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ORIGINAL PAPER

Deadbeat controller applied to induction motor direct torque control with low-speed operation

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Abstract This paper proposes a deadbeat controller applied to direct torque control strategy for a three-phase induction motor. The deadbeat control method uses the discretized dynamic model of the machine to calculate the theoretical stator voltage vector required to reach the references of torque and flux in a single switching period. In this proposal controller, it is used the stator flux and current vectors in the machine model. The induction motor is powered by a three-phase inverter, which is modulated through a vector modulation technique. The experimental results are presented to validate the proposed controller, including low-speed operation.

Keywords Deadbeat · Controller · Induction motor · Direct torque control

1 Introduction

In developed or developing countries, more than half of the total electric energy produced is converted into mechanical energy through electric motors. Among several types of motors, induction motor is the one that dominates the market. At least 90% of industrial drive systems use this type of machine [1]. The induction motor (IM) is used in a wide range of industrial applications due to its simple construction, reliability, robustness, and low cost, besides being used in alternative generation systems [2,3] and smart grids of electric energy [4]. Comparing them with DC motors, these IMs may be used in hazardous environments since they do not present electrical spark issues. Most IMs are connected directly to the electric power grid without any control. However, while the use of electronic converters for IM's actuation in variable speed is continuously growing, the use of drives in DC Motors (DCM) is being reduced over time. However, induction motors control requires sophisticated control techniques in applications demanding high-performance drive systems.

The main difficulties in controlling IM are related to the need of providing a variable voltage frequency, nonlinearity and complexity of the IM's dynamic model, followed by the uncertainty caused by their parameters. In recent decades, researchers have worked on developing systems for alternating current actuation to control IM's speed and electromagnetic torque. Mainly, this is due to induction motor to be robust and cost-effective to the industry. The appropriated design of the drive systems for IMs, using vector control strategies, transforms induction motor's non-linear torque–speed feature into a constant feature for torque–speed similar to that on DCMs. In the 1980s, at [5,6], it was proposed a new strategy for controlling IM. Its coordinates transformation and PI regulators, used for controlling via field orientation [7], have been replaced by hysteresis controllers. Since its appearance, this control strategy, called direct torque control (DTC), has been under constant development. Particularly in such strategy, electromagnetic torque presents oscillations permanently. However, an alternative approach to reduce torque ripples through space vector modulation (SVM) was presented at [8,9]. Another strategy for direct torque control, based on controlling load angle, was proposed at [10]. However, such strategy had a permanent error on stator flux module when put into operation.

In [11], it was proposed a DTC strategy based on vector flux acceleration method. This strategy uses a proportional

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controller to the flux error and uses direct injection method to compensate the voltage drop in the stator electrical resistance and the counter electromotive force. This strategy uses rotor flux reference, electromagnetic torque and synchronous speed of the reference system oriented by rotor flux to calculate the stator flux reference. Today, many researchers are still studying and proposing DTC strategies aiming to improve their performance or even proposing new strategies for high performance control of IMs, as shown in [12–19]. Another interesting alternative is DTC strategy via deadbeat method [20–24]. The deadbeat method uses the discretized dynamic model of the machine to calculate the theoretical stator voltage vector required to reach the references of torque and flux in a single switching period. In most of the works mentioned, machine's model is carried out according to stator and rotor fluxes, being that inaccurate estimates of these vectors may cause errors in the calculation of the voltage vector done by controller.

In deadbeat DTC proposed in this study, current and stator flux were considered as state variables. The representation of these state variables in the reference system driven by the stator flux determines the specific expressions for the calculation of the stator voltage from the discretized model of the induction motor, so torque and flux references are reached. Also, experimental results are presented to validate the proposal, demonstrating its operational capacity.

2 IM dynamic model

Differential equations of the stator and rotor voltages, represented in the reference system driven by the stator flux (synchronous), are [25]:

$$\mathbf{u}_\mathrm{s} = R_\mathrm{s}\mathbf{i}_\mathrm{s} + \frac{\mathrm{d}\boldsymbol{\psi}_\mathrm{s}}{\mathrm{d}t} + j\omega_\mathrm{s}\boldsymbol{\psi}_\mathrm{s} \tag{1}$$

$$\mathbf{u}_\mathrm{r} = R_\mathrm{r}\mathbf{i}_\mathrm{r} + \frac{\mathrm{d}\boldsymbol{\psi}_\mathrm{r}}{\mathrm{d}t} + j(\omega_\mathrm{s} - \omega_\mathrm{r})\boldsymbol{\psi}_\mathrm{r} \tag{2}$$

