Control of Modular Multilevel Converters under Loading Variations in Distributed Generation Applications

Edris Pouresmaeil
Dep. of Elec. Eng. and Auto.,
Aalto University,
Finland
edris.pouresmaeil@gmail.com

Majid Mehrasa, Eduardo Rodrigues, Radu Godina,
C-MAST/UBI, Covilha,
Portugal
m.majidmehrasa@gmail.com;
erodrigues0203@gmail.com; radugodina@gmail.com

João P. S. Catalão
INESC TEC and FEUP, Porto,
C-MAST/UBI, Covilha, and
INESC-ID/IST-UL, Lisbon, Portugal
catalao@fe.up.pt

***Abstract*—In this paper, a function-based modulation control strategy for modular multilevel converters (MMCs) in a distributed generation (DG) system is proposed. Two novel modulation functions are introduced in this paper for the switching state functions of the lower and upper sub-modules of the interfaced MMC, which is considered as the main contribution of this control technique over other control methods. The amplitude and phase angle of the output current of the interfaced MMC can be easily applied to the proposed modulation functions to prepare a specific active and reactive power injection into the demand side. In addition, the equivalent capacitors of the lower and upper sub-modules are defined by taking into account the introduced modulation functions to guarantee an appropriate operation for the interfaced MMC in DG systems. Simulation results validate the capability of the proposed control method for MMCs under load variations.**

Keywords—Modular multilevel converter (MMC), modulation function control, loads variations, sub-modules.

I. Introduction

Development of distributed generation (DG) technology, HVDC transmission systems, AC transmission systems, and the variable-speed drives (VSD) are the main motivation of essential advancements in different power electronic converters design and switching technologies for more than last twenty years. Between the different converter topologies, modular multilevel converters (MMCs) have attracted high attentions of academic and industrial interest during the last decade because of their superior advantages over the conventional power converters i.e., modular structure, scalability to higher voltage and power levels, better voltage quality, less filter expenses, and performance compatibility with one common DC source. The unique structure and different characteristics of the MMCs initiate the essential need to design a suitable control technique for control of MMCs in power systems [1], [2] and offering adequate modulation techniques for these classes of converter topologies [3], [4].

Several studies can be found in the literature regarding different control methods for control and operation of MMCs in power system.

One of the most important objectives for control of the MMCs is to offer an appropriate dynamic model according to the assumed state variables in the structure of the engaged controller. The summation of the voltage of capacitor in every arm is considered in [5] instead of the separate voltages of capacitors with the intent to form the model of MMC and an operative DC-bus model from the capacitors of sub-modules results to complete the MMC's assessment. In [6] a more developed phase disposition pulse width modulation (PDPWM) is proposed for a modular converter, which operated as an interface between the power grid and solar power plant. In this publication the proposed modulation technique is based on the concept of selective virtual loop mapping in order to reach the dynamic capacitor voltage balance but deprived of the requirement of an additional compensation signal. A dynamic model-based analysis is proposed in [7] for the operation and control of modular converters in multi-terminal HVDC (MTDC) power system. The proposed dynamic model of the presented MMC-based MTDC model is consisted of the circuit model of MTDC, the inner and the outer control loops, the modulation strategies, and AC side circuit. Ref. [8] proposed a control technique for control of interfaced MMCs between the renewable energy sources (RESs) and power grid. The authors of this paper provided dynamic and steady state analysis of a grid-connected MMC supplied by RESs through DC, first and second harmonic models of the interfaced converter in dq reference frame. The outputs of these analyses have been used for converter's modulation and design of the proposed control technique. Similarly, many researchers have considered several other pulse-width modulation (PWM) methods and capacitor voltage balancing techniques in order to control the MMCs in a variety of operating conditions and operations [9]-[13].

Two novel modulation functions techniques are addressed and studied in this paper with the purpose of controlling the performance of MMCs in the inverter operating setting. By application of the proposed modulation functions, the core control objectives can be obtained appropriately and comprise operating precise reactive and active power sharing and regulating the sub-modules voltages.

