Reference Design for Predictive Control of Modular Multilevel Converters

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***Abstract*—This paper proposes a reference design technique for the control of Modular Multilevel Converters. Assuming balanced operation, a reduced-order model for the power converter is developed and its state trajectories are characterized in closed form. This allows one to specify desired references for the current and voltage at the load, and also for the circulating current and capacitor voltages in the converter. A simulation study using finite-set constrained predictive control illustrates advantages of the proposed method.**

I. Introduction

Power electronics is an essential part of energy distribution systems (Smart-grids), allowing the control of the energy flow and enabling the incorporation of renewable energy sources [1]. The manipulable inputs in power converters are discrete-valued switches. This makes the development of high-performance control laws inherently difficult. Modular multilevel converters (MMC) are a relatively new type of converters that uses a series connection of several basic modules, allowing very high voltage stress (hundreds of kilovolts) by dividing it among all the modules. Their potential to yield high quality waveforms makes MMCs an excellent candidate for energy distribution systems [2]. An MMC usually has tens or even hundreds of switches that can be driven independently. Classical approaches using PWM and linear controllers, can become very complex when the number of control variables increases, often leading to poor performance. This motivates the use of Model Predictive Control (MPC) for governing MMCs. MPC has the advantage of dealing easily with constraints and system failures; it also has the potential to reduce switching losses and harmonic distortion, in comparison with classical PWM techniques [3]–[5]. Another advantage of the MPC framework is the possibility to explicitly consider the future behavior of the system in the presence of constrains and take that into account into the current control action [6]–[10].

There are three important variables to control in an MMC: the output current, the capacitor voltage of each module, and the internal current, usually called circulating current. The output current is the current delivered to the load and its desired form is a pure sinusoidal waveform. The voltage of the capacitors is desired to be the same for all modules in each arm, distributing the voltage stress evenly in all the modules. The role of the circulating current is to transfer the power from the DC input voltage source to the whole circuit; therefore, a DC component is required, see Fig. 1. In current works with MMC, the references given to the MPC are simplified DC versions of the actual desired waveforms. These assume an ideal case of infinite capacitances [11], [12]. In a realistic case, with finite value capacitances, several AC components appear in the circulating current and the capacitance voltages. With existing methods, these AC components are left uncontrolled if the simplified DC references are used. To improve control loop performance, it is important that the references are designed adequately, this requires the knowledge of the possibilities and limitations of the system, cf. [13].

In the present work, we propose a method to design the references (AC+DC) for use in MPC of MMCs. The analysis shows how the effect of the circulating current can be modeled and manipulated. To do this, a reduced order continuous model of the MMC is proposed and used to obtain analytical expressions showing the relation between each of the variables of the converter. Finally, the references are computed and used with the MPC. The proposed method is tested and compared with the simplified method of [11], [12]. It is shown how the flexibility of our design can be used to give performance gains.

This paper is organized as follows: Section II presents the MMC. Section III shows the proposed simplified order model. Section IV describes the analytical computation of the references for the MPC. Section V describes an application to MPC.

II. Modular Multilevel Converter (MMC)

The MMC is a power converter topology which transforms the energy from DC to AC. For each AC phase (see Fig. 1), this is accomplished by two arms inserted between the upper and the lower dc-link rail, with the center tap being the phase terminal. Each branch consists of the series-connection of N modules. Each module consists of two semiconductor switches and one capacitor.

The present work studies the single phase MMC shown in Fig. 1. Applications to 3-phase operation are currently being investigated.

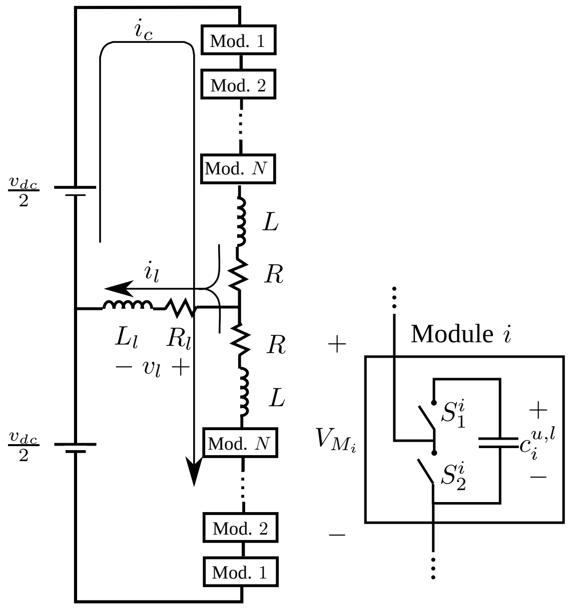


Fig. 1. Typical single-phase MMC configuration with N modules per arm. V_{dc} is the DC input voltage and v_l the voltage of the load (output)

