Letters

Enhancing the Reliability of Modular Multilevel Converters Using Neutral Shift

Jakub Kucka, *Student Member, IEEE*, Dennis Karwatzki, *Student Member, IEEE*, and Axel Mertens, *Member, IEEE*

***Abstract*—This letter presents an approach for modular multilevel converters that enables a stable operation with failed nonredundant modules. This is achieved by using a neutral shift with a dedicated power feed-forward control. The feasibility of the approach is verified by simulation.**

***Index Terms*—Availability, failed module, HVDC, modular multilevel converter (MMC), redundancy, reliability.**

I. Introduction

THE modular multilevel converter (MMC) has already become a standard in HVDC applications and is a valid option for medium-voltage high-power drives. Since this topology has first been presented by Marquardt *et al.* [1], a lot of efforts have been invested into this research area.

The advantages of this topology are not only its simple scalability to higher voltage levels with the use of low-voltage devices, and low harmonic distortion because of its multilevel property, but also the simply applicable redundancy providing a high reliability and availability of the converter. This can be achieved by adding redundant modules in series to the other modules in the branch. If a failure occurs in one module, the output of this module can be short-circuited and the converter can continue its operation with the remaining modules.

In the patent by Winkelnkemper and Apeldoorn [2], an approach for MMC with space-vector modulation is presented, which enables converter operation even if some nonredundant modules have failed. The approach is based on avoiding those redundant switching states that cannot be synthesized because of failed modules. Nevertheless, the approach is strongly linked to the modulation strategy and, thus, inherits its drawbacks, such as very high complexity for a large number of modules.

Another approach for maximizing the output voltage after module failure without redundant modules, called neutral shift, was primarily presented for the cascaded H-bridge converter by Hammond in [3]. The possibility to use this approach with MMC was first discussed by the authors of this letter in [4]. In the paper, the capability of this approach in wind energy applications for different modular multilevel topologies, i.e., MMC, Modular Multilevel Matrix Converter, and Hexverter, was investigated. However, the neutral shift is used only at the ac side with MMC. Recently, a paper by Yang *et al.* [5] applying the neutral shift to the ac side was published, with regard to MMC applications with uncontrolled dc-side and circulating currents. Another recent paper by Li *et al.* [6] presents a direct voltage injection in the star-point voltage (results in neutral shift at the dc side) for MMC. However, the need for a proper power feed-forward control is not mentioned there. Consequently, the authors of that paper conclude that the implemented approach causes a module voltage imbalance between the branches.

The main contribution of this letter is the simultaneous usage of the neutral shift on both ac and dc side. This would not be possible without controlling the dc-side and circulating currents (decoupled current control; e.g., [7]–[9]) and a dedicated feed-forward control. Contrary to the aforementioned papers, the voltage available by the redundant modules is used to compensate for the missing branch voltage in branches where also nonredundant modules failed (although the principles described in this letter are generally valid), as the converter ac-side voltage cannot be reduced in most applications.

II. Converter Description

The MMC is depicted in Fig. 1. It comprises six branches, each consisting of branch inductor—denoted with L_{b}—and series-connected modules. Depending on the application, full-bridge or half-bridge modules can be used.

The converter branches can be viewed as ideal voltage sources setting the branch voltages $v_{\mathrm{b},1..6}$ (as a mean value during a short modulation period) in order to set the star-point voltage v_{st} and control the currents at the ac side $i_{\mathrm{A}}, i_{\mathrm{B}}, i_{\mathrm{C}}$, the dc side i_{dc}, and the circulating currents $i_{\mathrm{cir},1}$, $i_{\mathrm{cir},2}$. In the literature, there are several definitions for these currents; in this letter, the following is used ($i_{\mathrm{b},1..6}$ are branch currents):

$$\begin{bmatrix} i_{\mathrm{cir1}} \\ i_{\mathrm{cir2}} \end{bmatrix} = \frac{1}{4} \cdot \begin{bmatrix} i_{\mathrm{b1}} + i_{\mathrm{b2}} - i_{\mathrm{b3}} - i_{\mathrm{b4}} \\ i_{\mathrm{b3}} + i_{\mathrm{b4}} - i_{\mathrm{b5}} - i_{\mathrm{b6}} \end{bmatrix}. \quad (1)$$