$$\boldsymbol{\psi}_\mathrm{s} = L_\mathrm{s}\mathbf{i}_\mathrm{s} + L_\mathrm{m}\mathbf{i}_\mathrm{r} \tag{3}$$

$$\boldsymbol{\psi}_\mathrm{r} = L_\mathrm{r}\mathbf{i}_\mathrm{r} + L_\mathrm{m}\mathbf{i}_\mathrm{s} \tag{4}$$

where R_s and R_r are the electrical resistances of the phase windings of the stator, and the rotor, respectively, L_s, L_r and L_m are the inductances of the stator, rotor and magnetization, respectively, and ω_r is the instantaneous angular velocity of the rotor. The electromagnetic torque can be calculated using the following expression:

$$t_\mathrm{em} = \frac{3}{2}P\boldsymbol{\psi}_\mathrm{s} \times \mathbf{i}_\mathrm{s} \tag{5}$$

$$t_\mathrm{em} = \frac{3}{2}P(\psi_{\alpha\mathrm{s}}i_{\beta\mathrm{s}} - \psi_{\beta\mathrm{s}}i_{\alpha\mathrm{s}}) \tag{6}$$

The expression that relates the electromagnetic torque and rotor speed is given by:

$$t_\mathrm{em} = J\frac{1}{P}\frac{\mathrm{d}\omega_\mathrm{r}}{\mathrm{d}t} + T_\mathrm{L} \tag{7}$$

where P is the number of pole pairs, J is the moment of inertia and T_L is the load torque. At IM, due to the coupling between variables that control flux and current, sophisticated control strategies such as DTC or field orientation control (FOC) must be used.

3 Deadbeat direct torque control

A discrete-time system has a deadbeat response if the reference is reached in a finite number of sampling periods without fluctuations [26]. Therefore, the application of the deadbeat DTC controller for IM modeled using stator flux and current vectors will be shown in this section. It makes possible to calculate the stator voltage vector to be applied to the IM so that the references of torque and flux are reached.

3.1 Stator flux direct control

To control the magnitude of the stator flux, it will be assumed—in the reference system driven by the stator flux—the quadrature axis component of the flux is zero ($\psi_\mathrm{qs} = 0$); thus, rewriting the real part of the Eq. (1), we have:

$$u_\mathrm{ds} = R_s i_\mathrm{ds} + \frac{\mathrm{d}\psi_\mathrm{ds}}{\mathrm{d}t} \tag{8}$$

Discretizing the Eq. (12) and considering the sampling period as T_s, we have:

$$u_\mathrm{ds}(k+1) = R_s i_\mathrm{ds}(k) + \frac{\psi_\mathrm{ds}(k+1) - \psi_\mathrm{ds}(k)}{T_\mathrm{s}} \tag{9}$$

$$\psi_\mathrm{ds}(k+1) = \psi_\mathrm{ds}(k) + [u_\mathrm{ds}(k+1) - R_\mathrm{s}i_\mathrm{ds}(k)]T_\mathrm{s} \tag{10}$$

To comply with the requirements of the deadbeat controller, u_ds voltage should be such that, in the next sample period, the stator flux should be equal to its reference, i.e., $\psi_\mathrm{ds}(k+1) = \psi_\mathrm{s}^*$. Thus, rewriting the Eq. (9), we have:

$$u_\mathrm{ds}(k+1) = R_s i_\mathrm{ds}(k) + \frac{\psi_\mathrm{s}^* - \hat{\psi}_\mathrm{ds}(k)}{T_\mathrm{s}} \tag{11}$$

where: ψ_s^* and $\hat{\psi}_\mathrm{ds}(k)$ are the reference flux and the estimated flux, respectively.

3.2 Electromagnetic direct torque control

For the control loop, only in the electromagnetic torque, we rewrite the imaginary part of the Eq. (1), and we obtain:

$$u_\mathrm{qs} = R_s i_\mathrm{qs} + \omega_\mathrm{s}\psi_\mathrm{ds} \tag{12}$$

