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A multi-loop control technique for the stable operation of modular multilevel converters in HVDC transmission systems

Majid Mehrasa[a], Edris Pouresmaeil[b,c], Sasan Zabihi[d], Ionel Vechiu[c], João P.S. Catalão[a,b,e,*]

[a] C-MAST, University of Beira Interior, R. Fonte do Lameiro, 6201-001 Covilhã, Portugal
[b] INESC-ID, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal
[c] ESTIA Institute of Technology, ESTIA, F-64210, Bidart, France
[d] ABB Australia Pty Limited, Berrimah, Northern Territory, Australia
[e] INESC TEC and Faculty of Engineering of the University of Porto, R. Dr. Roberto Frias, 4200-465 Porto, Portugal

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ABSTRACT

A multi-loop control strategy based on a six-order dynamic model of the modular multilevel converter (MMC) is presented in this paper for the high-voltage direct current (HVDC) applications. For the initial analysis of the operation of MMC, a capability curve based on active and reactive power of the MMC is achieved through a part of the six order dynamic equations. According to the MMC's control aims, the first loop known as the outer loop is designed based on passivity control theory to force the MMC state variables to follow their reference values. As the second loop with the use of sliding mode control, the central loop should provide appropriate performance for the MMC under variations of the MMC's parameters. Another main part of the proposed controller is defined for the third inner loop to accomplish the accurate generation of reference values. Also, for a deeper analysis of the MMC's dc link voltage stability, two phase diagrams of the dc-link voltage are assessed. Matlab/Simulink environment is used to thoroughly validate the ability of the proposed control technique for control of the MMC in HVDC application under both load and MMC's parameters changes.

1. Introduction

The modular multilevel converter (MMC) topology has been a subject of increasing importance because of its special characteristics such as easy replacement of fault sub-modules (SMs), centralizing the distributed energies, modular structure, very low harmonic components and power losses, and also decreased rating values [1–5]. The MMCs have been widely utilized in various voltage/power levels of growing applications such as solar photovoltaic [6], large wind turbines [7,8], *ac* motor drives [9,10], high-voltage direct current (HVDC) transmission systems [11,12], *dc-dc* transformers [13], battery electric vehicles [14], distributed energy resources (DERs) [15,16], and flexible *ac* transmission systems (FACTS) [17].

Many researchers have focused on the control and modelling issues of the MMCs in various applications in recent years. Ref. [18] deals with the fault condition of the MMC and tries to provide normal performance for the MMCs by the help of an energy-balancing control. A binary integer programming based model predictive control for the MMCs is proposed in [19] to optimize the multi-objective problem with minimum computing effort related to the control method which is the main contribution of the paper. A closed loop-needless PID controller along with increasing the arm inductance are considered to evaluate the effects of output voltage and current total harmonic distortion (THD) response in a modular multilevel converter [20]. Ref. [21] presents a control strategy based on calculating the differential current references to provide desired operation for the MMCs in HVDC applications. Various dynamic models of the MMCs and their limitations in presenting robust control methods for these converters are investigated in [22]. In this paper, a complete derivation of the proposed switching state functions without losing any circuital characteristics of the converter is accomplished and a switching-cycle control approach proposed based on unused switching states of the MMCs. A modulation technique is proposed in [23] based on a fixed pulse pattern fed into the SMs to maintain the stability of the stored energy in each SM, without measuring capacitor voltages or any other sort of feedback control. It also removes certain output voltage harmonics at any arbitrary modulation index and any output voltage phase angle. A current control design for independent adjustment of several current components and a systematic identification of current and voltage components for balancing the energy in the arms of an MMC is presented in [24]. In [25], a control strategy based on adding a common zero-sequence voltage to the reference voltages is proposed for balancing the arm currents of the

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[*] Corresponding author at: Faculty of Engineering of the University of Porto, Portugal.
E-mail address: catalao@ubi.pt (J.P.S. Catalão).

