Modular Multilevel Converter Circulating Current Reduction Using Model Predictive Control

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***Abstract*—Modular multilevel converter (MMC) is a promising new topology for high-voltage applications. The MMC is made of several identical submodules. For proper operation, each submodule can be considered as a controlled voltage source where capacitor's voltage should be maintained at a certain level. Besides, the minimization of the circulating current, which does not flow to the load, is crucial for achieving stable and efficient operation of the MMC. The interrelations among the load current, circulating current, and capacitor voltages complicate the MMC control. This paper aims to achieve stable and balanced voltage and current control with reduced circulating current in various operating conditions. The proposed control uses weighted model predictive control based on a normalized cost function to select the inverter switching patterns which control the load current while minimizing voltage-fluctuation and circulating current. The weighting factors were selected based on minimizing the load current THD and circulating current. The analysis is conducted on a low power case study of single-phase 4-cells MMC with possible extension to higher number of cells. The low-power three-level prototype is designed and built to validate this proposed method. Theoretical analysis, simulation and experimental results are presented and compared. Parameters sensitivity analysis was also conducted. They all confirm the effectiveness of the proposed control method.**

***Index Terms*—Modular Multilevel Converter, MMC, Circulating Current, Weighted Model Predictive Control.**

Manuscript received May 30, 2015; revised September 16, 2015 and November 10, 2015; accepted November 20, 2015.

This work was supported by the Qatar National Research Fund (a member of the Qatar Foundation) under The National Priorities Research Program-Exceptional Proposals (NPRP-EP) Grant X-033-2-007.

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I. Introduction

Modular Multilevel Converter (MMC) topologies have been developed since the beginning of the 21st century. The MMC is a very promising and attractive converter used especially in high-power and high-voltage applications. Recently, the MMC became the center of interest for many researches, whereas many configurations and control methods have been developed [1]-[47]. The MMC is mainly used in High Voltage Direct Current (HVDC) transmission system applications [2]-[5]. Single-phase and three-phase topologies are both used. Fig. 1 shows a typical three-phase circuit topology where $SM_{i\{1\text{-}N\}}$ denote the cascaded connection of multiple submodules in each arm and leg. Note that there are two arms (upper and lower) in each leg, which are connected in series through two identical inductors L. The MMC is also used as a converter for DC or AC motor drive applications [13]-[15]. For AC motor drives, the MMC is called Modular Multilevel Inverter (MMI).

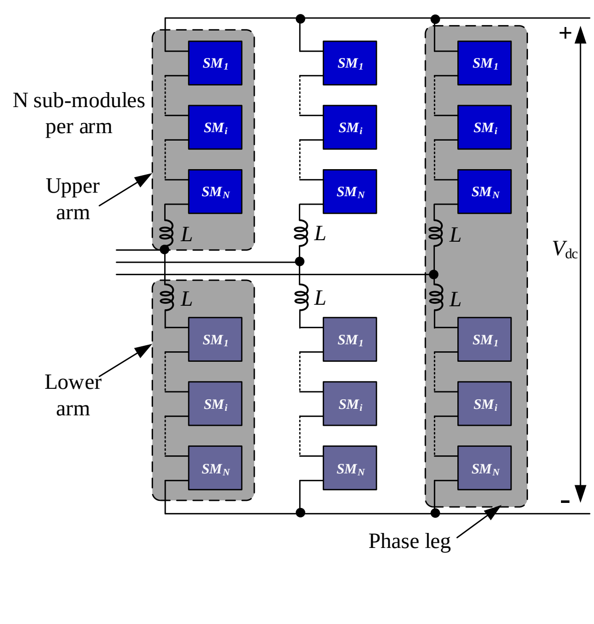


Fig. 1. Schematic of a three-phase MMC

Several control schemes were designed to enable the operation at different frequencies even very low ones. These are described extensively in [16]-[20]. Most of these papers focus on the simplification of the MMC models and development of reliable and stable control methods for the inverter. This is justified by the fact that the voltage balancing between the sub-modules of upper and lower arms is mandatory for a proper and stable operation.

If not properly implemented, the control of the total leg's voltage and differential voltage between the two arms may affect seriously the MMC operation. Many control techniques were recently proposed for the MMC including model predictive control (MPC) [16]-[41]. Most of these techniques were presented and discussed mainly through simulation studies only; very few presented experimental results [28][30]. In [21], a single-phase AC–AC MMC with predictive controller to reduce error terms related to the input, output, and circulating currents, was proposed. In [22], an MPC for a five-level MMC-based HVDC system was developed and evaluated based on simulation studies. In [23], an MPC for a grid-connected five-level DC-AC MMC system to control voltage balancing, circulating currents, and power flow was presented. A Finite-Control-Set MPC strategy for current tracking control of an MMC for either balanced or unbalanced reference current was proposed and evaluated by simulation in [24]. In [25], a slow-rate capacitor voltage balancing strategy was developed and confirmed by simulation using PSCAD/EMTDC environment. The results also highlighted the tradeoff between the magnitude of the capacitor voltages' ripple and the switching frequency for the proposed voltage-balancing strategies. In [26], authors presented a general predictive technique used for general multilevel inverter including MMC. Experimental results were carried out only for Flying Capacitor inverters. In [27], authors presented an approach to control the capacitor voltage of the MMC within a switching cycle, demonstrating benefits in greatly reducing the capacitance and arm inductance of the MMC. The simulation of the proven technique was capable to operate the MMC at lower-frequency. [28] proposed a reduced computation load MPC to reduce the heavy prediction computations that result from traditional MPC. The proposed MPC was simulated with 11-level MMC-based STATCOM. [29] presented a simulation study of an MPC method with a reduced number of states for the MMC-HVDC system. [30] proposed an experimental comparison between a cascaded control scheme based on conventional PI controllers and an MMC based on MPC technique. [31] proposed a capacitor voltage balancing strategy that works even at low switching frequencies while avoiding excessive capacitor voltage ripple. [32] proposed an adaptive observer of capacitor voltages for MMC. Recently, several papers were published about capacitor voltage balancing and circulating current reduction [33]-[40].

As noticed and highlighted from the above review, most of MPC for MMC were just presented through theoretical and simulation studies. However, the aim of this paper is to propose a new MPC technique for the control of single-phase MMC and to validate it experimentally. The ultimate goal is to accomplish stable and balanced voltage and current control with minimum circulating current under several operating conditions. The proposed method is based on weighted predictive control of the inverter switching patterns leading to optimum load current control with maximum balance among capacitor voltages and minimum circulating current in the MMC. The weighting factors are tuned based on minimizing the output current THD index and the circulating current rms value. The sensitivity to parameter variations of the proposed method is also discussed. The analysis is conducted on a single-phase case study of 4-cells MMC; however, it can be extended to higher number of cells.

