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Model Predictive Control of Transistor Pulse Converter for Feeding Electromagnetic Valve Actuator with Energy Storage

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Abstract— **The paper presents a novel technique to control the current of an electromagnetic linear actuator fed by a multilevel IGBT voltage inverter with dynamic energy storage. The actuator is designed for dynamically driving an engine valve in an automotive application. The proposed technique shows very promising results through simulations using real system data. In order to provide short response time, high precision and low switching frequency a regulation with model predictive control (MPC) is proposed. Energy storage in a capacitor by energy recovery utilizing mechanical kinetic energy is provided. MPC is able to manage a proper level of capacitor voltage in order to guarantee high dynamic current and disturbance compensation.**

I. INTRODUCTION AND MOTIVATION

In many mechatronic applications dynamic and precise linear motion control is an essential issue. In these cases electromagnetic linear actuators, especially those using permanent magnet excitation, are widely used. For short moving distances permanent magnet DC motors are often a proper choice due to their good controllability. In connection with Insulated Gate Bipolar Transistors (IGBT) dc-dc converters with very short response times and exact trajectory tracking can be realized. In various robotic applications repetitive transient motion loops are required so that the feeding converter acts in this context rather as a four-quadrant single-phase voltage source inverter.

For such trajectory-based motion cycles there is usually a need to control the actuator current separately. The reference value for the actuator current is normally generated by the speed or position controller in an outer control loop following desired speed or position profiles. The current control is used to provide quickly and precisely the force required for the desired motion. Generally, three main techniques are currently employed to current control of a Voltage Source Inverter (VSI):

- closed loop control (e.g. PID control) using pulse-width modulated terminal voltages [6];
- hysteresis control techniques [1];
- predictive current control [5].

The main advantage of the pulse-width modulation (PWM) techniques is that the inverter switches to operate at the fixed frequency and there are hardware or software based standard modulators available as industrial product (e.g. on-board of microcontrollers). Thus, this is presently the most popular method for the inverter current control.

Hysteresis current control gives very fast response and good accuracy. It can be implemented with a simple hardware structure and, in many cases, does not require any knowledge of load parameters. However, it can sometimes cause very high switching frequencies or, if the maximum switching frequency is limited, the current waveform may widely vary and the current peaks may appreciably exceed the hysteresis band, depending on the operation conditions and load parameters.

Conventional predictive current control as suggested in [5] uses a simple gradient model for predicting load current in vector space and determining the proper switching voltage vector according to the one-step prediction. However, no feedback loop is applied to compensate model uncertainties.

In order to overcome the disadvantages of the mentioned methods we developed a novel approach combining the hysteresis control with a model predictive control (MPC) strategy. Here a special energy storage and charging circuit have been designed to provide multilevel voltages for an effective and dynamic current control.

In this paper the control techniques including the optimization strategies are presented in depth.

In the last decade, researchers started dealing with *hybrid systems*, namely hierarchical systems constituted by dynamical and logical/discrete components, see e.g. [3]. The proper control of such systems is not an easy task. In fact, the resulting system is neither linear nor even smooth. Recently, also MPC has been developed for the so-called *mixed logical dynamical* MLD *systems* involving both continuous and binary variables , see e.g. [2]. Due to the switching nature of the power electronic circuit used in our application, the presented system here could also be classified as a kind of MLD systems, though we use a different approach for the predictive control strategy.

The paper is organized as follows: Sections II describes the actuator physics and the power electronic circuit. In section III we define the control goal and explain the idea of using model predictive control. Section IV is devoted to the analysis of the optimization techniques. Section V shows the effectiveness of the proposed control strategy. A short conclusion closes the paper.

II. DESCRIPTION OF THE PHYSICAL SYSTEMS

Fig. 1 shows the physical principle of the permanent magnet linear motor used as a dc actuator. The electromagnetic actuator is designed to operate a car engine valve where the required acceleration can be as high as 2500 m/s. The total transition from closed-position to open-position and vice-versa has to be controlled within a few milliseconds where the maximum allowable deviation in position is around 0.1 mm. Thus, a very dynamic and precise current control must be provided. Note that in normal operation repetitive valve opening and closing are required resulting in a cyclical motion where both acceleration energy (positive) and braking energy (negative) are needed. Fig. 2 shows the power electronic circuit feeding the permanent magnet linear actuator. The power supply is a constant voltage source U_S (battery). However, in order to realize a current change as fast as possible to ensure the required dynamic, it is desirable to have a higher voltage applicable to the actuator. Therefore, a capacitor C, charged with an initial voltage U_c higher than the battery level, is used. In order to keep the high voltage level of the capacitor during valve operation an energy storage block consisting of the capacitor C, the diode D5 and the IGBT switch V5 is used. Besides the current regulation, another task of the control strategy is therefore to appropriately re-charge the capacitor utilizing the braking energy. In the right part the IGBT inverter bridge and the linear actuator are represented.

