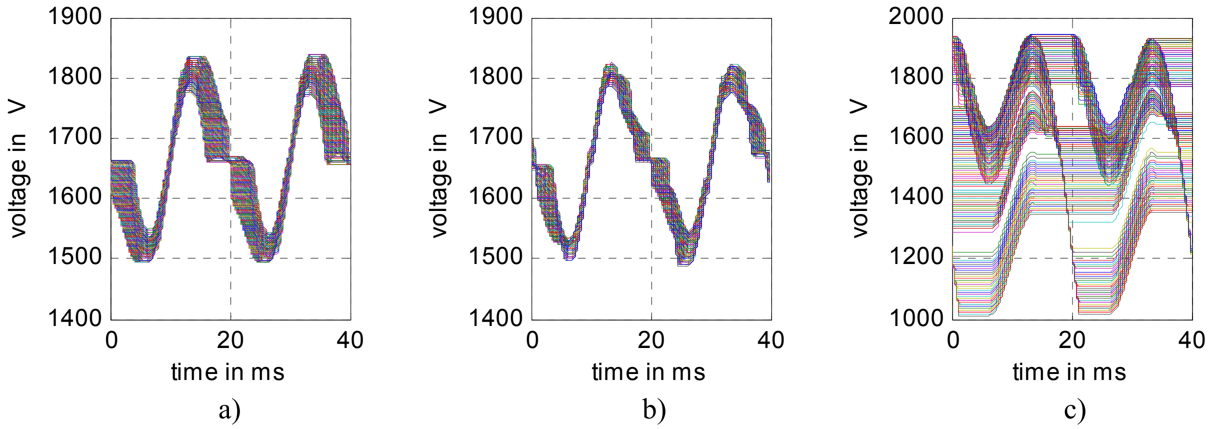

Fig 9: a) capacitor voltages with PWM-PSC method (f_s = 400 Hz) b) capacitor voltages with PWM-HPSC method (f_s = 696 Hz) c) capacitor voltages with DCA method (f_s = 114 Hz)

[1] PD, POD or APOD respectively
[2] Reference signal/driving signal > carrier signal
[3] Refer to equation (2)
[4] Frequency of carrier signal and phase disposition of the carrier signals

It can be shown that with exception of CD, PD, POD, and APOD all submodule drive methods generate stable capacitor voltages at a certain switching frequency (no spreading of the capacitor voltages; refer to Fig 9). Thus no energy balancing mechanisms are active during stationary operation using PWM (PSC, HPSC) or DCA drive method and thereby a separate capacitor voltage control function is not necessary.

The main challenge of the PWM drive method is the stable energy distribution along all submodules which can only be achieved by using high carrier signal frequencies which lead to high switching frequencies in stationary operation.

The DCA method provides a stable stationary operation for low switching frequencies (in comparison to PWM drive techniques) due to the switching necessity function. Therefore DCA drive method is the preferable solution for a loss optimized operation of a MMC converter.

The low switching frequency results in a higher voltage ripple (between the submodule capacitors of one converter arm of the converter; refer to Fig 9 acc. to Fig 7 ①). In stationary operation higher voltage ripples are not problematic. For dynamic operation (e.g. faults in the connected AC grid) a lower voltage ripple should be aspired to avoid a complete discharge of the submodules.

TABLE II
PARAMETERS FOR CONVERTER CALCULATION

Input variables	**Value**
Converter reactor: L_{arm}	50 mH
Capacitance of submodule capacitor: C_{SM}	10 mF
Number of submodules: N_{SM}	400
Active power: P	1000 MW
Reactive power: Q	0 MVar
Effective submodule voltage: $V_{\text{SM,eff}}$	1600 V
DC voltage: V_{DC}	640 kV
AC voltage: $V_{\text{RS=ST=TR}}$	380 kV
Carrier signal frequency PSC-PWM: f_{PSC}	200 Hz
Phase disposition of the carrier signals (PSC-PWM): φ_{PSC}	0.9°
Carrier signal frequency HPSC-PWM: f_{HPSC}	100 Hz
Number of carrier stacking actions per period: N_{STACK}	2500
Phase disposition of the carrier signals (PSC-PWM): φ_{HPSC}	0°
Error correction factor: *Korr*	0

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