This paper first explains the principle of operation and mathematical modelling of the MMC. A new MPC based control approach of the MMC is then presented and discussed. Simulation of the MMC and the proposed control algorithm is conducted using Matlab/Simulink. The simulation approach is applicable even for MMCs with a large number of submodules. Finally, experiments are conducted on a prototype in order to validate the presented concept and the proposed control technique.

II. Theoretical Background

A. MMC topology

The MMC considered in the case study has 2 submodules per arm (N=2) as shown in Fig. 2. Each submodule contains two switches which complementarily permute their states. The main idea of the MMC is to build a controlled multilevel output voltage. In general, each submodule acts as a controlled voltage source where its average capacitor's voltage should be maintained at V_{dc}/N. The control of each submodule consists of either inserting or bypassing the capacitors through proper selection of the switching patterns.

In our case-study, each arm consists of a series connection of two submodules, one inductor L and one resistor R supplied by a DC source of $V_{dc}/2$. The inductor is used to smooth the current and the resistor represents the inductor internal resistance. An RL load (R_L, L_L) is used for testing the operation of the system. Considering the system shown in Fig. 2, the following outputs are obtained:

- If ($V_{dc}/2$) is to be applied to the load, then the upper-arm submodules need to be bypassed and the lower ones to be inserted. This state is therefore obtained by only one switching pattern.
- If ($-V_{dc}/2$) is to be applied to the load, then the upper-arm submodules need to be inserted and the lower ones to be bypassed. This state is therefore obtained by only one switching pattern.
- If ($0V$) is to be applied to the load, then one submodule from each arm needs to be bypassed. This state is therefore obtained by four switching patterns.

Since there are four cells and each cell has two switches, then, there are sixteen (2^4) different combinations of switching patterns which can be obtained. However, based on the output voltage states presented above, there are only six valid switching patterns (C_2^4).

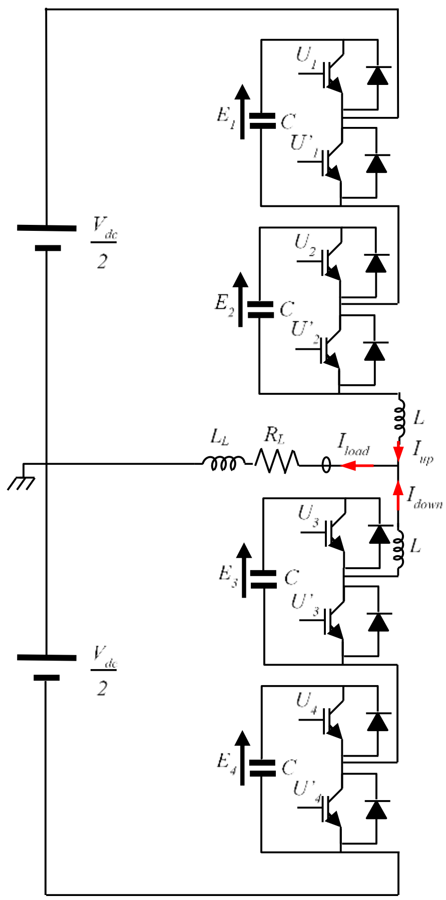


Fig. 2. Configuration of the MMC circuit

Depending on its switching states and current polarity, a basic cell capacitor is charged, discharged, or bypassed. The balancing of the sums of floating capacitors voltages of the upper and lower arms is crucial and should therefore be regulated as their unbalance affects the stability operation of the MMC as well as the level of the circulating current. The voltage balancing method is based on selecting the proper switching patterns according to the capacitor voltages' and currents' polarities in the submodules.

B. *Mathematical modeling*

Using Kirchhoff laws, relations between the arm currents, I_{up}, I_{down} the capacitor voltages, E_1~E_4, the load current, i_L, and the circulating current, I_{diff}, of the converter in Fig. 2 are expressed by (1)-(5). By choosing the four capacitor voltages, the load current and the circulating current as six state variables and the switching states as the control vector[26], the state space model can be derived as in (6), where:

V_{dc}	is the dc source voltage
E_1~E_4	are the capacitors voltages
U_1~U_4	are switching states (0:off, 1:on)
I_{up}	is the upper arm current
I_{down}	is the lower arm current
I_{Load}	is the load current
I_{diff}	is the circulating current
L,R	are the inductance and resistance of the arm inductor
L_L,R_L	are the load inductance and resistance
C	is the cell capacitor

$$V_{dc} = U_1E_1 + U_2E_2 + L\frac{dI_{up}}{dt} + RI_{up} - L\frac{dI_{down}}{dt} - RI_{down} + U_3E_3 + U_4E_4 \quad (1)$$

$$\frac{V_{dc}}{2} = U_1E_1 + U_2E_2 + L\frac{dI_{up}}{dt} + RI_{up} + L_L\frac{dI_{Load}}{dt} + R_LI_{Load} \quad (2)$$

$$\frac{V_{dc}}{2} = U_3E_3 + U_4E_4 - L\frac{dI_{down}}{dt} - RI_{down} \text{-} L_L\frac{dI_{Load}}{dt} - R_LI_{Load} \quad (3)$$

$$\begin{cases} I_{up} = \dfrac{I_{Load}}{2} + I_{diff} \\ I_{down} = \dfrac{I_{Load}}{2} - I_{diff} \end{cases} \quad (4)$$

$$\begin{cases} \dfrac{dE_1}{dt} = \dfrac{U_1}{C}\left(\dfrac{I_{Load}}{2} + I_{diff}\right) \\ \dfrac{dE_2}{dt} = \dfrac{U_2}{C}\left(\dfrac{I_{Load}}{2} + I_{diff}\right) \\ \dfrac{dE_3}{dt} = \dfrac{U_3}{C}\left(-\dfrac{I_{Load}}{2} + I_{diff}\right) \\ \dfrac{dE_4}{dt} = \dfrac{U_4}{C}\left(-\dfrac{I_{Load}}{2} + I_{diff}\right) \end{cases} \quad (5)$$

$$\begin{bmatrix} \frac{dI_{diff}}{dt} \\ \frac{dE_1}{dt} \\ \frac{dE_2}{dt} \\ \frac{dE_3}{dt} \\ \frac{dE_4}{dt} \\ \frac{dI_{load}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{U_1}{2L} & -\frac{U_2}{2L} & -\frac{U_3}{2L} & -\frac{U_4}{2L} & 0 \\ \frac{U_1}{C} & 0 & 0 & 0 & 0 & \frac{U_1}{2C} \\ \frac{U_2}{C} & 0 & 0 & 0 & 0 & \frac{U_2}{2C} \\ \frac{U_{31}}{C} & 0 & 0 & 0 & 0 & -\frac{U_3}{2C} \\ \frac{U_4}{C} & 0 & 0 & 0 & 0 & -\frac{U_4}{2C} \\ 0 & -\frac{U_1}{L+2L_L} & -\frac{U_2}{L+2L_L} & \frac{U_3}{L+2L_L} & \frac{U_4}{L+2L_L} & -\frac{R+2R_L}{L+2L_L} \end{bmatrix} \begin{bmatrix} I_{diff} \\ E_1 \\ E_2 \\ E_3 \\ E_4 \\ I_{load} \end{bmatrix} + \begin{bmatrix} \frac{V_{dc}}{2L} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (6)$$

C. Proposed control

It is important to mention that the challenges in the MMC control is to best track the load current reference while maintaining the capacitor voltages at a certain level (V_{dc}/N) and minimizing the circulating current. Note that the later doesn't flow to the load and is caused by the unbalance between the upper and lower currents of the MMC arms. Such large circulating current will not affect the quality of the MMC output currents. However, it has a major effect on the rating values of the used components, the ripples of capacitor voltage, and the overall losses of the MMC. Therefore, to minimize these undesirable impacts, the circulating current should be reduced.