TABLE I
SWITCH POSITIONS

S_1^i	S_2^i	V_i^M
ON	OFF	V_i
OFF	ON	0
ON	ON	n.a.
OFF	OFF	n.a.

In order to control the MMC, the switch positions of each module can be chosen independently to one of two possible positions as shown in Table I. A module is considered "inserted" when its voltage (V_i^M) is equal to the voltage of its respective capacitor.

The desired waveforms of output currents and voltages of the MMC are sinusoidal. They can be defined as

$$i_l(t) = \hat{i}_l \cos(\omega_0 t + \phi) \tag{1}$$

$$v_l(t) = \hat{v}_l \cos(\omega_0 t) \tag{2}$$

where $\hat{i}_l$ is the amplitude of the output current and ω_0 the angular frequency. The phase angle ϕ, can be calculated based on the values of the inductive an resistive components of the load as

$$\phi = \arctan\left(\frac{\omega_0 L_l}{R_l}\right) \tag{3}$$

and the value of $\hat{v}_l$ can be computed as

$$\hat{v}_l = \hat{i}_l \sqrt{(\omega_0 L_l)^2 + R_l^2} \tag{4}$$

Using electrical circuit analysis methods, an MMC (Fig. 1) with N submodules per arm can be described by the following state space model

$$\dot{x}(t) = \mathcal{A}\left(\vec{\mu}^u(t), \vec{\mu}^l(t)\right) x(t) + \mathcal{B} v_{dc} \tag{5}$$

$$x(t) \triangleq \begin{bmatrix} i_c(t) & i_l(t) & v_1^u(t) & \cdots & v_N^u(t) & v_1^l(t) & \cdots & v_N^l(t) \end{bmatrix}^T \tag{6}$$

where i_c and i_l are the circulating and load current respectively. v_i^u and v_i^l represent the capacitor voltages on the module i of upper (u) and lower (l) arms.

In (5), $\vec{\mu}^u(t)$ and $\vec{\mu}^l(t)$ represent the control signals for each module on the upper and lower arms. The components of these control signals can take the value of 1 (module inserted) or 0 (module not inserted) and are defined as follows

$$\vec{\mu}^u(t) \triangleq \begin{bmatrix} \mu_1^u(t) & \cdots & \mu_N^u(t) \end{bmatrix}^T, \ \mu_i^u(t) \in 0, 1 \tag{7}$$

$$\vec{\mu}^l(t) \triangleq \begin{bmatrix} \mu_1^l(t) & \cdots & \mu_N^l(t) \end{bmatrix}^T, \ \mu_l^u(t) \in 0, 1 \tag{8}$$

The matrix $\mathcal{A}\left(\vec{\mu}^u(t), \vec{\mu}^l(t)\right)$ is defined as

$$\begin{aligned} &\mathcal{A}\left(\vec{\mu}^u(t), \vec{\mu}^l(t)\right) \triangleq \\ &\begin{bmatrix} \mathcal{A}_{1,1} & \mathcal{A}_{1,2}\left(\vec{\mu}^u(t), \vec{\mu}^l(t)\right) \\ \mathcal{A}_{2,1}\left(\vec{\mu}^u(t), \vec{\mu}^l(t)\right) & 0 \end{bmatrix} \end{aligned} \tag{9}$$

with

$$\mathcal{A}_{1,1} = \begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R+2R_l}{L+2L_l} \end{bmatrix} \tag{10}$$

$$\mathcal{A}_{1,2}\left(\vec{\mu}^u(t), \vec{\mu}^l(t)\right) = \begin{bmatrix} -\frac{1}{2L}\vec{\mu}^u(t)^T & -\frac{1}{2L}\vec{\mu}^l(t)^T \\ -\frac{1}{L+2L_l}\vec{\mu}^u(t)^T & \frac{1}{L+2L_l}\vec{\mu}^l(t)^T \end{bmatrix} \tag{11}$$

