POWER ELECTRONICS AND DRIVES
2(37), No. 2, 2017 DOI: 10.5277/PED170208

MODIFIED SCHEME OF PREDICTIVE TORQUE CONTROL FOR THREE-PHASE FOUR-SWITCH INVERTER-FED MOTOR DRIVE WITH ADAPTIVE DC-LINK VOLTAGE IMBALANCE SUPPRESSION

PIOTR SOBAŃSKI

Wrocław University of Science and Technology,
Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland,
e-mail address: piotr.sobanski@pwr.edu.pl

Abstract: Classical voltage space vector modulation techniques cannot be efficiently applied in four-switch three-phase voltage inverter-fed electrical drives due to a voltage offset in DC-link capacitors. The capacitor voltages imbalance is a result of a bidirectional current which flows in a phase of an electric motor that is connected to a DC-link capacitor midpoint. To overcome this problem which leads to an incorrect inverter voltage modulation or even can affect the DC-link capacitors, predictive control algorithms considering the voltage offset in DC-link capacitors have been developed. Despite the predictive methods are highly effective, they require to adjust the cost function weighting factors which is normally an inexplicit task. In this paper, an on-line tuning method of the weighting factor related to the capacitor voltages imbalance incorporated in the cost function of the predictive algorithm has been proposed. According to the proposed approach, the weighting factor is self-adjusted so that the DC-link capacitor voltages are stabilized as well as a high quality of the drive control is remained simultaneously, regardless of its operating point. The proposed strategy has been validated by using simulation model of the induction motor drive system.

Keywords: *fault tolerant systems, semiconductor faults, four-switch inverter, predictive control, cost function, variable speed drives*

1. INTRODUCTION

The four-switch voltage inverter (FSVI) is often used in fault-tolerant electric motor drive systems as a post-fault configuration of the standard three-phase two-level voltage inverter [1, 2]. The main disadvantage of the four-switch inverter is the voltage offset in DC-link capacitors which is not considered in accordance with the classical voltage space vector modulation algorithms based on measurement of full DC-link voltage [3]. The capacitor voltages imbalance leads to the incorrect inverter phase voltages modulation or even could cause capacitor failures because of the overvoltage [3].

Manuscript received: October 8, 2017; accepted: November 11, 2017.

A potential solution that allows the voltage offset of DC-link capacitors is the use of an additional sensor to measure the capacitor voltages referred to DC-link midpoint [4 –12]. In some cases, inverter phase voltages are correctly modulated but the capacitor voltages are not efficiently stabilized [4, 5]. Other techniques consider the DC-link voltages stabilizing in the space vector modulation algorithms, so the DC-voltages imbalance effect is significantly reduced [6, 9]. Recently, the voltage imbalance problem in DC-links has been solved by defining an additional term in the cost function of predictive control algorithm, nevertheless this solution requires to fit the supplementary weighting factor, which can be made during offline test, so an implementation complexity increases.

This paper proposes an adaptive DC-link voltages offset suppression algorithm which considers a self-tuning of the weighting factor related to the DC-link voltages imbalance instead of constant value as it has been proposed in [10]. The influence of the control quality factor on the drive dynamic has been considered. The method can be implemented in case of the finite-state predictive control algorithms utilized in electric motor drive systems fed by FSVI. To prove the effectiveness of the proposed technique simulation study of the predictive torque control motor drive system has been conducted in Matlab/Simulink.

2. THEORETICAL BASICS

Depending on the motor drive system requirements, additional terms of the cost function are utilized in a predictive control algorithm, and therefore the number of weighting factors increases in the cost function. Unfortunately, they are no analytical techniques to tune these factors, so normally they are fitted based on empirical procedures. Taking into consideration the control algorithms dedicated to FSVI, the weighting factor that is related to the DC-link voltages control can be determined by using set searching algorithm [10]. Nevertheless, this solution requires many repeated tests and it does not ensure constant quality control of the stator flux and electromagnetic torque, regardless the drive operating point, in contrary to the proposed technique.