It is also worth noting that the controlled variables (load and circulating currents and capacitor voltages) are interrelated and any change in one of them may affect the others. This means that if the MMC smoothly controls one of the above variables, it may cause degradation in the control of others.

Therefore, one should be very careful in the choice of the controller type and its parameters. One way to control the complex dynamics of the MMC is the use of MPC. Due to its high performance and extensive flexibility, MPC has received a great deal of attention [42]-[47]. MPC can handle multivariable control, input and output time delays, and unstable systems. MPC includes prediction features taking into account system states constraints. Therefore, it is considered suitable for the multivariable control of the MMC. The core components of an MPC are more less the same, i.e. 1) prediction model of the process, 2) objective function and 3) optimizing algorithm.

The proposed MMC control method is based on the weighted MPC (WMPC) approach. This WMPC is designed to control the load current while keeping minimum circulating current and balancing the capacitor voltages. At each control sampling time, the WMPC predicts the next switching pattern that assures best tracking of the reference variables for E_1~ E_4, I_{load}, and I_{diff}. The proposed control proceeds as follows during each sampling period:

a) Measure state vector $X(k)$ formed by the capacitor voltages $E_1(k)$, $E_2(k)$, $E_3(k)$, $E_4(k)$, the circulating current $I_{diff}(k)$ and the load current $I_{load}(k)$.
b) Predict the state vectors $X(k+1)$ at the next sampling instant for the six valid switching patterns by:.

$$X_i(k+1) = X(k) + \dot{X}_i(k) \cdot T_s \quad (7)$$

c) The difference between the predicted state vector $X_i(k+1)$ and the reference state $X_{ref}(k)$ is calculated and normalized by dividing it by the maximal variations of the state variables during the sampling period [36].

It is worth noting that the standard MPC techniques are not taking into account the dissimilarity of the variation ranges (hundreds Volts for voltages and few Amperes for current) which may lead to heterogeneous tracking performance of the controlled state variables. This paper proposes a normalization of the state variables by calculating the maximal variations of each state variable, which is considered as an additional optimization criteria in the cost function calculation. This normalization technique influences the switching states selection.

The WMPC will then minimize the normalized and weighted cost function $Cost_i$ given by (8) and select the appropriate switching pattern. The proposed whole controller strategy is described in Fig. 3 and the main steps of the control algorithm are illustrated in Fig. 4.

where:

ΔI_{diff} =	$\lvert max\,(I_{diffi}(k+1)) - min(I_{diffi}(k+1))\rvert$
ΔE_1	$\lvert max\,(E_{1i}\,(k+1)) - min(E_{1i}\,(k+1))\rvert$
ΔE_2	$\lvert max\,(E_{2i}\,(k+1)) - min(E_{2i}\,(k+1))\rvert$
ΔE_3	$\lvert max\,(E_{3i}\,(k+1)) - min(E_{3i}\,(k+1))\rvert$
ΔE_4	$\lvert max\,(E_{4i}\,(k+1)) - min(E_{4i}\,(k+1))\rvert$
ΔI_{load}	$\lvert max\,(I_{loadi}(k+1)) - min(I_{loadi}(k+1))\rvert$
$I_{Loadref}$	is the load current reference
$I_{diffref}$	is the circulating current reference (=0)
E_{1ref}~E_{4ref}	are the capacitors voltages references (=V_{dc}/N)
k	is the sampling number
i	is the pattern number ($1 \le i \le N_p$)
N_p	is the total number of switching patterns
μ_1, μ_2	are weighting factors

$$Cost_i = \sqrt{\left(\frac{I_{diffref} - I_{diffi}}{\mu_1 \Delta I_{diff}}\right)^2 + \left(\frac{E_{1ref} - E_{1i}}{\Delta E_1}\right)^2 + \left(\frac{E_{2ref} - E_{2i}}{\Delta E_2}\right)^2 + \left(\frac{E_{3ref} - E_{3i}}{\Delta E_3}\right)^2 + \left(\frac{E_{4ref} - E_{4i}}{\Delta E_4}\right)^2 + \left(\frac{I_{loadref} - I_{loadi}}{\mu_2 \Delta I_{load}}\right)^2} \quad (8)$$

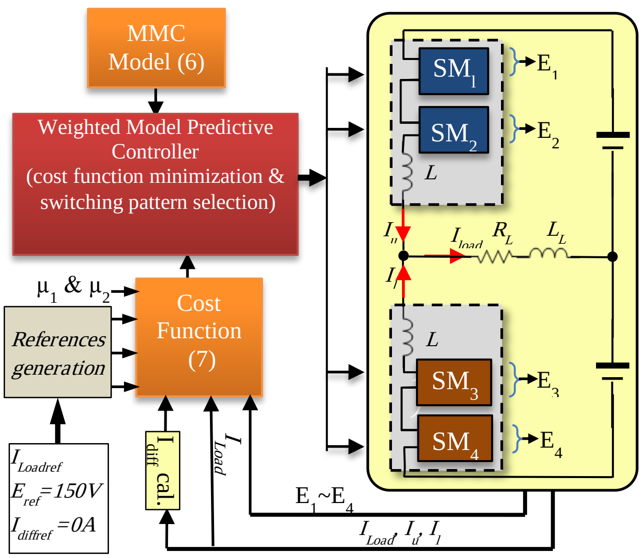


Fig. 3. Proposed controller for the 4-cell MMC

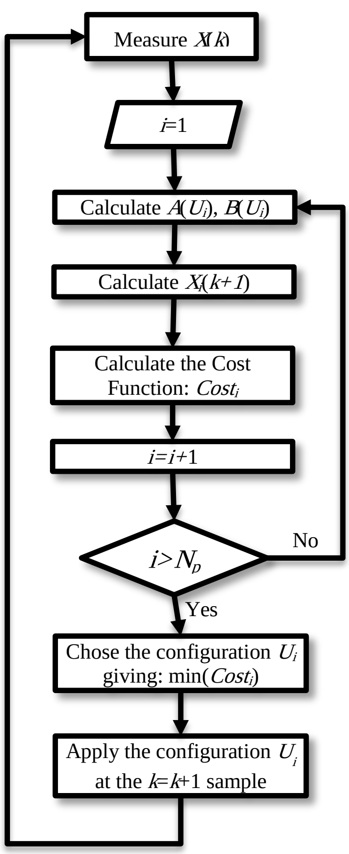


Fig. 4. Flowchart of the proposed WMPC algorithm

It should be mentioned that the weighting factors used with the currents' equations have crucial effects on the quality of the controlled variables, as it will be shown in the simulation and experiment sections.