III. Main Idea

If a nonredundant module fails in one branch, the maximum achievable voltage that can be synthesized by the modulation is reduced, not allowing to continue a normal operation of the

Manuscript received February 22, 2017; revised March 22, 2017; accepted April 10, 2017. Date of publication April 18, 2017; date of current version August 2, 2017. *(Corresponding author: Jakub Kucka.)*

The authors are with the Institute for Drive Systems and Power Electronics, Leibniz Universität Hannover, Hannover 30167, Germany (e-mail: jakub.kucka@ial.uni-hannover.de; dennis.karwatzki@ial.uni-hannover.de; mertens@ial.uni-hannover.de).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPEL.2017.2695327

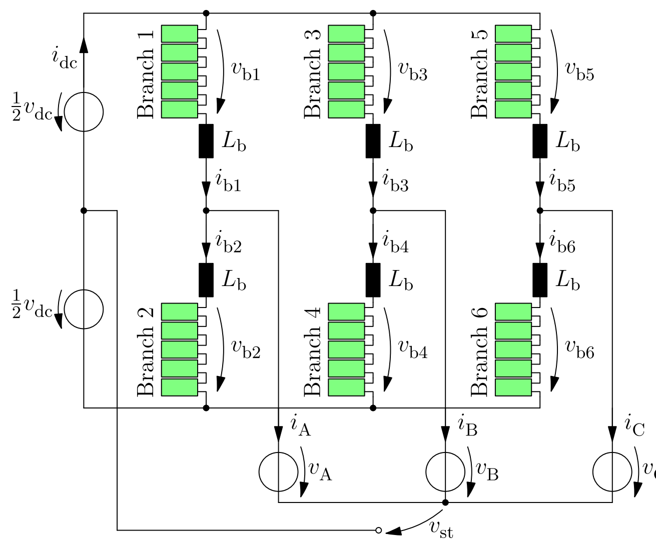

Fig. 1. Modular mutlilevel converter.

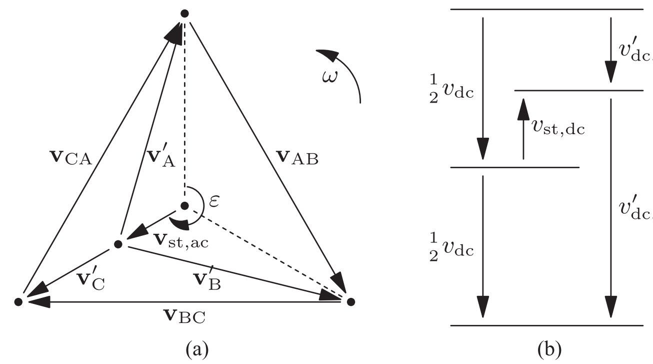

Fig. 2. Neutral-shift principle. (a) ac side: $\mathbf{v}'_{\rm A..C}$ are the shifted voltage phasors, $\mathbf{v}_{\rm st,ac}$ represents the ac component of $v_{\rm st}$, the phasors $\mathbf{v}_{\rm AB}$, $\mathbf{v}_{\rm BC}$, $\mathbf{v}_{\rm CA}$ represent the line-to-line voltages. (b) dc side: The virtual midpoint is shifted using the star-point voltage dc component $v_{\rm st,dc}$ splitting the dc-side voltage $v_{\rm dc}$ unequally between the upper $v'_{\rm dc,u}$ and lower branches $v'_{\rm dc,d}$.

converter. In [6], it is shown that in this case, the currents are distorted and the voltages in the module capacitors rise unintentionally to critical levels.