The cost function F_p used in the analyzed here modified control algorithm is determined as follows [11, 12]:

$$F_p(\mathbf{u}_j) = \left(\frac{M_{e\mathrm{ref}}(t_k) - M_e(t_{k+1})}{M_{e\mathrm{nom}}} \right)^2 + \tau_\psi \left(\frac{\psi_{s\mathrm{ref}}(t_k) - \psi_s(t_{k+1})}{\psi_{s\mathrm{nom}}} \right)^2$$

$$+\tau_{DC} \left(\frac{U_{DC1}(t_k) - U_{DC2}(t_{k+1})}{\frac{U_{DC\mathrm{nom}}}{2}} \right)^2 + I_{s\lim}(t_{k+1}) \tag{1}$$

where $M_{e\,\mathrm{ref}}(t_k)$, $M_e(t_{k+1})$, $M_{e\,\mathrm{nom}}$ means a reference, predicted and nominal value of the electromagnetic torque, $\psi_{s\,\mathrm{ref}}(t_k)$, $\psi_s(t_{k+1})$, $\psi_{s\,\mathrm{nom}}$ are a reference, predicted and nominal values of the stator flux, respectively, $U_{DC1}(t_{k+1})$, $U_{DC2}(t_{k+1})$, $U_{DC\,\mathrm{nom}}$ indicate predicted values of DC-link capacitor C_1 and C_2 voltages and a nominal values of a full DC-link voltage, while τ_ψ and τ_{DC} are the weighting factors.

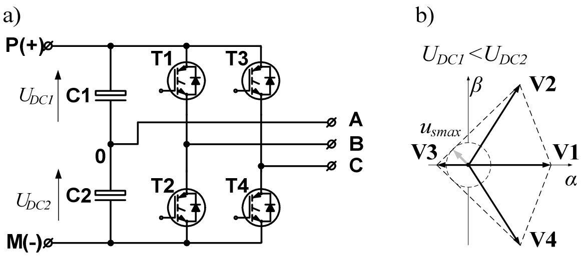

Fig. 1. Four-switch inverter topology (a) and a maximal voltage vector $u_{s\,\max}$ under DC-link voltage imbalance (b)

In accordance with the finite-state predictive controller (Fig. 1), for each possible inverter voltage vector $\mathbf{u}_j$, the cost function is calculated. Then, the vector is applied that gives a minimum value of the cost function. The weighting factor τ_ψ and τ_{DC} is adjusted according to a block diagram in Fig. 2.

In accordance with the proposed algorithm, the weighting factor τ_ψ is adjusted by minimizing $F_m(\tau_\psi)$ function, which does not consider the DC-link voltages imbalance. For this purpose, a set searching algorithm can be utilized during offline test. For the optimal τ_ψ, the value of the function F_m is calculated during a test with a various load and speed condition of the drive. Since the capacitor voltages imbalance is not provided in $F_m(\tau_\psi)$, during the test the drive speed should be commanded, so that the modulation index M, which is defined in accordance with the following equation, is lower than 1.

$$M\left(t_k\right)=\frac{u_{s\,\mathrm{ref}}\left(t_k\right)}{u_{s\,\max}\left(t_k\right)} \tag{2}$$

where $u_{s\,\mathrm{ref}}$ is a commanded inverter voltage and $u_{s\,\max}$ means a maximal inverter voltage, which can be generated in linear modulation mode of the inverter (Fig. 1b).

This function evaluates a quality of the drive control. A variable m depends on the duration D of the test and the sampling time T_s

$$m=\frac{D}{T_s} \tag{3}$$

Depending on the absolute value of a difference $\mathrm{Err}(t_k)$ between capacitor voltages and actual value of the function $F_m(t_k)$, the value of the weighting factor $\tau_{DC}(t_k)$ is updated.