J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, UID/EMS/00151/2013, 02/SAICT/2017 - POCI-01-0145-FEDER-029803, and also funding from the EU 7th Framework Programme FP7/2007-2013 under GA no. 309048.

978-1-5386-5186-5/18/$31.00 ©2018 IEEE

II. PROPOSED MODULATION FUNCTIONS

Fig.1 indicates the three-phase schematic diagram of the presented MMC-based model considered for the analysis in this paper. Conventional signs of voltages and currents components are illustrated in this figure. The required input power for the operation of the MMC is provided through the DC-link voltage, which is associated with a DG source. Every arm is comprised of an inductance and resistance, and N sub-modules, which are connected together in series. Every sub-module operates as a voltage source, which happens to be in fact a half-bridge rectifier with a particular output capacitor matching to its needed DC voltage. The complementary state occurs in case of the lower and upper switches of the sub-modules. This signifies that whenever the upper switch is off, the lower switch will be on and the other way around. Furthermore, the output of MMC comprises a filter inductance and an integral resistance. The point of common coupling (PCC) is taken into account in the presented MMC in standalone operating mode as it can be observed in Fig.1, where the consumable three-phase load and the output capacitance filter are connected. Next it is addressed the manner of attaining the presented modulation function for the operation of the interfaced MMC in the presented model.

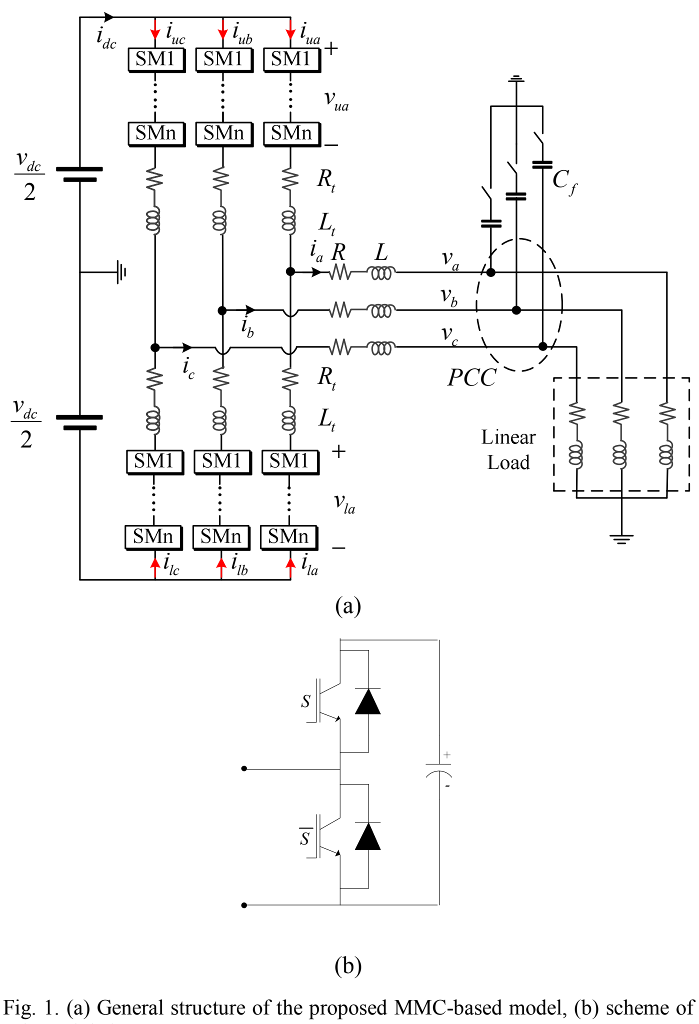

Fig. 1. (a) General structure of the proposed MMC-based model, (b) scheme of sub-module in MMC.