III. Simulation Results

Digital simulations are carried out using Matlab/Simulink to show the performance and effectiveness of the proposed WMPC in controlling the 4-cells MMC. The considered simulation parameters are listed in Table 1.

TABLE 1 SIMULATION PARAMETERS

Parameters	Values
Inductor load L_L	50mH
Resistor load R_L	19Ω
Inductor arm L	1mH
Resistor arm R	0 Ω
Capacitor C	1000 μF
Fundamental frequency f	50 Hz
Sampling frequency F_s	10 KHz
Input Voltage V_{dc}	150 V
Reference Current $I_{Loadref}$ (peak)	3A
Number of cells per arm	2

A. *Tuning of weighting factors*

Since the proposed method is based on weighted predictive control, the weighting factors are first tuned to achieve the stability and desired performance of the MMC. The tuning is conducted based on minimizing the output current THD index and the circulating current rms value. To illustrate the effect of the weighting factors on the currents tracking quality and selecting the optimum values for best control results, the load current THD and the rms value of the circulating current were measured for different values of μ_1 and μ_2. For normalization of the different magnitudes among the variables of the cost function [42], μ_2 is chosen equal to $0.1\mu_1$. Fig. 5 shows the variation of the load current THD and the rms value of the circulating current as function of μ_1. Notice that the THD fluctuates between 0.6 and 1.9% for different values of μ_1 while the rms value of the circulating current is increasing considerably for μ_1>5x10^{-2}.

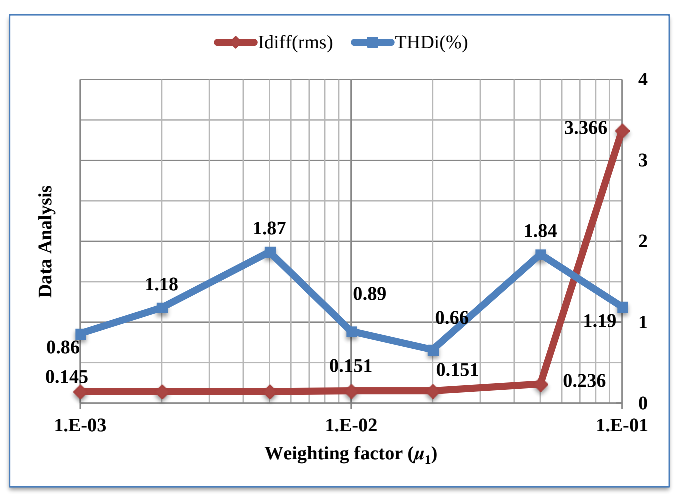


Fig. 5. Variation effect of the weighting factor μ_1 on the load current THD and rms value of the circulating current.

One could conclude that the optimum performance is obtained for μ_1=2x10^{-2} and μ_2=2x10^{-3}. Hence, these values will be considered as the optimum values and will be used for the validation tests.

B. Simulation Results for tuned weighting factors (μ_1=2x10^{-2}, μ_2=2x10^{-3})

The corresponding results are presented in Fig. 6-Fig. 10. Notice that the simulation results are consistent with their theoretical counterpart. It is clear from Fig. 6 that the capacitor voltages are oscillating around the value $V_{dc}/2$ and the steady state error margin is relatively small (less than 4%). It is worth to note that the sum of upper-arm capacitor voltages is balanced with the sum of the lower-arm capacitor voltages as depicted in Fig. 7. Fig. 8 shows that the load current is perfectly tracking its reference. In addition, the circulating current calculated using (4), is controlled and kept at very low value that maintains the MMC at stable and efficient operating condition (Fig. 9). This result is very promising and shows that the WMPC is very effective in dealing with the complex control aspects of the MMC. Finally, as shown in Fig. 10, a 3-level (N+1) output voltage waveform is synthetized.

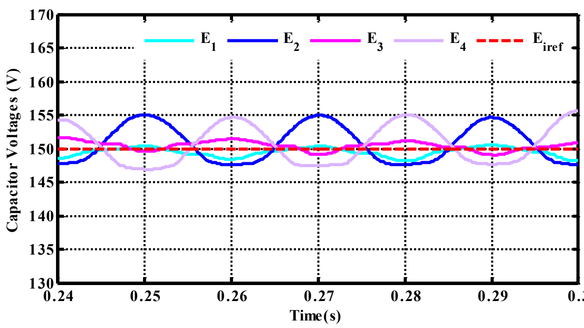


Fig. 6. Capacitor voltages waveforms

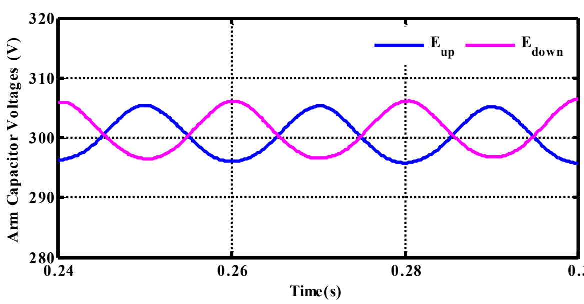


Fig. 7. The sum of upper-arm & lower-arm capacitor voltages waveforms

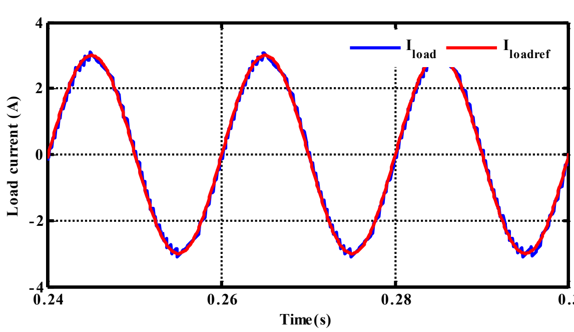


Fig. 8. Load current waveforms

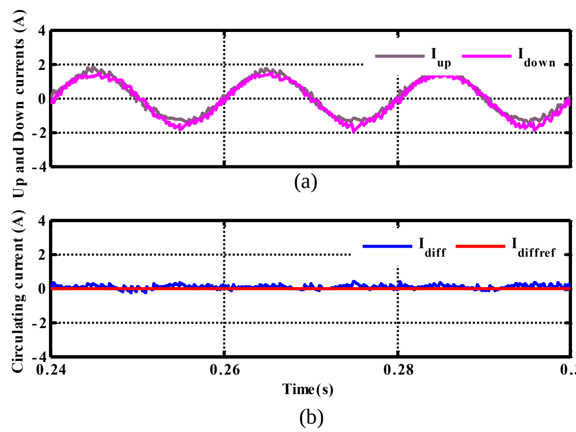


Fig. 9. Current waveforms (a) Upper and lower arm currents; (b) Circulating current