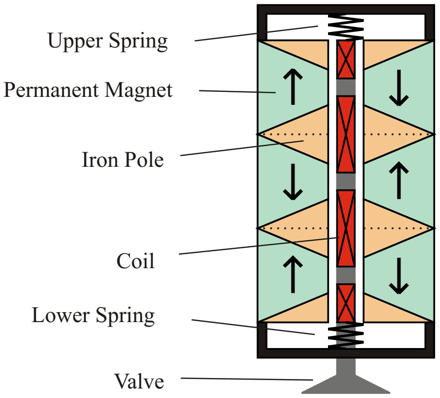

Fig. 1. Cross-section of the perpendicular linear actuator.

III. MPC PROBLEM FORMULATION AND PREDICTION MODEL DESCRIPTION

The central point of a model predictive controller is a process model, which is capable for predicting future system signals based on up-to-date measurements and possible future input signals, carried out for a prediction horizon. This predicted system behavior can be used to minimize an open loop performance criterion (e.g. the squred sum of control errors and control effort) and calculate the control input signals $u(k)$ for a control horizon. Outside the control horizon, the input remains constant. The calculated input signals are fed into the plant until a new measurement becomes available. This procedure is repeated with a receding prediction and control horizon. The receding horizon strategy makes a closed loop control law from the originally open loop minimization. The minimization step can easily include constraints, such that input, output or state constraints can be already taken into account in the controller design. The principle of the predictive control design for the considered current control problem presented in this paper is depicted in Fig. 3 with the desired current (dashed-point line) which results from the outer position control loop[1] and the measured current (solid line). At the present time t all the possible currents for the future two time steps $t + T_S ... t + 2T_S$ are calculated. This calculation is performed based on a multi-mode model and assessed afterwards with the help of a defined cost function (details follow). The optimum switching configuration is also shown (bold-dashed line).

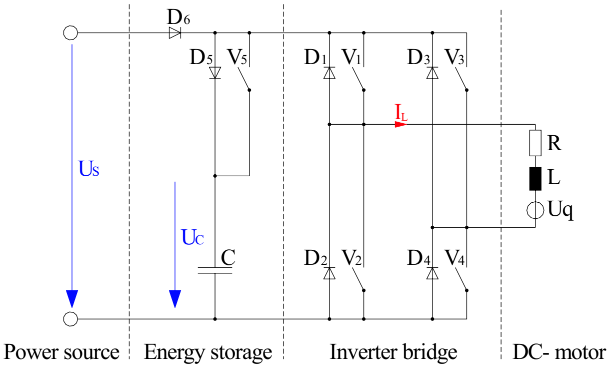

Fig. 2. Feeding inverter bridge.

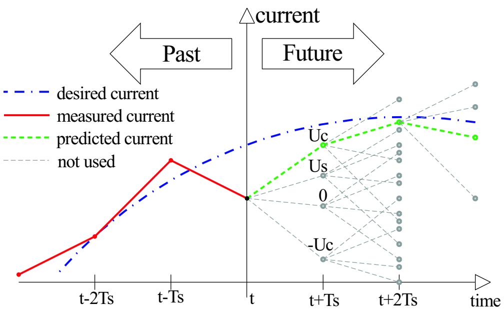

Fig. 3. Principle of the applied MPC strategy.

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[1] Further details in the next sections.

Given a desired current reference, the goal is to control the real actuator current following this signal by a switched voltage. A direct control of the switching states has some advantages over the conventional pulse-width modulation method: the reachable dynamic is higher and no pulse-pattern generation is needed. However, a proper switching strategy is necessary in this case and chattering phenomena can take place due to measurement noise.