A. Assessment of the Arms Currents of the MMC

The control of the MMC in Fig.1 is assumed as to provide the sinusoidal voltages at the PCC, and supply the loads, which are connected to this point. Therefore, based on the reactive and active power demanded from the loads and the assumed conditions, the current and the output voltage of the MMC can be expressed as:

$$\begin{aligned} v_k &= v_m \cos\left(\omega t + j\frac{2\pi}{3}\right) \\ i_k &= I_m \cos\left(\omega t + j\frac{2\pi}{3} + \alpha\right) \end{aligned} \quad (1)$$

where the defining variable for producing the necessary reactive and active power of the connected load in various operating conditions is represented by the phase angle α. As depicted in Fig.1, the link between the output and the currents of the arms of the interfaced MMC and the circulating currents can be calculated as follows:

$$i_k = i_{uk} + i_{lk} \quad (2)$$

$$i_{cirk} = \frac{\left(i_{uk} - i_{lk}\right)}{2} - \frac{i_{dc}}{3} \quad (3)$$

In case of a managed MMC with a precise operation, the circulating currents ought to be close to zero. Therefore, by imposing i_{cirk}=0 into (3) and resolving both expressions extracted from equations (2) and (3), the currents of the lower and upper arms of the interfaced converter can be calculated as follows:

$$i_{uk} = 0.5 I_m \cos\left(\omega t + j\frac{2\pi}{3} + \alpha\right) + i_{dc}/3 \quad (4)$$

$$i_{lk} = 0.5 I_m \cos\left(\omega t + j\frac{2\pi}{3} + \alpha\right) - i_{dc}/3 \quad (5)$$

Every current of the arms is integrated with the input DC and output AC currents as can be seen by taking into account both equations (4) and (5).

B. The Proposed Modulation Function

A proper pulse width modulation should be design for an appropriate control and operation of the interfaced MMC in electrical network. Consequently, two reference signals are considered for lower and upper sub-modules of the interfaced converter in this sub-section to implement whole switching samples in the utilized shift-level PWM. If the neutral point in the DC link represented in Fig.1 is taken under consideration and utilizing the law of KVL in the obtained direction, equations (6) and (7) can be expressed as:

$$\frac{-v_{dc}}{2} + v_{uk} + L_t\frac{di_{uk}}{dt} + R_t i_{uk} + L\frac{di_k}{dt} + Ri_k + v_k = 0 \quad (6)$$

$$\frac{v_{dc}}{2} - v_{lk} + L_t\frac{di_{lk}}{dt} + R_t i_{lk} + L\frac{di_k}{dt} + Ri_k + v_k = 0 \quad (7)$$

By substituting (1) and (4) into (6) and assuming $i_{dc} = I_{dc} + i_{dcrip}$, $di_{dcrip} / dt = \tilde{i}_{dcrip}$, $L_{eq} = 0.5L_t + L$ and considering $R_{eq} = 0.5R_t + R$, the voltages of superior sub-modules of the interfaced converter are calculated as follows:

$$v_{uk} = \frac{v_{dc}}{2} - L_t \tilde{i}_{dcrip} / 3 - i_{dc} R_t / 3 + \left[I_m R_{eq} \sin(\alpha) + L_{eq} I_m \omega \cos(\alpha) \right] \sin\left(\omega t + j \frac{2\pi}{3} \right) + \left[L_{eq} I_m \omega \sin(\alpha) - I_m R_{eq} \cos(\alpha) + v_m \right] \cos\left(\omega t + j \frac{2\pi}{3} \right) \quad (8)$$

By considering the following relation represented by (9),

$$\gamma \sin(\omega t) + \lambda \cos(\omega t) = \sqrt{\gamma^2 + \lambda^2} \cos\left(\omega t + tag^{-1}(\lambda / \gamma) - \pi / 2 \right) \quad (9)$$

The modulation function recommended in this paper associated with the switching state functions of the superior sub-modules is assessed as:

$$u_{uk} = \frac{\left[\begin{array}{l} \frac{v_{dc}}{2} - L_t \tilde{i}_{dcrip} / 3 - i_{dc} R_t / 3 \\ + V_{mu} \cos\left(\omega t + j \frac{2\pi}{3} + \theta_u - \pi / 2 \right) \end{array} \right]}{v_{dc}} \quad (10)$$