$$\mathcal{A}_{2,1}\left(\vec{\mu}^u(t), \vec{\mu}^l(t)\right) = \begin{bmatrix} \frac{1}{C}\vec{\mu}^u(t) & \frac{1}{2C}\vec{\mu}^l(t) \\ \frac{1}{C}\vec{\mu}^u(t) & -\frac{1}{2C}\vec{\mu}^l(t) \end{bmatrix} \tag{12}$$

and

$$\mathcal{B} \triangleq \begin{bmatrix} \frac{1}{2L} & 0 & \cdots & \cdots & 0 \end{bmatrix}^T \tag{13}$$

III. REDUCED ORDER MODEL

The MMC is a highly nonlinear, discontinuous system with multiple inputs as it is shown in (5). The discontinuities make the system harder to analyze. In order to simplify the analysis of the system and obtain analytical expressions for the variables of interest, this section proposes an approximation method to reduce the order of the model, the number of inputs and remove the discontinuities.

Lemma 1. *Consider the MMC model described in* (5)*, and assume that the capacitor voltages are balanced:*

$$v_i^u(t) = v_j^u(t) = v^u(t), \quad \forall i, j \in \{1, 2, \ldots, N\} \tag{14}$$

and

$$v_i^l(t) = v_j^l(t) = v^l(t), \quad \forall i, j \in \{1, 2, \ldots, N\} \tag{15}$$

[1]*Then the MMC model* (5) *reduces to:*

$$\dot{x}(t) = A\left(\mu^u(t), \mu^l(t)\right) x(t) + B v_{dc} \tag{16}$$

[1]Note that $v^u = v^l$ is not imposed.

$$A\left(\mu^u(t),\mu^l(t)\right) \triangleq \begin{bmatrix} -\frac{R}{L} & 0 & -\frac{1}{2L}\mu^u(t) & -\frac{1}{2L}\mu^l(t) \\ 0 & -\frac{R+2R_l}{L+2L_l} & -\frac{1}{L+2L_l}\mu^u(t) & \frac{1}{L+2L_l}\mu^l(t) \\ \frac{1}{NC}\mu^u(t) & \frac{1}{2NC}\mu^u(t) & 0 & 0 \\ \frac{1}{NC}\mu^l(t) & -\frac{1}{2NC}\mu^l(t) & 0 & 0 \end{bmatrix} \tag{17}$$

$$x(t) \triangleq \begin{bmatrix} i_c(t) & i_l(t) & v^u(t) & v^l(t) \end{bmatrix}^T \tag{18}$$

$$B \triangleq \begin{bmatrix} \frac{1}{2L} & 0 & 0 & 0 \end{bmatrix}^T \tag{19}$$

where

$$\mu^u(t) \triangleq \sum_{j=1}^{N} \mu_j^u(t), \quad \mu^u(t) \in \{0,\ldots,N\} \tag{20}$$

and

$$\mu^l(t) \triangleq \sum_{j=1}^{N} \mu_j^l(t), \quad \mu^l(t) \in \{0,\ldots,N\} \tag{21}$$

are the modulation functions, which depend on the control law.

Proof. Note that in the equation related to the derivative of i_c in (5), (14) gives the following :

$$\begin{aligned} -\frac{v_1^u(t)}{2L}\mu_1^u(t) - \cdots - \frac{v_N^u(t)}{2L}\mu_N^u(t) &= -\sum_{j=1}^{N}\frac{v_j^u(t)}{2L}\mu_j^u(t) \\ &= -\frac{v^u(t)}{2L}\sum_{j=1}^{N}\mu_j^u(t) \end{aligned} \tag{22}$$

Let $\mu^u(t)$ be the modulation function defined in (20). This modulation function represents the number of modules inserted in the upper arm and takes integer values between 0 and N.