In order to provide a good reference tracking the following control problem is stated:

Given the system depicted in Fig. 2 and the following linear system for the actuator:

$$\dot{i}_{Coil} = -\frac{R_{Coil}}{L_{Coil}} i_{Coil} + \frac{u_{in} - u_q}{L_{Coil}} \qquad (1)$$

with $\mathcal{U}_{in} \in [u_1, u_2, u_3, u_4, u_5] = \mathcal{I}$ *is the available set of input voltages applied to the actuator and* u_q *the induced back emf of the linear actuator. Find a sequence* $\mathcal{U}^*$ *of* p *elements* $u \in \mathcal{I}$ *such that*

$$J = \min_{\mathcal{U}_{in}} \sum_{j=1}^{N_p} \left(\hat{i}_{Coil}(k+j) - i_{Coil_d}(k+j)\right) \mathbf{Q}_j \left(\hat{i}_{Coil}(k+j) - i_{Coil_d}(k+j)\right). \qquad (2)$$

Where $\hat{i}_{Coil}$ *is the predicted current,* i_{Coil_d} *is the reference current,* N_p *is the prediction horizon (equal to the control horizon in our case).* $\mathbf{Q}_j$ *is the selection matrix of the weights of the current error.*

It is worthwhile to remark that the matrix $\mathbf{Q}_j$ weights in an adaptive way depending on the length of the prediction horizon. The formulation in (1) and (2) is a well known system with switching command variables. In our case, if a *short prediction horizon* $(2-4$ samples time) is considered, the induced voltage u_q could, in this interval, be treated as constant. Observing Fig. 2 five working phases are pointed out. These working phases are summarized in the following way.

- Working phase one: IGBT 2 and IGBT 3 on, IGBT 1 and IGBT 4 off, IGBT 5 off Fig. 4.
- Working phase two: IGBT 2 and IGBT 3 off, IGBT 1 and IGBT 4 on, IGBT 5. off Fig. 4.
- Working phase three: IGBT 1 and IGBT 4 on, IGBT 2 and IGBT 3 off, IGBT 5 on. Fig. 5.
- Working phase four: IGBT 1 and IGBT 4 off, IGBT 2 and IGBT 3 on, IGBT 5 on. Fig. 5.
- Working phase five: IGBT 2 and IGBT 3 off, IGBT 1 and IGBT 4 off, IGBT 5 on. Fig. 6.

MPC representation

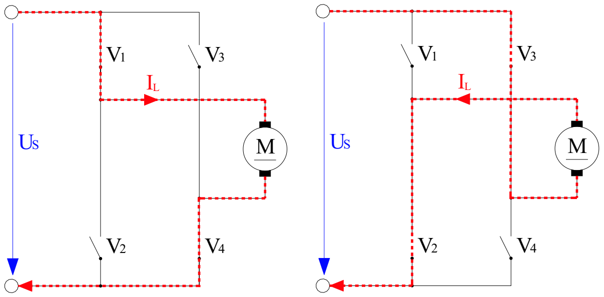

Fig. 4. Working phase one and two. (fed by U_S)

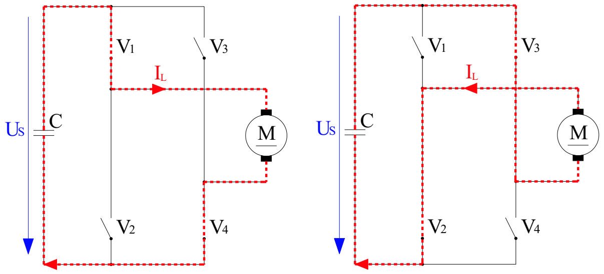

Fig. 5. Working phase three and four. (fed by U_C)

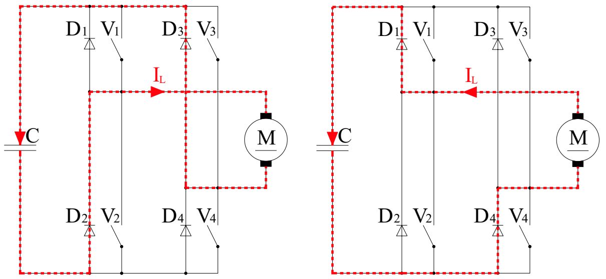

Fig. 6. Phase five: capacitor charging phase.