The main idea of this letter is to change the voltage sharing between the branches in a way that the missing voltage (of a branch with failed nonredundant modules) will be compensated by the branches comprising redundant modules. The voltage sharing between the branches is shifted using star-point voltage $v_{\rm st}$, which is a degree of freedom in MMC and does not disturb the current control.

However, the injected dc term in the star-point voltage interacts with the dc component of the dc-side current $i_{\rm dc}$. Similarly, the ac term in the injected voltage interacts with the ac terms in the ac-side currents $i_{\rm A..C}$. This leads to constant power terms $P_{\rm b,1..6}$ in different branches, which cause an imbalance in the branch energy $e_{\rm b,1..6}$ (causing potentially critical levels of the module capacitor voltages). In order to compensate these power terms, a dedicated power feed-forward control using circulating currents must be applied.

IV. Neutral-Shift Principle

For the following investigation, it is assumed that the current $i_{\rm dc}$ and voltage $v_{\rm dc}$ at the dc side are constant values $I_{\rm dc}$ and $V_{\rm dc}$, respectively. (Nevertheless, the principle is valid also for ac-ac MMC.) The ac-side voltage $v_{\rm A}$ and current $i_{\rm A}$ comprise only one harmonic term with angular speed $\omega = 2 \cdot \pi \cdot f$

$$v_{\rm A}(t) = \hat{v}_{\rm ac} \cdot \cos(\omega \cdot t) \tag{2}$$

$$i_{\rm A}(t) = \hat{i}_{\rm ac} \cdot \cos(\omega \cdot t - \varphi). \tag{3}$$

The ac-side voltages and currents $v_{\rm B}$, $i_{\rm B}$ and $v_{\rm C}$, $i_{\rm C}$ are symmetrically shifted by 120°.

In order to apply a neutral shift to the ac side of the converter, an ac star-point voltage component $v_{\rm st,ac}$, rotating with the frequency of the ac system, must be included. To apply it to the dc side, a dc component $v_{\rm st,dc}$ must be present. The resulting star-point voltage

$$v_{\rm st} = \underbrace{\hat{v}_{\rm st,ac} \cdot \cos(\omega t - \varepsilon)}_{v_{\rm st,ac}} + \underbrace{V_{\rm st,dc}}_{v_{\rm st,dc}} \tag{4}$$

is the sum of both components.

To investigate the maximum of the branch voltage values, the components at each frequency must be cumulated

$$v'_{\rm A} = v_{\rm A} + v_{\rm st,ac}, \quad v'_{\rm B} = v_{\rm B} + v_{\rm st,ac}, \quad v'_{\rm C} = v_{\rm C} + v_{\rm st,ac} \tag{5}$$

$$v'_{\rm dc,u} = \frac{1}{2} \cdot v_{\rm dc} - v_{\rm st,dc}, \quad v'_{\rm dc,d} = \frac{1}{2} \cdot v_{\rm dc} + v_{\rm st,dc}. \tag{6}$$

Neglecting the voltage drop across branch inductances, the maximum required branch voltages are calculated using amplitudes of $v'_{\rm A}$, $v'_{\rm B}$, and $v'_{\rm C}$ and the direct voltage values of $v'_{\rm dc,u}$ and $v'_{\rm dc,d}$

$$\begin{bmatrix} v_{\rm b1,max} \\ v_{\rm b2,max} \\ v_{\rm b3,max} \\ v_{\rm b4,max} \\ v_{\rm b5,max} \\ v_{\rm b6,max} \end{bmatrix} = \begin{bmatrix} V'_{\rm dc,u} \\ V'_{\rm dc,d} \\ V'_{\rm dc,u} \\ V'_{\rm dc,d} \\ V'_{\rm dc,u} \\ V'_{\rm dc,d} \end{bmatrix} + \begin{bmatrix} \hat{v}'_{\rm A} \\ \hat{v}'_{\rm A} \\ \hat{v}'_{\rm B} \\ \hat{v}'_{\rm B} \\ \hat{v}'_{\rm C} \\ \hat{v}'_{\rm C} \end{bmatrix}. \tag{7}$$

In the normal operation state without neutral shift, the amplitudes $\hat{v}'_{\rm A}$, $\hat{v}'_{\rm B}$, and $\hat{v}'_{\rm C}$ have the same value. The direct voltage $v_{\rm dc}$ is divided equally between the direct voltage values $V'_{\rm dc,u}$ and $V'_{\rm dc,d}$.