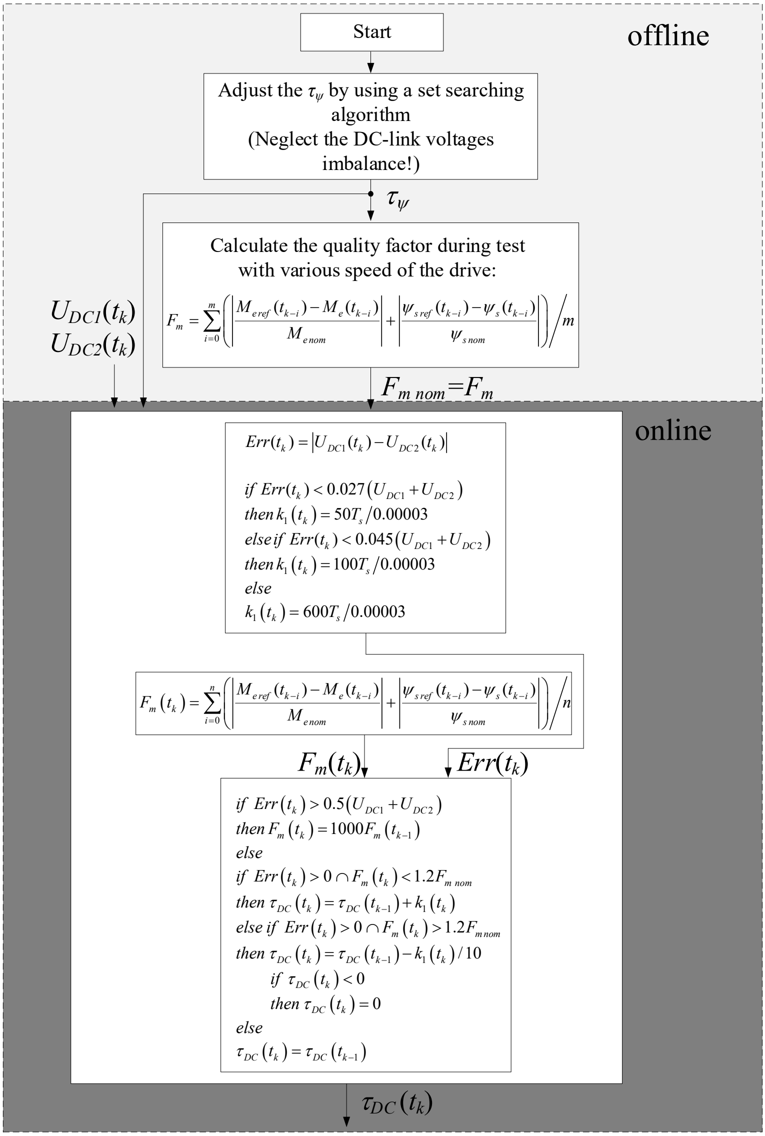

Fig. 2. Fitting procedure of weighting factors

The $F_m(t_k)$ consists the drive control quality factor, which is figure out similar to previously described procedure. A length n of the moving window, for which the function $F_m(t_k)$ is calculated, is limited to $n = 0.18/T_s$. The value of the coefficient $k_1(t_k)$ increases when Err(t_k) increases, so the $\tau_{DC}(t_k)$ increases as well and therefore the capacitor voltage imbalance is effectively decreased.

3. RESULTS OF SIMULATION

To validate the effectiveness of the proposed DC-link voltage balancing control method, the adaptive algorithm has been compared with the classical approach assuming a constant value of the $\tau_{DC}(t_k)$, which is normally fitted offline. This corresponds to the direct finite-state predictive flux and torque control of an induction motor drive system fed by the four-switch three-phase voltage inverter. According to the assumed simulation model of the drive, a voltage-oriented controlled active rectifier converts AC grid voltages into a DC voltage. This voltage is filtered by using capacitors $C_1 = C_2 = 4$ mF. The parameters of the capacitors are chosen basing on the analysis of standard inverters which are commonly manufactured. The input voltage of the inverter is stabilized at $U_{DC\mathrm{ref}} = 563$ V which is normal for the six pulses rectifier that is connected to the voltage grid. Nominal parameters of an induction motor, which is simulated, are given in the Appendix, Table 1A. The simulation sampling time T_s is equal to 30 µs.