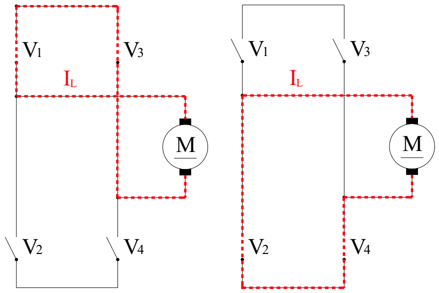

Fig. 7. Working phase six. (free wheeling)

In general, in dependence on the switching configuration the discrete-time dynamic model of the considered system can be formulated in one of the following two ways:

$$i_{\text{Coil}}(k+1) = A_1 i_{\text{Coil}}(k) + B_1(u_{\text{s}} - u_{\text{q}}), \qquad (3)$$

where the couple (A_1, B_1) represents the "R-L" system of first order depicted in Fig. 4, or by defining

$$x(k) = \begin{bmatrix} i_{\text{Coil}}(k) \\ u_c(k) \end{bmatrix}. \tag{4}$$

the dynamic of the phase three and four can be written as:

$$x(k+1) = A_2 x(k) + B_2(-u_{\text{q}}) \tag{5}$$

$$y(k) = C_2 x(k) = i_{\text{Coil}}(k), \tag{6}$$

where the couple (A_2, B_2, C_2) represents the "R-L-C" system of second order depicted in Fig. 6. Normally many predicted steps are suitable in order to have some benefits from the control system. For sake of brevity only a hint is given here.

- During the commutation from the phase "one and two" to phase "three and four" the predicted current with prediction horizon equal to two sampling intervals is:

  $$i_{\text{Coil}}(k+2) = C_2 A_2 \begin{bmatrix} A_1 i_{Coil} + B_1(u_{\text{s}} - u_{\text{q}}) \\ u_c \end{bmatrix} + C_2 B_2(-u_{\text{q}}). \tag{7}$$

  u_c is the measured capacitor voltage, i_{Coil} the measured coil current and u_{q} is induced voltage (back emf) which can be estimated by an state observer.

- During the commutation from the phase "three and four" to the phase "one and two" the predicted current with prediction horizon equal to two samples is :

  $$i_{\text{Coil}}(k+2) = A_1 C_2 A_2 \begin{bmatrix} i_{\text{Coil}} \\ u_c \end{bmatrix} + C_2 B_2(-u_{\text{q}}) + C_1 B_1(u_{\text{s}} - u_{\text{q}}). \tag{8}$$

- Phase five is the phase in which the capacitor is charged and it could be represented as

  $$i_{\text{Coil}}(k+2) = -C_2 A_2 \begin{bmatrix} A_1 i_{Coil} + B_1(u_{\text{s}} - u_{\text{q}}) \\ u_c \end{bmatrix} - C_2 B_2(-u_{\text{q}}). \tag{9}$$

  The voltage of the capacitor u_c is measurable and the voltage u_q is assumed to be constant in the prediction period.

IV. CURRENT CONTROL TECHNIQUES

Generally MPC can suffer from the high calculation complexity in on-line applications. In the presented case there are theoretically 32 possible configurations of the IBGT switching states, but only the circuits represented above are used in practice. In fact most of them cannot be used because they generate short circuits and the other ones are practically redundant. If a global optimum is wanted in "one-step" prediction horizon, then there are maximum 5 possible voltage combinations. In general for $N-steps$ prediction, there are 5^N possible combinations. It is known that the problem formulated so is a NP-complete problem[2].

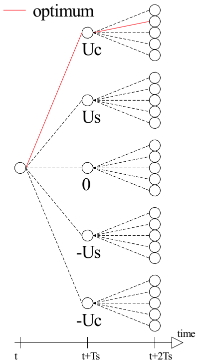

Fig. 8. Three of the combinations in two-steps prediction.

Thus, in a general solution to the optimization problem all the 5^N possible states must be taken into account which means that the calculation time is expected to be relatively high. However, for short prediction horizons this is still a reasonable way to find the controller.

In Fig. 8 this situation is depicted.

Besides the general optimization solution described above we also used a different optimization procedure which is actually the well- known branch and bound method. The feasible region is systematically partitioned in sub-domains, and valid upper and lower bound are generated at different levels of the binary tree. In principle, also this method is classified as NP-complete. In this special constellation, however, only in the "worst case" situation the solution time will grow exponentially with the problem size.

The main advantage of the branch and bound methods is that it can be interrupted at any intermediate step to obtain a suboptimal solution, although, in this case the tracking performance will deteriorate.

In order to build a procedure to find a local optimum the following definition is introduced.

Definition 1: Given a voltage and the inverter bridge configuration at the time k corresponding to the minimum of the function defined in (2) and its logical code. A "near permutation" at the time $k+1$ is defined as "the combination code" which identifies the two nearest possible voltages to the minimum at the time k.