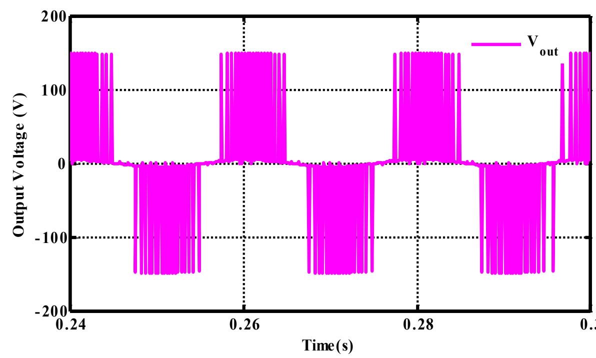


Fig. 10. Output voltage waveform

C. Sensitivity to parameters variation

The effect of parameter variations is investigated by changing the electric circuit parameters in the MPC algorithm within the range from -50% to +50% of their nominal values. The parameters encompassed by the analysis are L (inductor arm) and C (cell capacitor). Seven points are taken into account within the established range. For simplicity purpose, only one parameter is varied at a time. The rms value of the circulating current is selected as the performance indicator.

Fig. 11 shows the obtained results when L and C are varied within the above mentioned range.

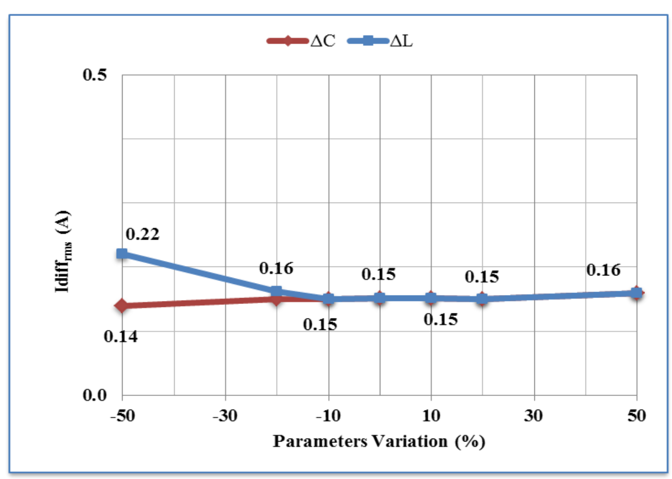


Fig. 11. Sensitivity of the proposed WMPC to the inductor arm variation

Note that in practical cases, the errors induced in the measurement of L and C are usually within the range of ±10%. It can be noticed that the circulating current is almost not affected within this range. These results are very promising and show that the proposed WMPC is very less sensitive to parameters change.

IV. Experimental System

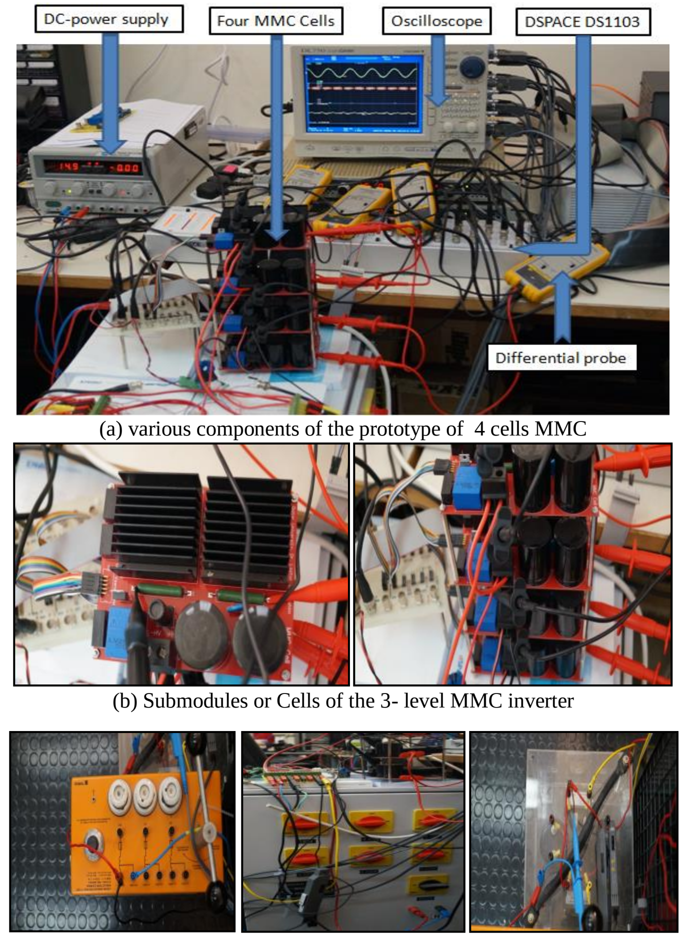
To validate the proposed WMPC, a scaled version of the single-phase MMC is built and tested. The power rating of the scaled prototype model is 500 W, which is restricted by the rating of the power used in the laboratory. This power rating limitation is not a problem since our objective is to prove the concept of the proposed controller. The number of basic cells per phase is four (2 per arm). IGBTs with custom designed gate drives are used as power semiconductor switches in the MMC. In order to implement the control strategy, the DSPACE 1103 is used. Table 2 gives the parameters of the scaled experimental prototype.

TABLE 2 Parameters of the scaled experimental prototype

Parameters	Values
Inductor load L_L	50 mH
Resistor load R_L	19.071 Ω
Inductor arm L	738.1 μH
Resistor arm R	0 Ω
Capacitor C	1000 μF
Fundamental frequency f	50 Hz
Sampling frequency F_s	10 kHz
Input Voltage V_{dc}	150V
Reference Current $I_{Loadref}$ (peak)	3A
Number of cells per arm	2
Controller or Processor	dSPACE dS1103

Fig. 12 shows the test bench and all its components. The connection of the set with all auxiliary devices and power supplies are depicted in Fig. 12(a). The set is composed of an MMC with 4 sub-modules, DSPACE1103, oscilloscope, auxiliary power supply, and voltages and currents sensors. Fig. 12(b) shows details of the MMC submodules or cells while Fig. 12(c) shows the RL load and arm inductors. Three current sensors and four isolating voltage sensors for the measurement of feedback signals are used in the implementation of the MMC.