If some modules fail, for example in Branch 5, the maximum available voltage in Branch 5 $v_{\rm b5,max}$ is reduced. According to (7), in order to continue the converter operation, the value $V'_{\rm dc,u}$ or $\hat{v}'_{\rm C}$ must also be reduced.

The value of $\hat{v}'_{\rm C}$ can be reduced with a star-point voltage vector $\mathbf{v}_{\rm st,ac}$ with the phase angle of the vector $\mathbf{v}_{\rm C}$, see Fig. 2(a). Accordingly, the amplitudes of voltages $v'_{\rm A}$ and $v'_{\rm B}$ rise. The corresponding additionally required branch voltage is covered by the redundant modules in branches 1, 2, 3, and 4.

The value of $V'_{\rm dc,u}$ is reduced with a positive value of the star-point voltage dc component $V_{\rm st,dc}$ (6), see Fig. 2(b). The value of $V'_{\mathrm{dc,d}}$ rises. The additional branch voltage is covered by the redundant modules in branches 2, 4, and 6.

The neutral shift can also be applied to both sides at the same time. This way, part of the missing voltage in Branch 5 would be compensated by the direct voltage component of star-point voltage $v_{\mathrm{st,dc}}$ and part by the component $v_{\mathrm{st,ac}}$.

Note that if the voltage drops across the inductances are not negligible, the ac-side voltages $v_{\mathrm{A..C}}$ must be corrected by the voltage drop estimated using ac-side currents $i_{\mathrm{A..C}}$—e.g., $\mathbf{V}_{\mathrm{A,corr}} = \mathbf{V}_{\mathrm{A}} - j \cdot \omega \cdot \frac{L_{\mathrm{b}}}{2} \cdot \mathbf{I}_{\mathrm{A}}$. After the correct voltage amplitudes are estimated, exactly the same principles can be used.

V. Power Feed-Forward Control

The additional components in the star-point voltage needed for the neutral shift are combined with the currents of the connected systems, resulting in the constant power imbalances between the branches. These power terms are disturbances for the branch energy control and must be compensated for a good dynamic behavior with a feed-forward control. For the feed-forward control, the circulating currents

$$\begin{aligned} i_{\mathrm{cir1}} &= \hat{i}_{\mathrm{cir1},\alpha} \cdot \cos(\omega t) + \hat{i}_{\mathrm{cir1},\beta} \cdot \sin(\omega t) + I_{\mathrm{cir1,dc}} \\ i_{\mathrm{cir2}} &= \hat{i}_{\mathrm{cir2},\alpha} \cdot \cos(\omega t) + \hat{i}_{\mathrm{cir2},\beta} \cdot \sin(\omega t) + I_{\mathrm{cir2,dc}} \end{aligned} \tag{8}$$

are used.

The component of star-point voltage $v_{\mathrm{st,ac}}$ interacts with ac-side currents i_{A}, i_{B}, and i_{C}, causing a constant power imbalance $\Delta P_{\mathrm{b}\{x,y\}}$ at the particular branches x and y

$$\begin{bmatrix} \Delta P_{\mathrm{b}\{1,2\}} \\ \Delta P_{\mathrm{b}\{3,4\}} \\ \Delta P_{\mathrm{b}\{5,6\}} \end{bmatrix} = -\frac{1}{4} \cdot \hat{v}_{\mathrm{st,ac}} \cdot \hat{i}_{\mathrm{ac}} \cdot \begin{bmatrix} \cos(\varepsilon - \varphi) \\ \cos\left(\varepsilon - \varphi - \frac{2}{3} \cdot \pi\right) \\ \cos\left(\varepsilon - \varphi - \frac{4}{3} \cdot \pi\right) \end{bmatrix}. \tag{9}$$