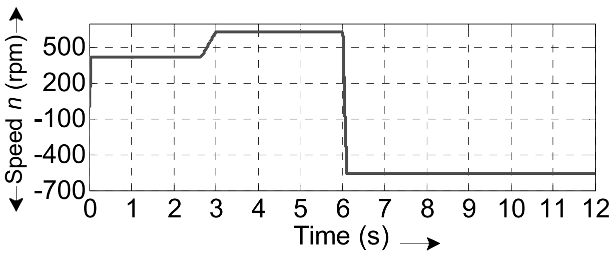

Fig. 3. Speed of the drive for $F_m(t_k) < 1.5F_{m\,\mathrm{nom}}$

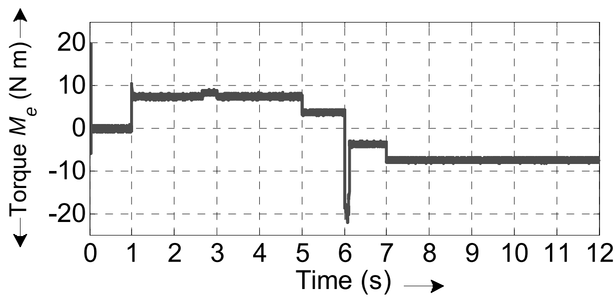

Fig. 4. Electromagnetic torque of the drive for $F_m(t_k) < 1.5F_{m\,\mathrm{nom}}$

To compare properties of the proposed adaptive capacitor voltages balancing method with the solution assuming the constant τ_{DC} weighting factor, a simulation research has been carried out. According to the test, shortly after start-up of the drive, at $t = 1$ s, the motor was loaded to its full-load torque $M_e = 7.5$ N·m. After that, the speed of the drive was ramped up to $n = 630$ rpm. At $t = 5$ s, the load was suddenly reduced to $M_e = 3.75$ N·m and then at $t = 5$ s the motor speed direction was rapidly changed up to $n = -560$ rpm. Afterwards, at $t = 7$ s the load was increased to a nominal value. The transient of the drive speed and the electromagnetic torque are shown in Figs. 3 and 4, respectively. According to this test, in Figs. 5–8, the simulation results related to the various control quality requirements have been presented. Four cases have been considered, namely:

- weighting factor τ_{DC}, that has been estimated by using set searching method, is assumed as a constant $\tau_{DC} = 2\,981\,463$,
- weighting factor τ_{DC} is increased until $F_m(t_k) < 1.1F_{m\,\mathrm{nom}}$,
- weighting factor τ_{DC} is increased until $F_m(t_k) < 1.5F_{m\,\mathrm{nom}}$,
- weighting factor τ_{DC} is increased until $F_m(t_k) < 2.0F_{m\,\mathrm{nom}}$.

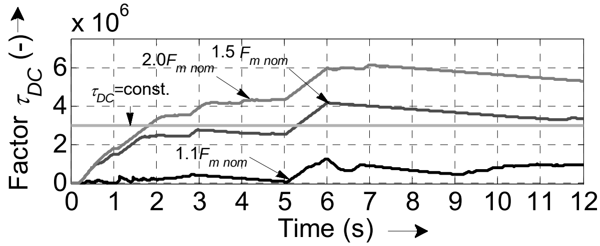

Fig. 5. Weighting factor τ_{DC} for various control quality requirements

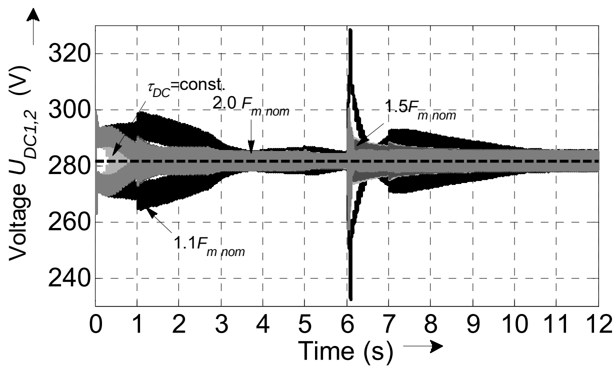

Fig. 6. DC-link capacitor voltages $U_{DC1,2}$ for various control quality requirements