Therefore, it can be concluded that

$$-\frac{v_1^u(t)}{2L}\mu_1^u(t) - \cdots - \frac{v_N^u(t)}{2L}\mu_N^u(t) = -\frac{v^u(t)}{2L}\mu^u(t) \tag{23}$$

An analogous procedure can be carried out for the remaining terms in the equations of the derivatives of i_c and i_l for the lower arm of the converter

Since the capacitor voltages on each arm are assumed equal, only two state space variables are now required to represent the voltages of all the modules. Adding all the capacitor voltages of the upper arm yields

$$\sum_{j=1}^{N} v_j^u(t) = \sum_{j=1}^{N}\left(\frac{i_c(t)}{C}\mu_j^u(t) + \frac{i_l(t)}{2C}\mu_j^u(t)\right). \tag{24}$$

Using (14) and (20), the previous expression can be simplified as follows:

$$Nv^u(t) = \frac{i_c(t)}{C}\mu^u(t) + \frac{i_l(t)}{2C}\mu^u(t) \tag{25}$$

An analogous procedure can be followed for the voltages in the lower arm, leading to (16)-(19)

□

This reduced-order model in (16), allows one to take into account or neglect the discontinuities (quantization) presented in the inputs $\mu^{u,l}$. Note that these inputs represent the number of modules inserted on each arm, and take only integer values between 0 and N. Therefore, a quantization effect is observed. If desired, this effect can be neglected using a soft continuous version of $\mu^{u,l}$ easing the analysis. This stands in contrast to the model presented [14], where the discontinuities cannot be taken into account without going back to the original model. Moreover, the reduced order model presented in the present work facilitates the derivation of analytical solutions, by reducing the number of input variables and the size of the state vector.

IV. Reference design

This section shows how to use the model of section II to design the references for an MPC. It has been shown that, in steady-state, i_c can only contain even order harmonics [15], [16]. For the sake of simplicity, only a second order harmonic is taken into account in the subsequent analysis:

$$i_c(t) = i_0 + \hat{i}_2 cos(2\omega_0 t + \phi_2) \tag{26}$$

where $\hat{i}_2$ and ϕ_2 represent the amplitude and phase of the second harmonic of the current, and they are free parameters. The DC component i_0 is in charge of extracting the power from the DC input voltage. In previous approaches, [11], [12], $\hat{i}_2$ and ϕ_2 are set to 0 and only i_0 is considered. When a MMC is controlled using MPC, the whole state space vector x from (18) needs a reference. We shall consider a situation where, at the load, i_l and v_l have been predefined, see (1) and (2). The relevant design question now becomes one of specifying parameters in (26) and compatible references for the capacitor voltages v^u and v^l. These quantities are linked as specified as follows:

Lemma 2. *Consider the system described in* (16) *and the definitions of i_c and i_l in* (26) *and* (1) *respectively. For a given $\hat{i}_2$ and ϕ_2, the analytical solution of* (16) *in steady-state is given by the following equations:*

$$i_0 = \frac{v_{dc} - \sqrt{v_{dc}^2 - 8R\left(\frac{\hat{v}_l\hat{i}_l}{2}cos(\phi) + 2R\left(\frac{\hat{i}_l^2}{8} + \frac{\hat{i}_2^2}{2}\right)\right)}}{4R} \tag{27}$$

$$v^u(t) = \sqrt{\frac{2}{CN}\int_0^t \left(i_c(\tau) + \frac{i_l(\tau)}{2}\right) a^u(\tau)\, d\tau + (v_{DC}^u)^2} \tag{28}$$

$$v^l(t) = \sqrt{\frac{2}{CN}\int_0^t \left(i_c(\tau) - \frac{i_l(\tau)}{2}\right) a^l(\tau)\, d\tau + (v_{DC}^l)^2} \tag{29}$$

where

$$a^u(t) = -((L+2L_l)\dot{i}_l(t) + 2L\dot{i}_c(t) + 2Ri_c(t) + (R+2R_l)i_l(t) - v_{dc}) \quad (30)$$

$$a^l(t) = (L+2L_l)\dot{i}_l(t) - 2L\dot{i}_c(t) - 2Ri_c(t) + (R+2R_l)i_l(t) + v_{dc} \quad (31)$$

and

$$v^u_{DC} = v^l_{DC} = \frac{v_{dc} - 2Ri_0}{N} \quad (32)$$

Proof. The component i_0 depends on the power delivered to the load an the additional power losses in the circuit, as follows

$$v_{dc}i_0 = \frac{\hat{v}_l\hat{i}_l}{2}cos(\phi) + 2R\left(\frac{\hat{i}_l^2}{8} + \frac{\hat{i}_2^2}{2} + i_0^2\right). \quad (33)$$

Solving for i_0 leads to (27).