It should be noted that the variables V_{mu} and θ_l are defined in detailed as:

$$V_{mu} = \sqrt{ \left[I_m R_{eq} \sin(\alpha) + L_{eq} I_m \omega \cos(\alpha) \right]^2 + \left[L_{eq} I_m \omega \sin(\alpha) - I_m R_{eq} \cos(\alpha) + v_m \right]^2 } \quad (11)$$

$$\theta_u = tag^{-1} \left(\frac{ \left[L_{eq} I_m \omega \sin(\alpha) - I_m R_{eq} \cos(\alpha) + v_m \right] }{ \left[I_m R_{eq} \sin(\alpha) + L_{eq} I_m \omega \cos(\alpha) \right] } \right) \quad (12)$$

If the same scenario is applied for the equation (7), the modulation function recommended in this paper associated with the switching state functions of the lower sub-modules is assessed as the following equation:

$$u_{lk} = \frac{\left[\begin{array}{l} \frac{v_{dc}}{2} - L_t \tilde{i}_{dcrip} / 3 - R_t i_{dc} / 3 + \\ V_{ml} \cos\left(\omega t + j \frac{2\pi}{3} + \theta_l - \pi / 2 \right) \end{array} \right]}{v_{dc}} \quad (13)$$

The variables V_{ml} and θ_l are specified in (14) and (15) as:

$$V_{ml} = \sqrt{ \left[I_m R_{eq} \sin(\alpha) + L_{eq} I_m \omega \cos(\alpha) \right]^2 + \left[-v_m - R_{eq} I_m \cos(\alpha) + L_{eq} I_m \omega \sin(\alpha) \right]^2 } \quad (14)$$

$$\theta_l = tag^{-1} \left(\frac{ \left[-v_m - R_{eq} I_m \cos(\alpha) + L_{eq} I_m \omega \sin(\alpha) \right] }{ \left[L_{eq} I_m \omega \cos(\alpha) + R_{eq} I_m \sin(\alpha) \right] } \right) \quad (15)$$

The proposed expressions could be utilized for the control of interfaced MMC in any operating condition which fully comprises both steady and dynamic states.

The steady state operation of the proposed modulation functions can be obtained by replacing the designated amount of the reference signals for the parameters of the MMC and specifications in V_{mi} and θ_i in addition to considering the preferred values of DC side voltage and current in the equations (10) and (11).

III. Determination of I_m and α

By taking into account the proposed modulation functions represented by the equations (10) and (13), it can be deduced that the key parts of the abovementioned functions are very significant to the requirements of the MMC's output currents.

In contrast, by taking into account the achieved equation associated to instantaneous powers of the arm, it is noticeable that the angle phase and magnitude of the output currents of the MMC show a substantial impact on every power element.

Consequently, by advancing with a precise control technique the assessment of the requirements of the output current of the MMC is made in this particular chapter according to its rated output reactive and active power. As such, the immediate reactive and active power of the MMC is given as follows:

$$p_{3\varphi} = 1.5 V_m I_m \cos(\alpha) \quad (16)$$

$$q_{3\varphi} = 1.5 V_m I_m \sin(\alpha) \quad (17)$$

By dividing (17) by (16) and utilizing the attained phase angle expressed by equation (16), the key elements of the MMC output current is calculated as follows:

$$I_m = \frac{p_{3\varphi}}{1.5 V_m \cos\left(\tan^{-1}\left(\frac{q_{3\varphi}}{p_{3\varphi}} \right) \right)} \qquad \alpha = \tan^{-1}\left(\frac{q_{3\varphi}}{p_{3\varphi}} \right) \quad (18)$$

In case of the given modulation-based control method associated with the interfaced MMC with the given output reactive and active power, equation (18) is used to correctly accomplish the operation and control of the MMC in its distinct operating conditions.