If the "near permutation" at the time k are considered, then the following procedure is proposed:

- **step 1** Let $\mathbf{u}_l^\star$ an initial optimum of logic inputs which is found by a total search.

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[2] The solution time grows exponentially with the problem size

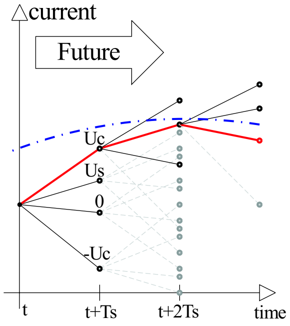

Fig. 9. Optimum search

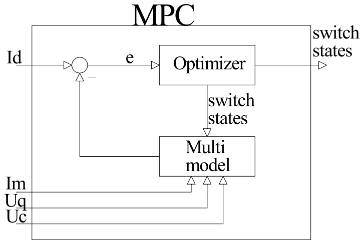

Fig. 10. Scheme with MLDS in MPC.

- **step 2** Consider for $\mathbf{u}_l^\star$ its "near permutations" in an N_p prediction horizon *branch phase*.
- **step 3** Check the cost function defined in (2) around the $\mathbf{u}_l^\star$ to *bound the branch*.
- **step 4** Find the minimum in the branch.
- **step 5** Branch *around* the new minimum candidate and check the cost function (2) to *bound the branch*.
- **step 6** Go to **step 4** till the specified *time out*!

The above described procedure is conceived and suitable for current reference values which do not contain step or very fast changes. In these cases it is possible to assume that the optimum in (2) changes slowly and the computational advantages are known. Fig. 9 shows a possible graphic interpretation of the above described procedure. At the first step control horizon of all the switching possibilities are considered in order to manage some abrupt changes which can arise. The following step horizons consider just the "adjacent switch possibility".

In general, independently from the optimal seeking technique, Fig. 10 shows the structure of the proposed controller.

In systems with repetitive motion, like in our application, it is possible to know the reference current in advance and an utilization of the MPC strategy can be obtained by using a simple control and cyclical prediction algorithm in the position current loop. More generally, it is also possible to build a MPC outer loop, as depicted in Fig. 11. In other words, then a desired current is calculated to minimize the quadratic error performed through the desired position and predicted for the current control loop.

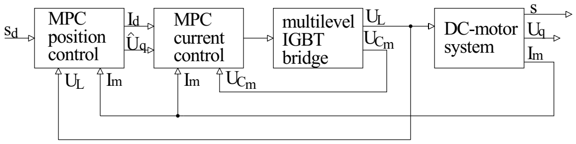

Fig. 11. Control scheme.

More about that can be found in [4].

V. CAPACITOR RE-CHARGING AND SIMULATION RESULTS

Together with the tracking task another interesting aspect could be considered: the self re-charging voltage capacitor control. The charging of the capacitor is indeed possible in the working phase 5 where either the motor inductance allows the charging current or the mechanical braking energy can be fed back. That means, appropriately partitioning of the working phases can make both tracking and re-charging possible. The balance between these two tasks is achieved by the following cost function

$$J = \min_{\mathcal{U}_{\text{in}}} \Bigg(\sum_{j=1}^{N_p} \big(\hat{i}_{\text{Coil}}(k{+}j) {-} i_{\text{Coil}_d}(k{+}j)\big) \mathbf{Q}_j \big(\hat{i}_{\text{Coil}}(k{+}j) - i_{\text{Coil}_d}(k+j)\big) + \sum_{k=1}^{N_p} (\Delta u_c(k+j)) \mathbf{R}_j (\Delta u_c(k+j)) \Bigg). \tag{10}$$

It is not difficult, depending on the motion cycle dynamic, to set the weights $\mathbf{Q}_j$ and $\mathbf{R}_j$ in order to maintain in an acceptable tolerance the level of the voltage capacitor. That means in particular $\Delta u_c = (u_c - u_{cd}^*)$, where u_c is the measured voltage of the capacitor and u_{cd}^* is its desired level, should be kept within a tolerance band. Actually, the capacitor voltage is used to enable high dynamic changes of the actuator current, which in turn will cause large variations of the capacitor voltage itself. Thus, a continuous operation of the system is not possible if the control of the capacitor was not included in the optimization procedure. Furthermore, the efficiency is improved by properly utilizing the mechanical braking energy.