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Nomenclature

Indices

K	*a, b, c*
J	1, 2

Abbreviations

KVL	Kirchhoff's Voltage Law
KCL	Kirchhoff's Current Law
CLC	Central Loop Controller
ILC	Inner Loop Controller
v_c	rated capacitor voltage
$S_{(ul)jk}$	switches of the MMCs
$v_{(ul)kj}$	lower and upper arms voltages
v_{kj}	output voltages of the MMCs
v_{dc}	*dc*-link voltage
u_{kj1}	first equivalent modulation function of the respective SM stacks
u_{kj2}	second equivalent modulation function of the respective SM stacks
$v_{sm(ul)kj}$	SMs voltages
$v_{t(dq)j}$	*ac*-side voltages of the MMCs
$v^*_{(dq)j}$	reference value of output voltages of the MMCs
v^*_{dc}	reference value of *dc*-link voltage
i_{kj}	currents of MMCs
i_{cirkj}	circulating currents of the MMCs
$i_{(ul)kj}$	lower and upper arms currents
i_{dcj}	MMCs *dc*-link currents
$i_{sm(ul)kj}$	currents of SMs
$i^*_{(dq)j}$	reference values of MMCs currents
$i^*_{cir(dq)j}$	reference values of circulating currents
$i_{l(dq)j}$	load currents
$I_{av(dq)j}$	average currents of the MMCs
$i_{(dq)\max j}$	maximum value of MMCs currents
$\sum_{h=1}^{\infty} i_{l(dq)h}$	total harmonic current components of loads
P_j	injected active power of MMCs
Q_j	injected reactive power of MMCs
P^*_j	reference values of active power of MMCs
OLC	Outer Loop Controller
SMs	Sub-Modules
LPF	Low Pass Filter
DLM	Direct Lyapunov Method
HVDC	High-Voltage, Direct Current
MMCs	Modular Multilevel Converters
PI	Proportional-Integral
SLPWM	Shift Level Pulse Width Modulation

Variables

Q^*_j	reference values of reactive power of MMCs
$H_{(dq)j}(s)$	transfer function
Z_{dqj}	error vector
E_{dqj}	total saved energy
S_{dqj}	time-variable sliding surface

Parameters

$1/\xi_{(dq)}$	proportional gain
L	inductance of the MMCs
R	resistance of the MMCs
L_p	arm's inductance
R	arm's resistance
C_{eq}	equivalent *dc*-link capacitor
R_{dc}	equivalent *dc*-link resistance
	injection resistances
f_{ac}	*ac*-side frequency
f_s	switching frequency
n	numbers of SMs in each arm
C	capacitor of SM
C_{fi}	capacitor of *ac* filter
$\omega_{(dq)2}$,$\omega_{(dq)\max 2}$	cut-off frequency
$\omega_{p(dq)2}/\xi_{(dq)}$	integral gain
$k_{(dq)j}$	positive constant of CLC
$\psi_{cir(dq)j}$	positive constant of CLC
$\psi_{(dq)j}$	positive constant of CLC

MMCs under unbalanced load conditions. To reach it, a relationship between the dc-link active power and ac-link average active power is achieved and then, the dc component of the arm current is calculated through the ac-link average active power in the corresponding phase [25]. In the medium voltage systems, the energy storage can be embedded in MMC that causes several SMs to operate at significantly lower voltages [26]. In the structure presented in [27], the low-frequency components of the SM's output currents are removed by utilizing the interfaced batteries through the non-isolated dc/dc converters. Control algorithms proposed in this paper are developed to balance the state of charge of batteries. A compact and clear representation of differential equations is obtained for the MMC by introducing two nonlinear coordinate transformations in [28]. In the proposed model, two candidate outputs leaded to the internal dynamics of second or third order and a quasi-static feedback generates a linear input-output behaviour. Other different aspects of MMC application in HVDC system such as DC fault and DC solid-state transformers operating conditions are assessed in the references of [31–34].

In many existing methods, simultaneously having robustness against MMC parameters changes and also having very good dynamic tracking responses against the MMC's load changes have not been considered in their designed control techniques. But, in this paper, a multi-loop control strategy is aimed at providing a stable operation of the MMCs in HVDC application under both MMC's arm inductance and resistance parameters variations and also loads changes as well. This the first feature of the proposed controller that can increase the stability margins of the MMC performance with existence of more variations. According to the achieved six order dynamic equations of the MMCs, firstly the outer loop formed by passivity based control technique is introduced to enable the convergence ability of the MMC's state variables for its reference values in dynamic changes. Then, sliding mode controller is used to prepare the MMCs for stable operation against the MMC's parameters variations as the central loop of the proposed controller. The inner loop is employed to help other loops have accurate reference values for its used state variables that as another feature of the proposed controller, can generate instantaneously the needed references values of both MMCs in various operating conditions. Also, a capability curve is obtained to specify the allowable area of the MMC's active and reactive power generation in HVDC application and also R and L variations effects on the curve are evaluated that can provide some control considerations to understand more about the simulation results of the MMC's performance. Stability analysis of dc-link voltage is done in final part of this paper. Simulation results executed by Matlab/Simulink demonstrate the validity of the proposed control strategy in all operating conditions.

2. The proposed differential equation of MMC

Fig. 1(a) shows the proposed HVDC system which is consisted of two back-to-back MMCs. The *ac*-side of the MMC1 comprises *ac*-system-1, a