The power disturbance introduced by the ac component of the star-point voltage must be compensated with the dc component of the circulating currents. In this case, there is only one unique solution for the feed-forward control

$$\begin{bmatrix} I_{\mathrm{cir1,dc}} \\ I_{\mathrm{cir2,dc}} \end{bmatrix} = \frac{1}{V_{\mathrm{dc}}} \cdot \begin{bmatrix} \Delta P_{\mathrm{b}\{1,2\}} - \Delta P_{\mathrm{b}\{3,4\}} \\ \Delta P_{\mathrm{b}\{3,4\}} - \Delta P_{\mathrm{b}\{5,6\}} \end{bmatrix}. \tag{10}$$

In a similar way, the power disturbance introduced by the dc component of the star-point voltage must be compensated with the ac components of the circulating currents. To find a solution for the feed-forward control, the constant branch-power components $P_{\mathrm{b},1..6}$ must be determined as functions of the considered parameters, in the first step, and set to zero, as the nonzero values lead to energy imbalance (11). These parameters are $V_{\mathrm{st,dc}}$ and I_{dc}, which cause the power disturbances, and $\hat{i}_{\mathrm{cir1},\alpha}$, $\hat{i}_{\mathrm{cir1},\beta}$, $\hat{i}_{\mathrm{cir2},\alpha}$, and $\hat{i}_{\mathrm{cir2},\beta}$, which are used with the component $\hat{v}_{\mathrm{ac}}$ to compensate those

$$P_{\mathrm{b},1..6} = f(V_{\mathrm{st,dc}}, I_{\mathrm{dc}}, \hat{v}_{\mathrm{ac}}, \hat{i}_{\mathrm{cir1},\alpha}, \hat{i}_{\mathrm{cir1},\beta}, \hat{i}_{\mathrm{cir2},\alpha}, \hat{i}_{\mathrm{cir2},\beta}) = 0 \tag{11}$$

Solving this set of equations for the circulating-current amplitudes shows that there is no unique solution. In this case, there are only three independent equations in the equation set, while there are four degrees of freedom ($\hat{i}_{\mathrm{cir1},\alpha}$, $\hat{i}_{\mathrm{cir1},\beta}$, $\hat{i}_{\mathrm{cir2},\alpha}$, and $\hat{i}_{\mathrm{cir2},\beta}$) to synthesize the ac components of the circulating currents. Consequently, an optimisation for the sum of rms branch currents (similar to the one in [9]) is used to find the solution.

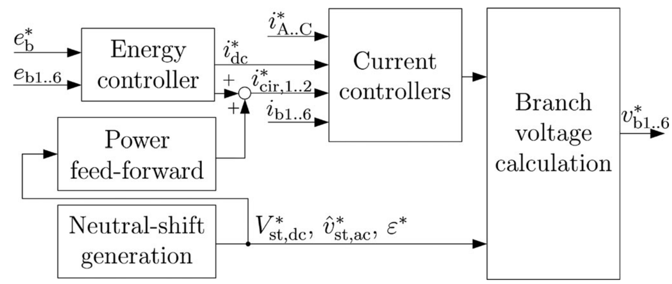

Fig. 3. Simplified control scheme with neutral-shift generation and power feed forward; variables marked with * represent setpoint values. The signals with estimated ac-side angle and voltage, and dc-side voltage are not shown.