Using the first two equations in (16) ($\dot{i}_c(t)$ and $\dot{i}_l(t)$), (1) and (26), the following is obtained

$$\dot{i}_c(t) = -2\hat{i}_2 sin\left(2\omega_0 t + \phi_2\right)\omega_0 \quad (34)$$

$$\dot{i}_l(t) = -\hat{i}_l sin\left(\omega_0 t + \phi\right)\omega_0 \quad (35)$$

The desired values of the modulation functions $\mu^{u,l}$ can be obtained solving the previous set of equations, which yields

$$\mu^u(t) = \frac{1}{2}\frac{a^u(t)}{v^u(t)} \quad (36)$$

$$\mu^l(t) = \frac{1}{2}\frac{a^l(t)}{v^l(t)} \quad (37)$$

where $a^u(t)$ and $a^l(t)$ are defined as in (30) and (31) respectively.

Using the last two equations in (16) ($\dot{v}^u$ and $\dot{v}^l$) and the result in (36) and (37), the following is obtained

$$\dot{v}^u(t) = \frac{1}{CN}\left(i_c(t) + \frac{i_l(t)}{2}\right)\frac{a^u(t)}{v^u(t)}. \quad (38)$$

This leads to (28), where v^u_{DC} represents the DC value of the capacitor voltage and can be computed as in (32)

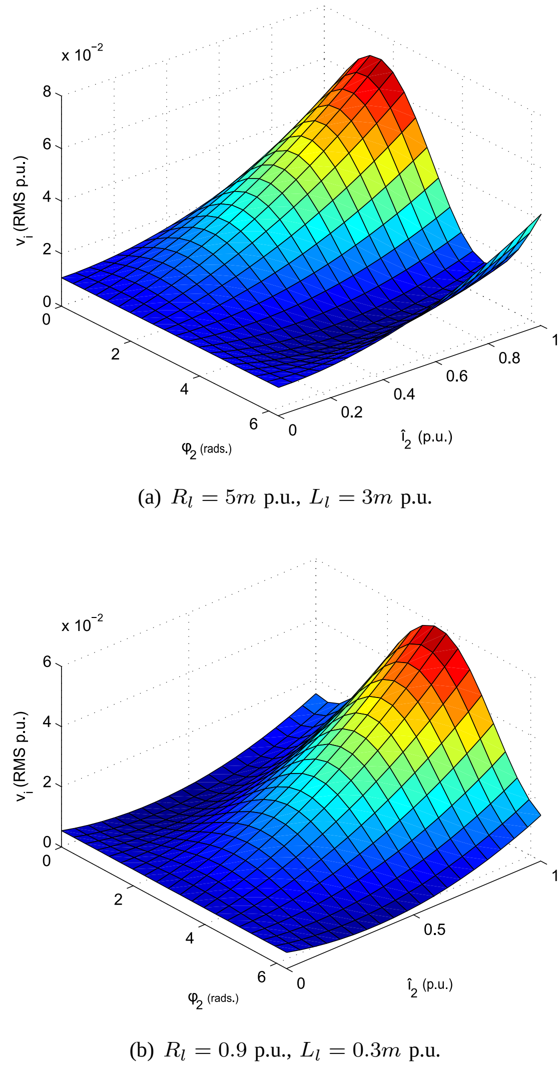
An analogous procedure can be followed to compute v^l, leading to (29) □

Note that all the expressions in Lemma 2 are composed by known integrable and derivable functions. Therefore, analytical explicit functions can be obtained. These can be used to select the values of $\hat{i}_2$, ϕ_2 to satisfy a variety of design objectives.

With the results of Lemma 2 it is easy to study the effect of the different variables over the behaviour of the system. Fig. 2 shows the effect of $\hat{i}_2$ and ϕ_2 over the RMS value of the ripple of the capacitor voltage. Two different load values are used, the rest of the parameters are shown in Table II. It is possible to see that the relation of the values of $\hat{i}_2$ and ϕ_2 with the capacitor ripple vary according to the load parameters. Note that, since this method is based on analytical expressions, the RMS value can be easily obtained just by evaluating numerically the corresponding expression. Other methods that lacks of an analytical expression require significantly more computational time [17].