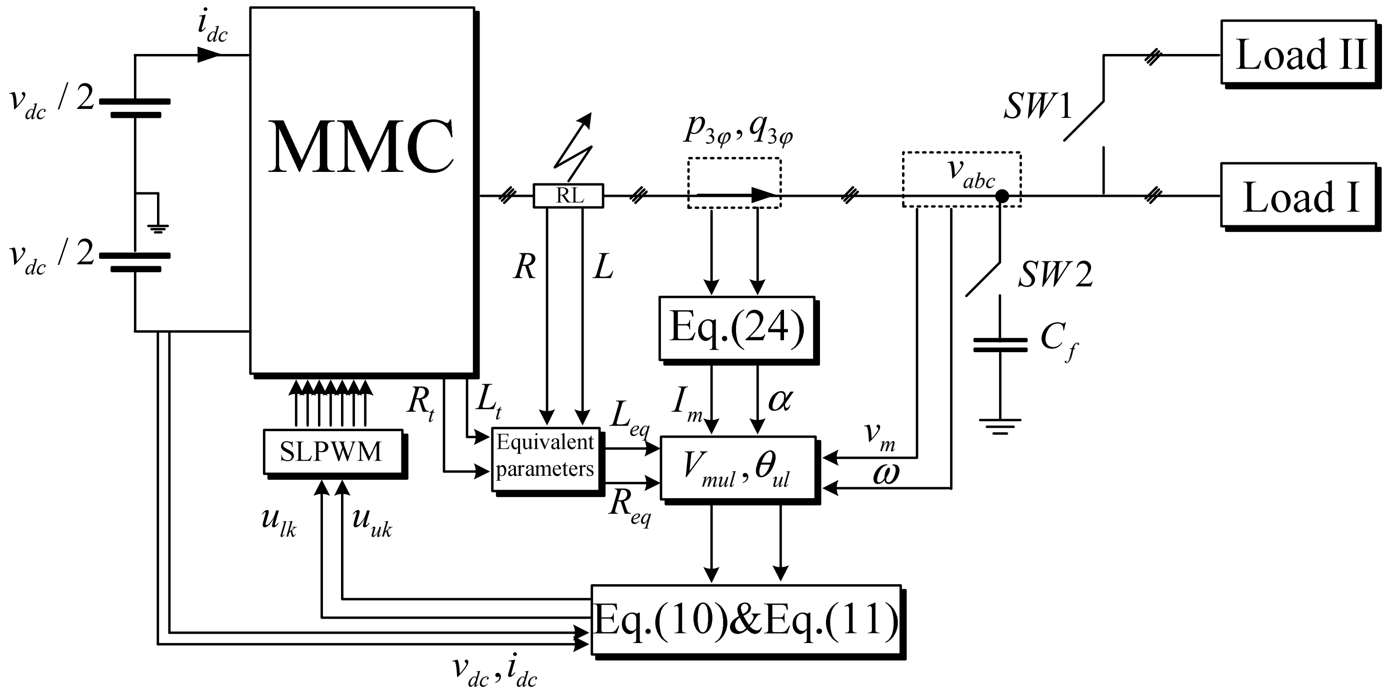

Fig. 2. The general schematic diagram of the proposed control technique for interfaced MMC.

IV. SIMULATION RESULTS

In order to demonstrate the high performance of the proposed control method under different operating conditions, the complete system model is simulated through the Matlab/Simulink environment in discrete operating mode. The complete schematic diagram and principle of the proposed model in Fig. 1, and the associated control technique are depicted in Fig. 2. One process of the MMC load changes is considered to the interfaced MMC in inverter operating mode, which will be explored more in the simulation results chapter. Furthermore, the adequate sample time for the simulation analysis is assumed to be one micro seconds (1 µsec) in order to achieve the satisfactory simulation results. In simulation processes, an AC capacitor filter is used at the PCC. Thus, the precise values of simulated model Fig. 2 are given in Table 1. In this section, capabilities of interfaced converter and performance of the proposed control technique to control the interfaced MMC in providing active and reactive power of different loads are demonstrated.