The set of equations is solved for $\hat{i}_{\mathrm{cir1},\alpha}$, $\hat{i}_{\mathrm{cir1},\beta}$, and $\hat{i}_{\mathrm{cir2},\alpha}$ as a function of $\hat{i}_{\mathrm{cir2},\beta}$. Using (1), the branch-current amplitudes considering only the ac components of the circulating currents $\hat{i}_{\mathrm{b},1..6,\mathrm{cir}}$ can be determined as functions of $\hat{i}_{\mathrm{cir2},\beta}$. Finally, the optimization equation

$$0 = \frac{\partial}{\partial \hat{i}_{\mathrm{cir2},\beta}} \left(\sum_{k=1}^{6} \hat{i}^2_{\mathrm{b},k,\mathrm{cir}}(\hat{i}_{\mathrm{cir2},\beta}) \right) \tag{12}$$

determines the solution for feed-forward control with minimum impact on the rms value of the branch currents

$$\begin{bmatrix} \hat{i}_{\mathrm{cir1},\alpha} \\ \hat{i}_{\mathrm{cir1},\beta} \\ \hat{i}_{\mathrm{cir2},\alpha} \\ \hat{i}_{\mathrm{cir2},\beta} \end{bmatrix} = \frac{1}{6} \cdot \frac{I_{\mathrm{dc}} \cdot V_{\mathrm{st,dc}}}{\hat{v}_{\mathrm{ac}}} \cdot \begin{bmatrix} -3 \\ \sqrt{3} \\ 0 \\ -2\sqrt{3} \end{bmatrix}. \tag{13}$$

Note that an additional cross-coupling power disturbance caused by the ac components of circulating currents and star-point voltage appears, if the neutral shift is applied to both converter sides. A similar power disturbance is caused by the combination of the dc components. These small disturbances can either be handled by a closed-loop energy control, or treated as a part of the (significantly more complex) solution for the feed-forward control.

VI. Simulation Results

To better illustrate the principle of neutral-shift and feed-forward control, a simulation was performed. In this simulation, an MMC with 22 full-bridge modules per branch was investigated. The control scheme presented in [9] extended by the feed-forward control and modulation with sorting based balancing were used for the converter control. The extension of the control can be seen in Fig. 3. This comprises the neutral-shift generation unit, which generates the setpoint values for the star-point voltage, and power feed-forward control, which calculates the setpoints for the circulating currents according to (10) and (13). These setpoint values are then added to the setpoint