In Figure 5, the transient of the τ_{DC} factor is depicted, when the adaptation procedure of the τ_{DC} was activated at $t = 0.2$ s. Additionally, relevant transients of the $U_{DC1,2}$ voltages (Fig. 6), the mean value of the maximal inverter voltage $u_{s\,\max}$ that can be generated in linear modulation mode of the inverter (Fig. 7) and the electromagnetic torque M_e (Fig. 8) during the rapid change of the motor speed are presented.

As can be seen in Fig. 5 and 6, since the DC-link voltages are balanced faster within increasing the τ_{DC} weighting factor, for the high requirements of the stator flux and the electromagnetic torque control, namely $F_m(t_k) < 1.1F_{m\,\mathrm{norm}}$, the $U_{DC1,2}$ voltages balancing method is less effective. For example, if it is assumed that $F_m(t_k)$ should be smaller than $1.1F_{m\,\mathrm{norm}}$, so that the condition $F_m(t_k) < 1.1F_{m\,\mathrm{norm}}$ is fulfilled, the DC-link voltages were averagely equal at $t = 4$ s of the test, but in case of $F_m(t_k) < 2.0F_{m\,\mathrm{norm}}$, the $U_{DC1,2}$ were balanced at $t = 1.5$ s. The simulation research has indicated, that for the condition $F_m(t_k) < 1.5F_{m\,\mathrm{norm}}$, the best drive performance is achieved. During drive steady states the weighting factor τ_{DC} is approximately equal to the optimal value that has been fitted by using the set searching method. During the transient states, τ_{DC} increases, which results in a better control of $U_{DC1,2}$. Thus the mean value of the maximum inverter voltage vector amplitude in linear modulation mode is bigger than in the case when τ_{DC} = const (Fig. 7) whereas the amplitude of the electromagnetic torque pulsations is smaller (Fig. 8).

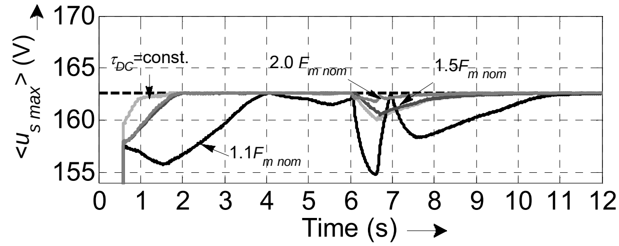

Fig. 7. Mean value of maximal inverter voltage $u_{s\,\max}$ that can be generated in linear modulation mode of the inverter for various control quality requirements

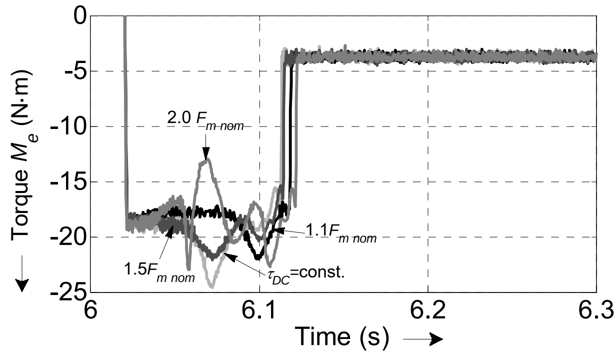

Fig. 8. Electromagnetic torque M_e during a rapid change of the motor speed for various control quality requirements

4. CONCLUSIONS

The adaptive algorithm has been described that allows one to adjust the weighting factor τ_{DC} of the term related to DC-link FSVI voltages control in the cost function. The proposed method consists in increasing the τ_{DC} coefficient until the assumed quality of the electromagnetic torque and the stator flux control is kept, regardless of the drive operation point. In accordance with this algorithm, the classical set searching procedure, which is normally utilized to tune the weighting factor τ_{DC} [10], is avoided. First of all, it is not required to determine an optimal value of the τ_{DC}, which is strongly dependent on the cost function scheme, but only a qualitative threshold should be assumed, which can be made intuitively.