TABLE 1: THE VALUES OF THE PARAMETERS OF THE PRESENTED MMC-BASED MODEL UNDER LOAD CHANGES OPERATING CIRCUMSTANCES

Parameters	Value	Parameters	Value
$L_t(mH)$	15	N	4
$L(mH)$	6	$f(Hz)$	50
$R_t(\Omega)$	0.6	Active Power of Load I	50 kW
$R(\Omega)$	0.1	Reactive Power of Load I	20 kVAr
$v_{dc}(V)$	11200	Active Power of Load II	35 kW
$v_m(V)$	5800	Reactive Power of Load II	25 kVAr

The proposed interfaced MMC in Fig. 1 is set to supply 50 kW+20 kVAr load during the time between [0 sec, 0.2 sec] which is assumed to be as a steady-state operating period. This process is continued until t=0.2 sec, while a 35 kW+25 kVAr load is linked to the MMC and the PCC is accountable for the injection of the required power to supply the extra load. As such, for the identified active and reactive power values of the MMC, the variables α and I_m are assessed with equation (18) in order to be utilized in the presented modulation function. In Table I can be observed the requirements of the MMC. The operation of the proposed modulation function-based control technique at the preferred regulation of the sub-modules voltages can be observed in Fig. 3(a). As represented by Fig. 3(a), the sub-module voltages are maintained in the preferred value region of 2.8 kV in the case of steady state. After the dynamic variation of load, the preferred values of the sub-module voltages is accurately attained with a slight and unimportant transient response that properly ascertains the correct presented controller's dynamic operation. The output AC voltages of the MMC are depicted in Fig. 3(b) before and after utilizing the AC filter capacitor (C_f=$50\mu F$), which confirms the proper performance of the presented modulation-based control method in the above-mentioned operating settings.

Evaluation of the MMC's output currents and its circulating currents is finally achieved in Fig. 4(a). In this depiction it is verified the ability of the MMC of producing proper output currents for the dynamic and steady state operating circumstances. In addition, it could be observed that the circulating currents of the MMC nearly reach the zero value with slight fluctuations.

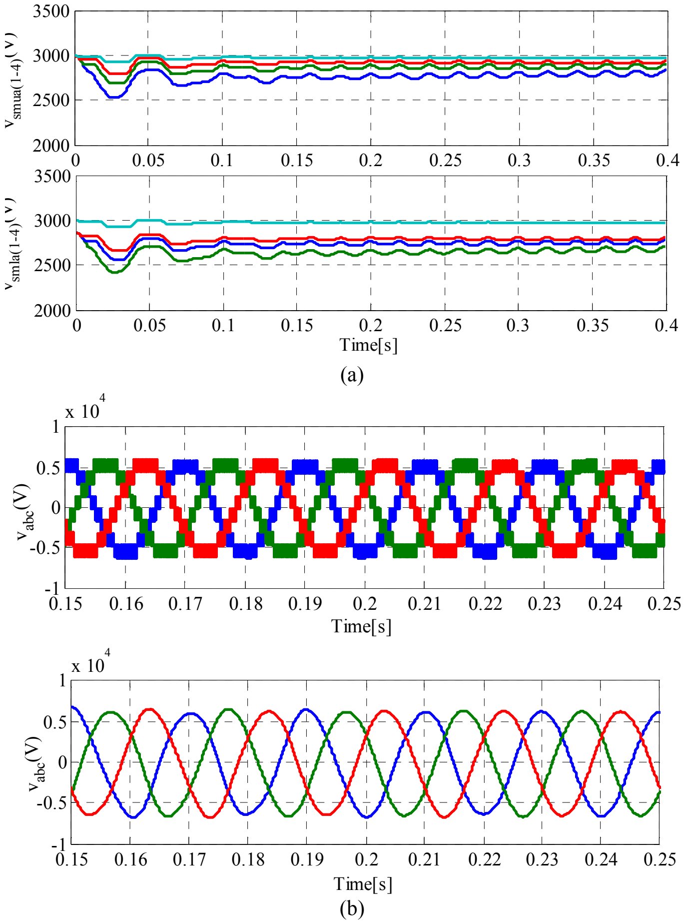

Fig. 3. (a) The sub-module voltages in phase "a" (b) Three phase output voltages of the MMC before and after connection of AC filter capacitor under load variation condition.