TABLE II
PARAMETER VALUES IN P.U. FOR AN MMC WITH $N = 8$ (P.U. (PER UNIT) VALUES ARE NORMALIZED WITH RESPECT TO A VOLTAGE REFERENCE (3800 V) AND CURRENT REFERENCE (650 A))

Variable	R	L	C	R_l	L_l	v_{dc}
Value	$2.6m$	$0.1m$	$51.4m$	$5m$	$3m$	1.79



(a) $R_l = 5m$ p.u., $L_l = 3m$ p.u.

(b) $R_l = 0.9$ p.u., $L_l = 0.3m$ p.u.

Fig. 2. RMS of the voltage ripple of each capacitor as a function of the 2nd harmonic of the circulating current i_c for different values of load parameters

V. MODEL PREDICTIVE CONTROL (MPC)

In order to control the MMC a one-step MPC frontier is used. This control minimizes a predefined cost function in every iteration using the switch positions as free variable. Let J be a cost function defined as follows

$$J = (x_{ref}(k+1) - \hat{x}(k+1|k))^T P (x_{ref}(k+1) - \hat{x}(k+1|k)) \tag{39}$$

where P is a diagonal weight matrix. $x_{ref}(k+1)$ represents the reference value of the state space vector at instant $k+1$. $\hat{x}(k+1|k)$ is the predicted state space vector at $k+1$ given its measured value at k ($\hat{x}_i(k)$). The computation of $\hat{x}(k+1|k)$ is based on an discrete time version of the full order continuous system from (5), and the current measure of the state space vector ($\hat{x}_i(k)$) in k.

In order to decide the control action, all the possible switching combinations are evaluated on each iteration, then the optimal switching combination that produces the lowest cost function J is applied. For the presented case, an MMC with $N = 8$ modules per arm has 2^{2N} (65536) different combination of switch positions. The evaluation of all the possible switch combinations is a very demanding task for the CPU and can take very long time. To improve the computing time, parallel computation is implemented using a GPU. This reduces the computation time by a factor of 40. [2]

Two different sets of references are tested via simulations. A simplified set of DC references (as used in the literature [11], [12]) given by:

$$\mathbf{i_c} = 0.0014 \tag{40}$$

$$\mathbf{v^u} = \mathbf{v^l} = 0.224 \tag{41}$$

This is compared with the proposed set of references that takes into account additional AC behaviour of the converter (see Lemma 2), given by (28), (29) and

$$\mathbf{i_c} = 0.0014 - 0.46\cos(4\pi 60 t + 1.6) \tag{42}$$

The reference for the load current i_l, in both cases, is given by:

$$\mathbf{i_l} = 0.8\cos(2\pi 60 t + 1.57) \tag{43}$$

Fig. 3 shows the response of the converter to both sets of references. The results show that, by specifying a reference signal for the entire state-vector, it is possible to control all variables of interest. In particular, the simplified set of references (see Fig. 3) manages to control the load current, but leaves the converter voltages and circulating current uncontrolled. Using Lemma 2, all electrical variables can now be tightly controlled.

VI. Conclusions

A novel method to compute the references of an MMC has been investigated. The method allows one to take into account AC components of the circulating current and capacitor voltages. Using analytical expressions, the behaviour of the system can be easily studied.

[2]The computational time can also be reduced by using a restricted control set [12], or sphere decoding methods [18], [19].

Future work may involve investigate potential performance gains by including higher order harmonics, studying reference design of MMCs governed by PWM-linear controllers and extension to 3-phase applications.