As the weighting factors used in the cost function have a significant effect on the quality of the tracking process and the performance of the MMC in general (Fig. 5), it is worth to illustrate this effect by trying to emphasis on the performance of the output current on the detriment of the circulating current and capacitor voltages. Fig. 13 shows the experimental results of a first test made by choosing $\mu_1 = \mu_2 = 10^{-3}$. Notice the unbalance of the capacitor voltages and the relatively high circulating current. Although the system is operating in stable condition, in the long run, this may cause overheat of the inverter due to the increase in the circulating current. This justifies the need for controlling the circulating current to a minimum possible level. This is realized by the proposed controller using the tuned (optimum) weighting factor values μ_1=2x10^{-2} and μ_2=2x10^{-3} as illustrated in Fig. 5.



(a) various components of the prototype of 4 cells MMC

(b) Submodules or Cells of the 3- level MMC inverter

(c) RL Load and Arm inductors

Fig. 12. Test bench setup and the scaled prototype model: (a) overall set; (b) MMC cell and (c) RL Load and Arm inductors

Fig. 14-Fig. 17 show the experimental results for this scenario. Referring to the upper waveforms of Fig. 14, the load current is perfectly tracking its sinusoidal reference. Thus, experimental results confirm well the simulation results of Fig. 8. The waveforms of the middle part of Fig. 14 show the floating-capacitor voltages E_1~ E_4 of the four cells. All upper-arm and lower-arm capacitor voltages are nearly equal and oscillate around 150V. This proves the voltage balancing capability of the proposed controller. The bottom waveform in Fig. 14 is the circulating current, I_{diff}. Notice that this current fluctuates around zero but at very low amplitude. This demonstrates the effectiveness of the proposed method in keeping the circulating current at very low level. Fig. 15 shows the experimental three-level output voltage waveforms of the MMC while Fig. 16 shows the waveforms of the upper- and lower-arm currents I_{up} and I_{down}, and the circulating current I_{diff}. Notice that I_{up} and I_{down} waveforms exhibit more or less the same waveforms and are mainly composed of dc (with opposite signs), fundamental, and other harmonic components. It is apparent that the circulating current contains a dc component and a second order harmonic component. This phenomenon was already reported and explained in previous research work [20]. This means that I_{up} and I_{down} have the second order component. All these characteristics are consistent with the theoretical analysis and the simulation

results shown in Fig. 9. Fig. 17 depicts the experimental results during the transient operation of the WMPC, where the load reference and actual currents are displayed. The bottom waveform in Fig. 17 is a zoomed region of the upper waveform at the transient instant. The load current reference is increased stepwise from 1.5A peak to 3A peak. Notice that the load current tracks its reference waveform in just few sampling periods. This proves the high dynamic performance of the proposed WMPC.

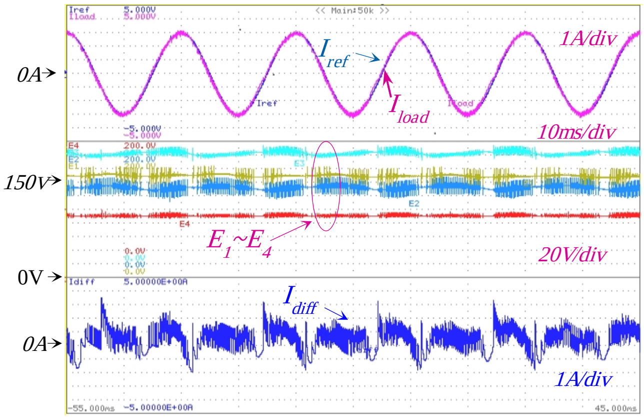


Fig. 13. Experimental results for untuned WMPC: Effect of weighting factors (μ_1= μ_2=10^{-3}) on the performance of the WMPC. Upper reference and actual load current; middle capacitor voltages E1~E4; bottom circulating current.

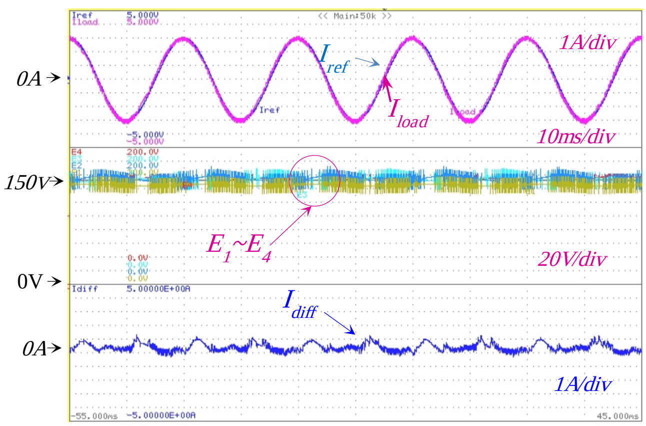


Fig. 14. Experimental results of the proposed WMPC performance with μ_1=2x10^{-2}, μ_2=2x10^{-3}: upper load reference current and actual load current; middle capacitor voltages E1~E4; bottom circulating current

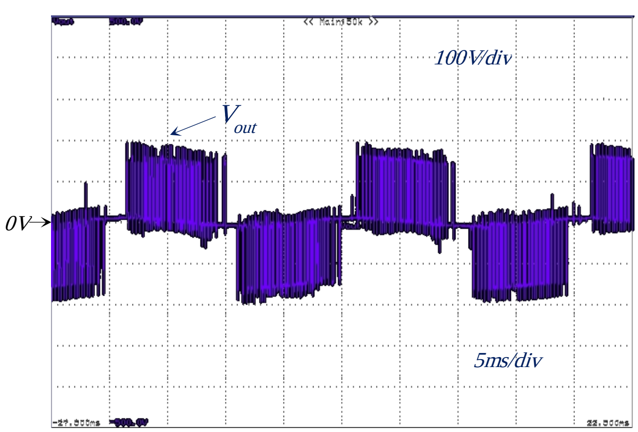


Fig. 15. Experimental results of the three-level output voltage waveforms

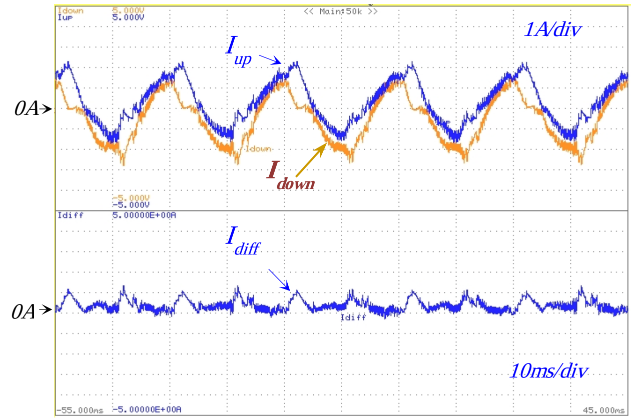


Fig. 16. Experimental results: Upper and lower arm currents (top) and circulating current (bottom)

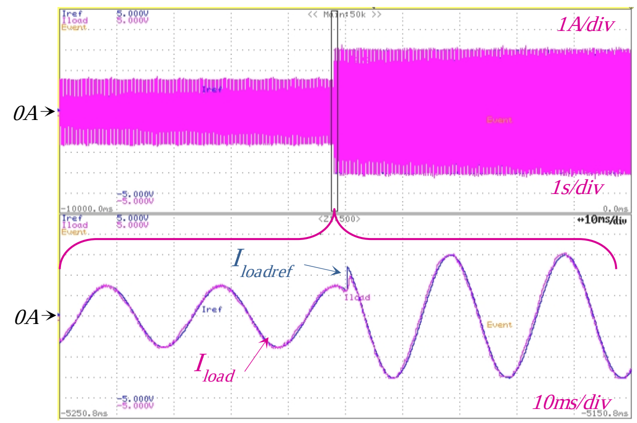


Fig. 17. Experimental results: Transient performance of the WMPC, load reference and actual current are depicted. Lower part is a zoom of the transient instant of the upper waveforms.