APPENDIX

Table 1A. Parameters of the induction motor

Parameters of an equivalent circuit		Rated data	
Stator resistance, r_s	5.9 Ω	Power, P_{nom}	1.1 kW
Rotor resistance, r_z	4.6 Ω	Torque, m_{nom}	7.5 N·m
Stator inductance, l_s	0.4173 H	Speed, n_{nom}	1400 rpm
Rotor inductance, l_r	0.4173 H	Voltage, u_{nom}	230/400 V
Main inductance, l_h	0.3925 H	Current, i_{nom}	5.0/2.9 A

REFERENCES

[1] MENDES A.M.S., CARDOSO A.J.M., *Fault-tolerant operating strategies applied to three-phase induction-motor drives*, IEEE Transactions on Industrial Electronics, 2006, 53(6), 1807–1817.

[2] FREIRE N.M.A., CARDOSO A.J.M., *A fault-tolerant direct controlled PMSG drive for wind energy conversion systems*, IEEE Trans. Ind. Electron., 2014, 61(2), 821–834.

[3] SOBANSKI P., ORLOWSKA-KOWALSKA T., *Analysis of space vector modulation technique in inverter-fed fault-tolerant induction motor drive*, IEEE Int. Conf. Power Electronics and Motion Control, PEMC 2014, Turkey, on CD.

[4] KAZEMLOU S., ZOLGHADRI M.L., *Direct torque control of four-switch three phase inverter fed induction motor using a modified SVM to compensate dc-link voltage imbalance*, IEEE Int. Conf. Power Electronics and Motion Control, PEMC 2014, Turkey, on CD.

[5] ZHIJIAN J., XU Z., FENG PING W., *An improved development of four-switch low cost inverter on voltage equilibrium with magnetic flux control method*, IEEE Int. Conf. Electric Power and Energy Conversion Systems, EPECS 2009, United Arab Emirates, on CD.

[6] HONG HEE L., PHAN QUOC K., LE DINH K., LE MINH P., *Dynamic adaptive space vector PWM for four switch three phase inverter fed induction motor with compensation of DC-link voltage ripple*, IEEE Int. Conf. Power Electronics and Drive Systems PEDS 2009, Taiwan, on CD.

[7] GOVIC G.A., PETERS G.L., *DC link imbalance compensation in four-switch inverter AC motor drives*, IET Electronics Letters, 1997, 33(13), 1101–1102.

[8] GI-TAEK K., LIPO T.A., *VSI-PWM rectifier/inverter system with a reduced switch count*, IEEE Trans. Ind. Appl., 1996, 32(6, 1331–1337.

[9] BLAABJERG F., NEACSU D.O., PEDERSEN J.K., *Adaptive SVM to compensate DC-link voltage ripple for four-switch three-phase voltage-source inverters*, IEEE Trans. Power Electron., 1999, 14(4), 743–752.

[10] DEHONG Z., JIN Z., YANG L., *Predictive torque control scheme for three-phase four-switch inverter-fed induction motor drives with DC-link voltages offset suppression*, IEEE Trans. Power Electron., 2015, 30(6), 3309–3318.

[11] SOBANSKI P., ORLOWSKA-KOWALSKA T., *Predictive flux and torque control of induction motor drive under post-fault operation of three-phase voltage inverter*, Scientific Works of the Institute of Electrical Machines, Drives and Measurements of the Wroclaw University of Technology, 74, Ser. Studies and Materials, 2014, 34, 1–16 (in Polish).
[12] SOBANSKI P., ORLOWSKA-KOWALSKA T., *Predictive flux and torque control of induction motor drive under post-fault operation of three-phase voltage inverter*, IEEE Int. Conf. Industrial Technology, ICIT 2015, Sevilla, Spain, on CD.