Simulation results are performed by using real system data and they show promising results. Some interesting aspects are worth to be pointed out. Fig. 12 shows how the self-charging phase can start in the meantime of the following phase. In this case the price to pay is an initial error amount, as long as the capacitor does not achieve the full voltage. In Fig. 12, 15 ms are simulated in order to emphasize the self-charging phase. In particular Fig. 13 shows a possible initial self-charging phase of the capacitor. It is possible to use an initial charging phase in which the valve is not moving and the reference signal to be tracked is equal to zero. An initial self-charging phase is possible if and only if the prediction horizon is not

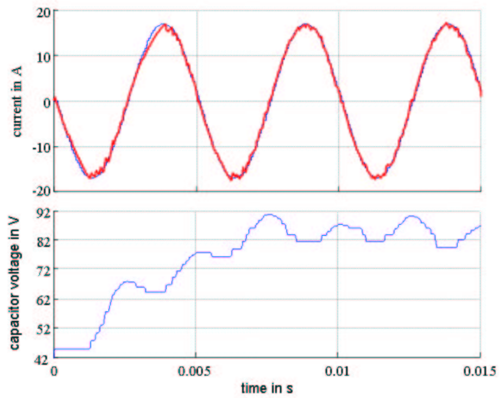

Fig. 12. On the top: current. On the bottom: Capacitor charging.

less than 2 steps. In fact, in order to minimize the index defined in (2) the MPC regulator generates an error around the desired value of the current. If the prediction horizon is equal to 1 step the MPC cannot charge the capacitor because it cannot predict that optimal correction of the error around the desired current. In other words with a prediction horizon more than 1 step the MPC can generate a relative small mean error and in the meantime charge the capacitor. To achieve a higher charging velocity it is necessary to increase the matrix $\mathbf{R}_j$ in the index (2). Fig. 14 shows in general the achieved performances. At the end it is interesting to notice that through MPC it is possible to obtain a self balance switch of the IBGT. In fact Fig. 7 shows two possible free wheeling circuits. It will be enough to balance the switching phase on these two circuits in order to obtain a balance frequency.

It is to remark that a compromise between a good tracking and a stability of the supply voltage is achieved. In particular, a good capacitor voltage stability provides the necessary condition for good following-up results. In other words it is always necessary to find a trade-off between a capacitor voltage stability and its following up. Fig. 11 shows a possible control system structure.

VI. CONCLUSIONS AND OUTLOOK

A novel approach to the current control of PWM inverters has been developed. It is based on the model predictive control strategy and in particular uses a special structure of energy storage in order to generate multilevel switching voltages. The proposed approach combines high dynamic with small current ripples and robust control behavior against model uncertainty.

VII. REFERENCES

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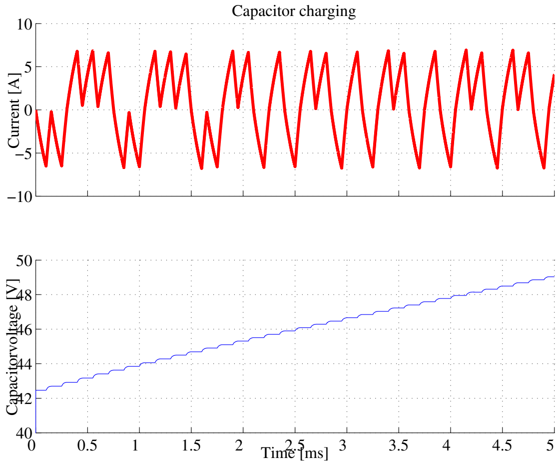

Fig. 13. On the top: current. On the bottom: Capacitor charging.

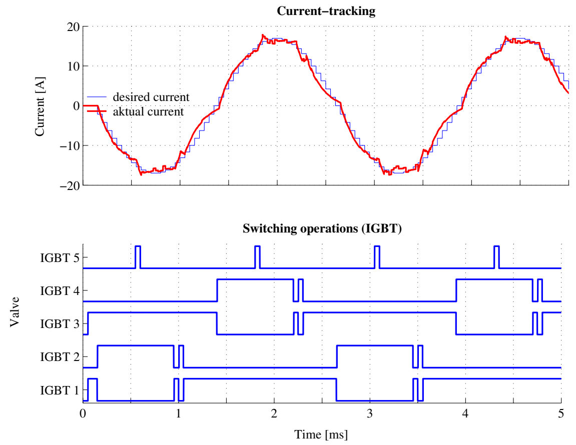

Fig. 14. On the top: current tracking. On the bottom: IGBT switching with balanced switching frequency.

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