V. Conclusion

This paper presented the design and implementation of a WMPC technique that properly deals with the complex nature of the MMC. A normalized multi-objectives cost function was defined. The normalization of the state variables by calculating the maximal variations of each state variable is used as additional optimization criteria in the cost function calculation. This normalization technique influences the switching states selection.

Digital simulations for a 3-level single-phase MMC were carried out. The simulation results showed that the proposed WMPC is capable of simultaneously controlling multi variables of the MMC. The tuning of the weighting factors was conducted successfully based on minimizing the load current THD as well as the circulating current. Using the properly selected weighting factors, the WMPC has shown an efficient and stable tracking of the reference current at steady state and fast transient response. It is also capable of maintaining the capacitor voltages at their pre-selected and desired levels while minimizing the circulating current. Parameters sensitivity analysis was carried out and showed that the parameters variation does not have a significant effect on the controller performance.

To validate the simulation results, a 500W prototype was built and tested. The obtained experimental results confirmed the simulation results and demonstrated that the proposed WMPC is effective in controlling the load current with high steady-state and dynamic tracking performances while keeping balanced capacitor voltages and low circulating current.

REFERENCES

[1] Daniel Siemaszko, Antonios Antonopoulos, Kalle Ilves, Michail Vasiladiotis, Lennart Ängquist, Hans-Peter Nee "Evaluation of Control and Modulation Methods for Modular Multilevel Converters," *in Proc. International Power Electronics Conference IPEC'2010*, June 2010.

[2] J. Rodriguez, J. S. Lai, and F. Z. Peng, "Multilevel Inverters: a survey of topologies, controls, and applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 724-738, Aug. 2002.

[3] R. Marquardt, and A. Lesnicar, "New Concept for High Voltage - Modular Multilevel Converter," *IEEE PESC 2004*, Aachen, Germany, June 2004.

[4] M. Glinka and R. Marquardt, "A New AC/AC Multilevel Converter Family", *IEEE Trans. Ind. Electron.*, vol. 52, no. 3, pp. 662 - 669, June 2005.

[5] B. Gemmel, J. Dorn, D. Retzmann, and D. Soerangr, "Prospects of multilevel VSC technologies for power transmission," *IEEE TDCE'2008*, pp. 1-6.

[6] M. Hagiwara, H. Akagi, "PWM Control and Experiment of Modular Multilevel Converters," *IEEE PESC'2008*, Rhodes, Greece, June 2008.

[7] A. Antonopoulos, L. Angquist, and H.-P. Nee, "On dynamics and voltage control of the modular multilevel converter," *European Power Electronics Conference (EPE)*, Barcelona, Spain, September 8-10, 2009.

[8] G.Bergna, M.Boyra, J.H.Vivas, "Evaluation and Proposal of MMC-HVDC Control Strategies under Transient and Steady State Conditions," *European Conference on Power Electronics and Applications EPE'2011*, pp:1-10, Birmingham, Aug./Sept. 2011.

[9] P.Munch, S.Liu, M.Dommaschk "Modeling and Current Control of Modular Multilevel Converters Considering Actuator and Sensor Delays," *IEEE IECON '09*, pp. 1633-1638, Porto, Nov. 2009.

[10] M.Hagiwara, R.Maeda, H.Akagi, "Control and Analysis of the Modular Multilevel Cascade Converter Based on Double-Star Chopper-Cells (MMCC-DSCC)," *IEEE Trans. Power Electron.*, V.26 , I. 6, pp. 1649-1658, June 2011.

[11] Ji-Woo Moon, Jin-Su Gwon, Jung-Woo Park, Dae-Wook Kang, and Jang-Mok Kim, "Model Predictive Control With a Reduced Number of Considered States in a Modular Multilevel Converter for HVDC System" *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 608-617, April 2015.

[12] S. Rohner, J. Weber and S. Bernet "Continuous Model of Modular Multilevel Converter with Experimental Verification," *IEEE ECCE'2011*, pp. 4021-4028, 17-22 Sept. 2011, Phoenix, AZ 2011.

[13] M. Hiller, D. Krug, R. Sommer, and S. Rohner, A new highly modular medium voltage converter topology for industrial drive applications. Power Electronics and Applications," *European Conference EPE'09*, pp. 1-10, Sept. 2009.

[14] A. Antonopoulos, K. Ilves, L. A. ngquist, and H.-P. Nee, "On Interaction between Internal Converter Dynamics and Current Control of High-Performance High-Power AC Motor Drives with Modular Multilevel Converters," *IEEE ECCE'2010*, Atlanta, Sept. 2010.

[15] M. Hagiwara, K. Nishimura, and, H. Akagi "A Medium-Voltage Motor Drive with a Modular Multilevel PWM Inverter," *IEEE Trans. Power Electron.*, vol. 27, no. 7, pp. 1786-1799, July 2010.

[16] A. Korn, M. Winkelnkemper, and P. Steimer, Low Output Frequency Operation of the Modular Multi-Level Converter," *IEEE ECCE'2010*, Atlanta, Sept. 2010.

[17] J. Kolb, F. Kammerer, and M. Braun, "A novel control scheme for low frequency operation of the Modular Multilevel Converter.," *PCIM'2011 Europe*, Nuremberg, Germany, 2011.

[18] J. Kolb, F. Kammerer, and M. Braun, "Straight forward vector control of the Modular Multilevel Converter for feeding three-phase machines over their complete frequency range," *IEEE IECON 2011*, Melbourne, 2011.

[19] J. Kolb, F. Kammerer, and M. Braun, "Operating performance of Modular Multilevel Converters in drive applications," *PCIM'2012 Europe*, Nuremberg, Germany, 2012.

[20] Kui Wang, Yongdong Li, Zedong Zheng, and Lie Xu, "Voltage Balancing and Fluctuation-Suppression Methods of Floating Capacitors in a New Modular Multilevel Converter," *IEEE Trans. Ind. Electron.*, Vol. 60, No. 5, pp. 1943-1954, May 2013.