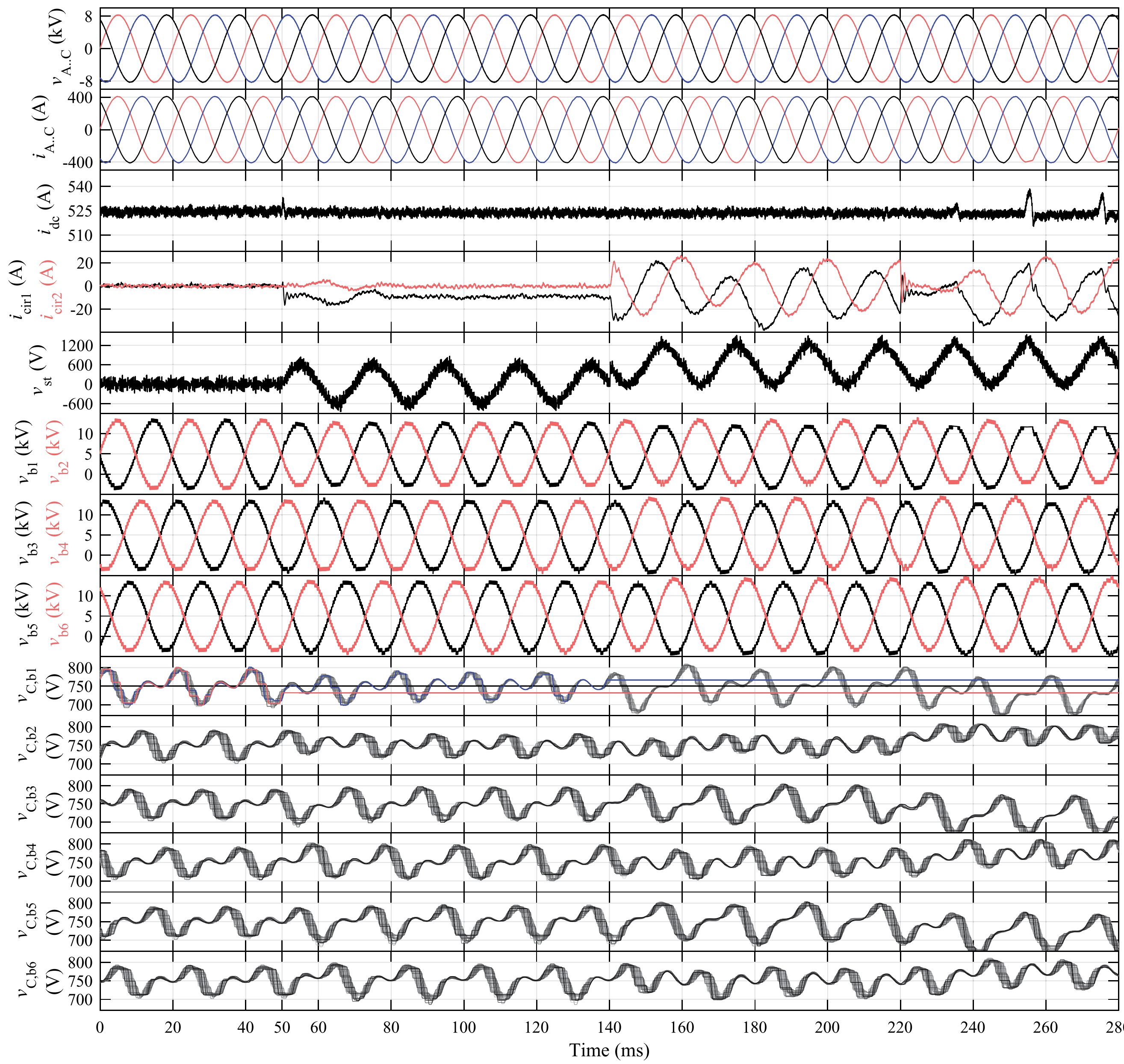

Fig. 4. Simulation of MMC operation. Four modules have already failed in Branch 1 at time $t = 0$ ms. At times $t = 50$ ms and $t = 140$ ms, another module failed in Branch 1. The fifth failed module is compensated with a neutral shift on the ac side, the sixth one with a neutral shift on the dc side. At time $t = 220$ ms, the feed-forward control is disabled to demonstrate its function for energy balancing.

values obtained from the closed-loop branch energy control. The simulation parameters are listed in Table I. The simulation results are depicted in Fig. 4.

At time $t = 0$ ms, all four redundant modules have already failed in Branch 1. It can be seen that the converter operates normally without any current disturbances and with module voltages within the specified range.

At time $t = 50$ ms, another module fails at Branch 1. The missing branch voltage is compensated using the ac neutral shift in the star-point voltage. As visible in the figure, the branch voltage at branches 1 and 2 is reduced, while higher branch voltage is required at branches 3, 4, 5, and 6. The module capacitor voltage of the failed module stays constant, as it is not part of the modulation anymore. The feed-forward control causes a dc component in Circulating Current 1. The system currents and module capacitor voltages are controlled stably without any disturbances.

At time $t = 140$ ms, another module fails at Branch 1. This time, the missing voltage is compensated by the dc neutral shift at the star-point voltage. The voltage at Branch 1 is further reduced, the voltages in branches 2, 4, and 6 rise. Besides, additional ac components appear in circulating currents as a result of the power feed-forward control. Note, that the dc circulating current component remains, as there is still an ac component in the star-point voltage.