Also, in the Fig. 4(b) it can be observed the ability of the MMC for reactive and active power sharing. In this case the active power of the MMC correctly follows the entire active power load in both operating conditions. Also, from Fig. 4(b) it can be seen that the capability of the presented controller for following the reactive power of the load in the dynamic and steady state operating circumstances.

As such, the difference angle between the output currents and voltages of the MMC under load variations condition is illustrated in Fig. 5. Thus, it can be observed that the angle is properly altered according to the demanded reactive and active power for the loads.

V. Conclusion

A control technique was proposed in this study based on two different modulation functions for creating the switching state functions for the lower and upper sub-modules of the interfaced MMC. The MMC arms currents, determined from output and circulating currents, were utilized into the mathematical model of the interfaced converter in a-b-c reference frame. The modulation functions presented in this paper were not very complex if compared to the alternative control techniques. However, it also guarantees the stable activity of the studied system under loads changes conditions. Altering the load linked to the PCC was taken into account for the evaluation of the proposed control technique, which was engaged for the regulation of the voltages of the sub-modules and for a precise reactive and active power sharing performance. The results of the simulations, which were performed via Matlab/Simulink, confirmed the ability of the presented control method for achieving the most important control objectives.

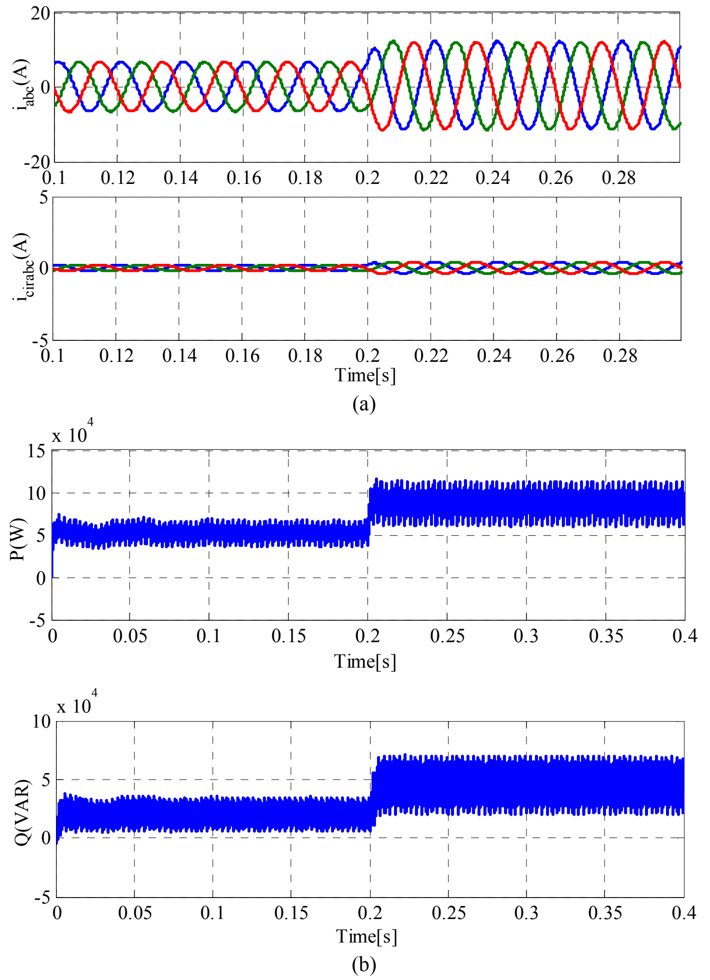

Fig. 4. (a) The MMC's output currents and circulating current, (b) the MMC's active and reactive power under load variation condition.

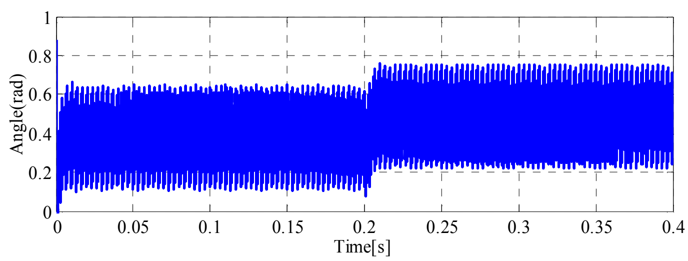

Fig. 5. Difference angle between the output voltages and currents of the MMC under load changes condition.