[21] Perez, M.A.; Rodriguez, J.; Fuentes, E.J.; Kammerer, F., "Predictive Control of AC–AC Modular Multilevel Converters," *IEEE Trans. Ind. Electron.*, vol. 59 , no. 7, pp. 2832 – 2839, July 2012

[22] Jiangchao, Q.; Saeedifard, M., "Predictive Control of a Modular Multilevel Converter for a Back-to-Back HVDC System," *IEEE Trans. Power Del.*, vol. 27 , Issue: 3, , pp. 1538 – 1547, June 2012

[23] Jiangchao, Q.; Saeedifard, M., "Predictive control of a three-phase DC-AC Modular Multilevel Converter," *IEEE ECCE'2012*, pp. 3500 – 3505.

[24] Fard, R.N; Nademi, H.; Norum, L., "Analysis of a Modular Multilevel inverter under the predicted current control based on Finite-Control-Set strategy," *International Conference on Electric Power and Energy Conversion Systems EPECS'*2013, pp. 1 – 6.

[25] Jiangchao, Q.; Saeedifard, M., "Reduced Switching-Frequency Voltage-Balancing Strategies for Modular Multilevel HVDC Converters," *IEEE Trans. Power Del.*, vol. 28, no. 4, pp. 2403 – 2410, Aug. 2013.

[26] Trabelsi, M.; Ben-Brahim, L. ; Gastli, A. ; Ghazi, K.A., "An improved predictive control approach for Multilevel Inverters," *IEEE SLED/PRECEDE'2013*, pp. 1 – 7, 2013.

[27] Wang, Jun; Burgos, Rolando ; Boroyevich, Dushan ; Bo Wen, "Power-cell Switching-Cycle Capacitor Voltage Control for the Modular Multilevel Converters," *International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE-ASIA)*, pp. 944 – 950, 2014.

[28] Yue Wang ; Wulong Cong ; Ming Li ; Ning Li ; Mu Cao ; Wanjun Lei, "Model predictive control of modular multilevel converter with reduced computational load," *IEEE APEC'2014*, pp. 1776 – 1779, 2014.

[29] Moon, J.-W. ; Gwon, J.-S.; Park, J.-W. ; Kang, D.-W. ; Kim, J.-M. , "Model Predictive Control With a Reduced Number of Considered States in a Modular Multilevel Converter for HVDC System," *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 608 - 617, Feb. 2014

[30] Bocker, J.; Freudenberg, B.; The, A.; Dieckerhoff, S., "Experimental Comparison of Model Predictive Control and Cascaded Control of the Modular Multilevel Converter," *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 422 – 430, Jan. 2015.

[31] Ilves, K.; Harnefors, L.; Norrga, S.; Nee, H-.P. , "Predictive Sorting Algorithm for Modular Multilevel Converters Minimizing the Spread in the Submodule Capacitor Voltages," *IEEE Trans. Power Electron.*, vol. 30, no. 1, pp. 440 – 449, Jan. 2015.

[32] Nademi, H.; Das, A.; Norum, L.E., "Modular Multilevel Converter with an Adaptive Observer of Capacitor Voltages," *IEEE Trans. Power Electron.*, Volume: 30, Issue: 1, Page(s): 235 – 248, 2015.

[33] W. Li, L. Gregoire, and J. Belanger, "A modular multilevel converter pulse generation and capacitor voltage balance method optimized for fpga implementation," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 2859–2867, May 2015.

[34] J. Pou et al., "Circulating current injection methods based on instantaneous information for the modular multilevel converter," *IEEE Trans. Ind. Electron.*, vol. 62, no. 2, pp. 777–788, Feb. 2015.

[35] Binbin Li; Yi Zhang; Gaolin Wang; Wei Sun; Dianguo Xu; Wei Wang "A Modified Modular Multilevel Converter With Reduced Capacitor Voltage Fluctuation," *IEEE Trans. Ind. Electron.*, vol. 62, no. 10, pp. 6108-6119, Oct. 2015.

[36] Vasiladiotis, M.; Cherix, N.; Rufer, A., "Impact of Grid Asymmetries on the Operation and Capacitive Energy Storage Design of Modular Multilevel Converters," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 6697 - 6707, Nov. 2015.

[37] Fujin Deng; Zhe Chen, "Voltage-Balancing Method for Modular Multilevel Converters Switched at Grid Frequency," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 2835 - 2847, May 2015.

[38] Debnath, S.; Jiangchao Qin; Saeedifard, M., "Control and Stability Analysis of Modular Multilevel Converter Under Low-Frequency Operation," *IEEE Trans. Ind. Electron.*, vol. 62, no. 9, pp. 5329 - 5339, Sept. 2015.

[39] Fujin Deng; Zhe Chen, "Voltage-Balancing Method for Modular Multilevel Converters Under Phase-Shifted Carrier-Based Pulsewidth Modulation," *IEEE Trans. Ind. Electron.*, vol. 62, no. 7, pp. 4158 - 4169, July 2015.

[40] Xiaojie Shi; Bo Liu; Zhiqiang Wang; Yalong Li; Tolbert, L.M.; Fei Wang, "Modeling, Control Design, and Analysis of a Startup Scheme for Modular Multilevel Converters," *IEEE Trans. Ind. Electron.*, vol. 62, no. 11, pp. 7009 - 7024, Dec. 2015.

[41] J. Mei, Y. Ji, J. Tian, et al, "Balancing control scheme for modular multilevel converters using virtual loop mapping with fault-tolerance

capabilities ," *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 38 - 48, Jan. 2016.

[42] M. Trabelsi, K.A. Ghazi, N. Al-Emadi, L. Ben-Brahim, “A weighted real-time predictive controller for a grid connected flying capacitors inverter,” *International Journal of Electrical Power & Energy Systems,* vol. 49, pp. 322-332, July 2013.

[43] J. Rodriguez, H. Abu-Rub, M. A. Perez, and S. Kouro, "Application of Predictive Control in Power Electronics: An AC-DC-AC Converter System," *Advanced and Intelligent Control in Power Electronics and Drives, ed: Springer*, 2014.

[44] J. Rodríguez, M. A. Pérez, H. Young, and H. Abu-Rub, "Model Predictive Speed Control of Electrical Machines," *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications, ed: John Wiley & Sons, Ltd*, 2014.

[45] M. Trabelsi, K. A. Ghazi, N. Al-Emadi, and L. Ben-Brahim, "An original controller design for a grid connected PV system," *IEEE IECON'2012,* pp. 924-929.

[46] M. Trabelsi, L. Ben-Brahim, and K. A. Ghazi, "An improved Real-Time Digital Feedback Control for grid-tie multilevel inverter," *IEEE IECON'2013,* pp. 5776-5781, 2013.

[47] H. Abu-Rub, M. Malinowski, K. Al-Haddad, “Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications,” *John Wiley & Sons,* 2014.

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