It must be mentioned that these additional circulating current components lead to slightly higher branch currents. If these

TABLE I
SIMULATED CONVERTER PARAMETERS

Transmitted power	P	2 MW
Reactive power	Q	0
AC-side frequency	f	50 Hz
AC-side line-to-line voltage	V_{ac}	10 kV
DC-side voltage	V_{dc}	10 kV
Modules per branch	n_{mod}	22
Redundant modules per branch	n_{red}	4
Maximum module voltage	$V_{\mathrm{c,max}}$	800 V
Module capacitance	C_{mod}	4 mF
Branch inductance	L_{b}	6 mH
Modulation frequency	f_{m}	6 kHz

higher currents cannot be managed by the branch modules, the output power must be reduced. Similarly, if the branch energy variation cannot be buffered by the remaining branch modules, the output power must also be reduced.

At time $t = 220$ ms, the feed-forward control is disabled to demonstrate the need for it. As we can see in Fig. 4, this leads to an energy imbalance between the branches. Consequently, the required voltage cannot be synthesized in some branches, which leads to current disturbances. We can also see that approximately after one period, the energy controllers try to compensate for the missing feed-forward control and generate circulating currents similar to those, the feed-forward control generated before being disabled.

VII. CONCLUSION

In this letter, an approach to enhance the reliability and availability of MMCs based on neutral shift was presented. To stabilize the branch energy control, a novel feed-forward power control was derived.

The main benefit of this approach is that it can be implemented for existing converters without any necessary hardware changes. The only limiting factors for the approach are the number of redundant modules, which can be used for neutral shift, and the ability of remaining modules to handle the energy variation and additional branch current components. If these cannot be handled by the modules, the converter power must be reduced accordingly. The analysis of the remaining operating area must be performed based on the particular converter design.

Future research will concentrate on experimental implementation of the approach and application to other modular multilevel topologies. Furthermore, the strategies for choosing the amount of branch voltage compensated by the ac-side neutral shift and the one compensated by the dc-side neutral shift will be investigated.

REFERENCES

[1] R. Marquardt, A. Lesnicar, and J. Hildinger, “Modulares Stromrichterkonzept für Netzkupplungsanwendungen bei hohen Spannungen,” in *ETG-Fachtagung*, Bad Nauheim, 2002, pp. 155–161.

[2] M. Winkelnkemper and O. Apeldoorn, “Method for operating a power electronics circuit,” Patent WO 2014 02 3562, Feb. 2014.

[3] P. Hammond, “Enhancing the reliability of modular medium-voltage drives,” *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 948–954, Oct. 2002.

[4] J. Kucka, D. Karwatzki, and A. Mertens, “Optimised operating range of modular multilevel converters for ac/ac conversion with failed modules,” in *Proc. 17th Eur. Conf. Power Electron. Appl.*, Sep. 2015, pp. 1–10.

[5] Q. Yang, J. Qin, and M. Saeedifard, “A postfault strategy to control the modular multilevel converter under submodule failure,” *IEEE Trans. Power Del.*, vol. 31, no. 6, pp. 2453–2463, Dec. 2016.

[6] J. Li *et al.*, “A zero-sequence voltage injection control scheme for modular multilevel converter under submodule failure,” in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2016, pp. 1–6.

[7] J. Kolb, F. Kammerer, M. Gommeringer, and M. Braun, “Cascaded control system of the modular multilevel converter for feeding variable-speed drives,” *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 349–357, Jan. 2015.

[8] N. Thitichaiworakorn, M. Hagiwara, and H. Akagi, “Experimental verification of a modular multilevel cascade inverter based on double-star bridge cells,” *IEEE Trans. Ind. Appl.*, vol. 50, no. 1, pp. 509–519, Jan. 2014.

[9] D. Karwatzki, L. Baruschka, M. Dokus, J. Kucka, and A. Mertens, “Branch energy balancing with a generalised control concept for modular multilevel topologies —Using the example of the modular multilevel converter,” in *Proc. 18th Eur. Conf. Power Electron. Appl.*, Sep. 2016, pp. 1–10.