REFERENCES

[1] C. Wang and B-T Ooi, "Incorporating deadbeat and low-frequency harmonic elimination in modular multilevel converters," IET Generation, Transmission & Distribution., vol. 9, no 4, pp. 369 – 378.

[2] E. Pouresmaeil, M. Mehrasa, M.A. Shokridehaki, E. Rodrigues, and J. P. S. Catalao, "Control of Multi Modular Converters for Integration of Distributed Generation Sources into the Power Grid," SEGE 2015, pp. 1-6.

[3] J. Mei, B. Xiao, K. Shen, L.M. Tolbert, and J. Y. Zheng, " Modular Multilevel Inverter with New Modulation Method and Its Application to Photovoltaic Grid-Connected Generator," IEEE Trans. Power Electron., vol. 28, no 11, pp. 5063 - 5073.

[4] Q. Tu, Z. Xu, and L. Xu L, "Reduced Switching-Frequency Modulation and Circulating Current Suppression for Modular Multilevel Converters," IEEE Trans. Power Delivery, vol 26, no 3, pp. 2009 - 2017.

[5] L. Harnefors, A. Antonopoulos, S. Norrg, L. Ängquist, and H. P. Nee, "Dynamic Analysis of Modular Multilevel Converters," IEEE Trans. Ind. Electron., vol. 60, no 7, pp. 2526 - 2537.

[6] M. Vasiladiotis, N. Cherix, and A. Rufer, "Accurate Capacitor Voltage Ripple Estimation and Current Control Considerations for Grid-Connected Modular Multilevel Converters," IEEE Trans. Power Electron., vol. 29, no 9, pp. 4568 - 4579.

[7] M. Mehrasa, E. Pouresmaeil, S. Zabihi, and J. P. S. Catalao,, " Dynamic Model, Control and Stability Analysis of MMC-HVDC Transmission Systems," IEEE Trans. on Power Delivery, vol. 32, no 3, pp. 1471 - 1482.

[8] F. Shahnazian, J. Adabi, E. Pouresmaeil, and J. P. S. Catalao, "Interfacing Modular Multilevel Converters for Grid Integration of Renewable Energy Sources," Electric Power Systems Research, vol. 160, pp. 439-449, Jul. 2018.

[9] M. Mehrasa, E. Pouresmaeil, S. Zabihi, J. C. T. Caballero, and J. P. S. Catalao, "A Novel Modulation Function based Control of Modular Multilevel Converters for HVDC Application," Energies, vol. 9, no. 11, pp. 1 – 14.

[10] M. Mehrasa, E. Pouresmaeil, M. F. Akorede, S. Zabihi, and J. P. S. Catalao, "Function-Based Modulation Control for Modular Multilevel Converter Under Varying Loading and Parameters Conditions," IET Generation, Transmission & Distribution, (DOI: 10.1049/iet-gtd.2016.1028).

[11] Z. Li, P. Wang, H. Zhu, Z. Chu, and Y. Li, "An Improved Pulse Width Modulation Method for Chopper-Cell-Based Modular Multilevel Converters," IEEE Trans. Power Electronic., vol. 27, no 8, pp. 3472 - 3481.

[12] M. Mehrasa, E. Pouresmaeil, S. Taheri, I. Vechiu, and J. P. S. Catalao, "Novel Control Strategy for Modular Multilevel Converters Based on Differential Flatness Theory," IEEE J. of Emerg. and Sel. Topics in Power Elect., (https://doi.org/10.1109/JESTPE.2017.2766047).

[13] M. Mehrasa, E. Pouresmaeil, S. Zabihi, I. Vechiu, and J. P. S. Catalao, "A Multi-Loop Control Technique for the Stable Operation of Modular Multilevel Converters in HVDC Transmission Systems," International Journal of Electrical Power and Energy Systems (IJEPES), vol. 96, pp. 194-207, Mar. 2018.