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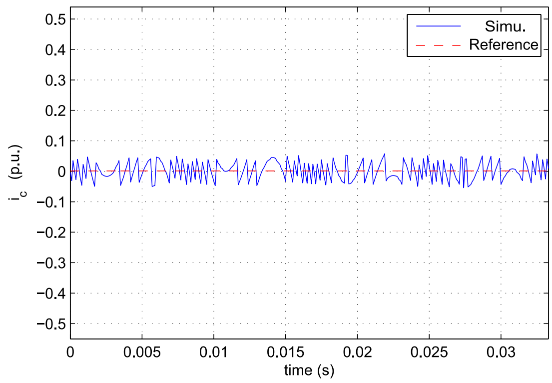
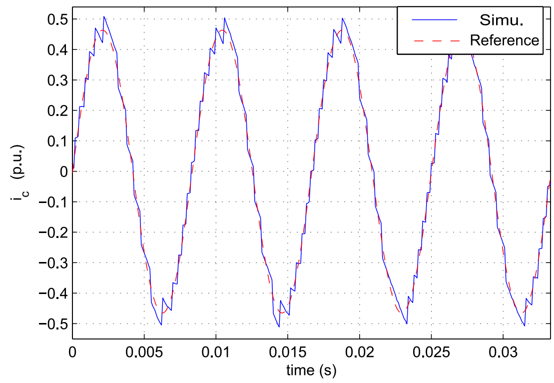
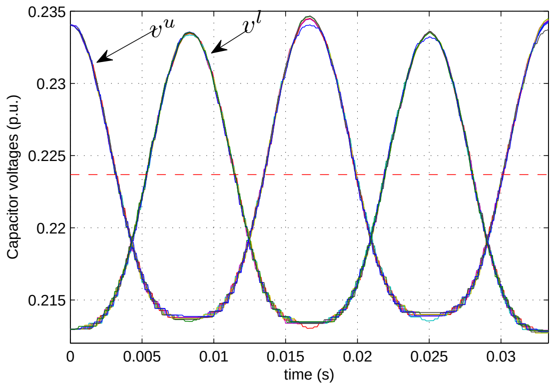


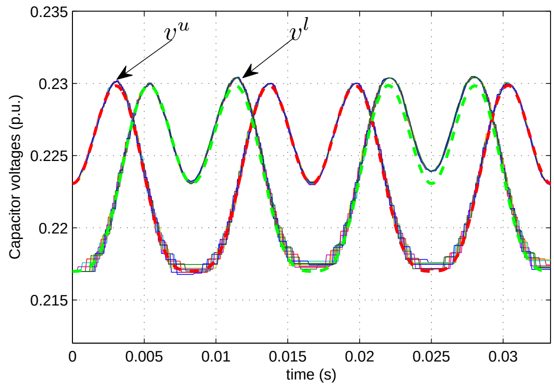
(a) i_c, Simplified DC reference for the circulating current i_c. The dashed line represents the reference ($i_0 = 0.0014$)



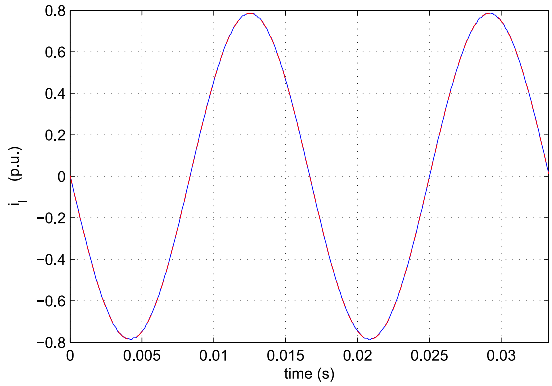
(b) i_c, Proposed Reference for the circulating current. The dashed line represents the reference ($i_0 = 0.0014$, $i_2 = -0.46$, $\phi_2 = 1.6$) see (26)



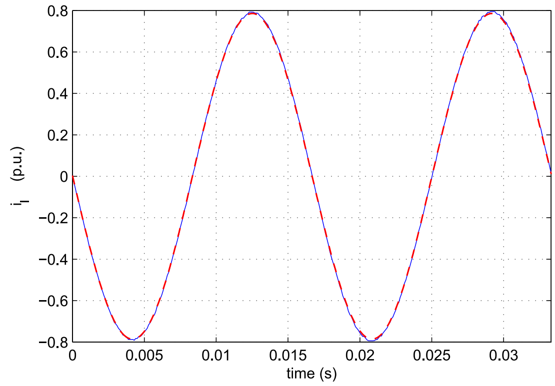
(c) v_l and v_u, Simplified DC reference for the voltages of the capacitors. The dashed line represents the reference ($v_{DC}^{u,l} = 0.224$)



(d) v_l and v_u, Proposed reference for the voltages of the capacitors. The dashed lines represent the references see (28) and (29)



(e) i_l, Reference for the load current. The dashed line represents the reference ($i_l = 0.8$, $\phi = 1.57$) see (1)



(f) i_l, Reference for the load current. The dashed line represents the reference ($i_l = 0.8$, $\phi = 1.57$) see (1)

Fig. 3. Response of the MPC to a set of simplified references (a), (c) and (d). And the proposed set of references (b), (d) and (e). Sampling frequency $5kHz$, $P = diag(1, 100, 100, \dots, 100)$