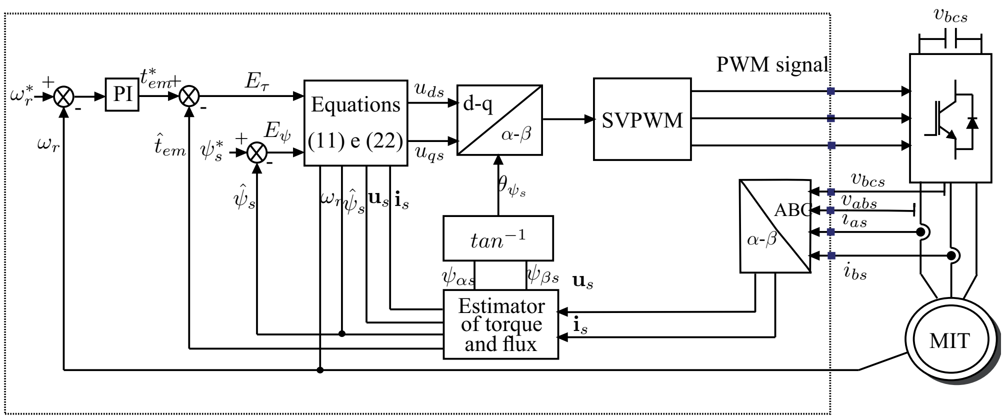

Fig. 1 Block diagram of deadbeat torque direct control proposed

Discretizing the above equation, we have:

$$u_{qs}(k+1) = R_s i_{qs}(k) + \omega_s(k)\psi_{ds}(k) \tag{13}$$

and

$$\omega_s(k) = \omega_{sl}(k) + \omega_r(k) \tag{14}$$

Rewriting and discretizing Eq. (6), in the reference system driven by stator flux, we have:

$$t_{em}(k+1) = \frac{3}{2}P\psi_{ds}(k)i_{qs}(k+1) = t_{em}^* \tag{15}$$

$$i_{qs}(k+1) = \frac{2t_{em}^*}{3P\psi_{ds}(k)} \tag{16}$$

And algebraically manipulating Eqs. (1)–(4), we see [27, 28]:

$$\frac{d\mathbf{i}_s}{dt} = \left[\frac{R_r}{\sigma L_s L_r} - j\frac{\omega_r}{\sigma L_s}\right]\boldsymbol{\psi}_s - \left[\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r} + j(\omega_s - \omega_r)\right]\mathbf{i}_s + \frac{\mathbf{u}_s}{\sigma L_s} \tag{17}$$

And getting the imaginary part of Eq. (17), we have:

$$\frac{di_{qs}}{dt} = -\frac{\omega_r}{\sigma L_s}\psi_{ds} - \left[\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right]i_{qs} + \omega_{sl}i_{ds} + \frac{u_{qs}}{\sigma L_s} \tag{18}$$

where $\omega_{sl} = \omega_s - \omega_r$ is the slip. Isolating the previous equation slip, we have:

$$\omega_{sl} = \frac{\frac{di_{qs}}{dt} + \frac{\omega_r}{\sigma L_s}\psi_{ds} + \left[\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}\right]i_{qs} - \frac{u_{qs}}{\sigma L_s}}{i_{ds}} \tag{19}$$

Discretizing the above equation, we have:

$$\omega_{sl}(k) = \frac{\frac{i_{qs}(k+1) - i_{qs}(k)}{T_s} + \frac{\omega_r}{\sigma L_s}\psi_{ds}(k) + C}{i_{ds}(k)} \tag{20}$$

where $C = [\frac{R_s}{\sigma L_s} + \frac{R_r}{\sigma L_r}]i_{qs}(k) - \frac{u_{qs}(k)}{\sigma L_s}$.

Rewriting the previous equation and considering Eq. (16), we have:

$$\omega_{sl}(k) = \frac{\frac{2(t_{em}^* - \hat{t}_{em})}{3P\hat{\psi}_{ds}T_s} + \frac{\omega_r}{\sigma L_s}\psi_{ds}(k) + C}{i_{ds}(k)} \tag{21}$$

Then, we will need such slip to reach electromagnetic torque references, and therefore, we will have the following expression to calculate u_{qs} voltage:

$$u_{qs}(k+1) = R_s i_{qs}(k) + \left(\frac{\frac{2(t_{em}^* - \hat{t}_{em})}{3P\hat{\psi}_{ds}T_s} + \frac{\omega_r}{\sigma L_s}\psi_{ds}(k) + C}{i_{ds}(k)} + \omega_r(k)\right)\psi_{ds}(k) \tag{22}$$

Thus, the references of torque and flux will be reached using Eqs. (22) and (11), which will be transformed into the stationary reference frame using stator flux spatial position.

In Fig. 1, we have the block diagram which summarizes DTC deadbeat strategy proposed in this paper.

3.3 Estimator

The stator flux estimation is performed by:

$$\boldsymbol{\lambda}_{1\alpha\beta} = \int (emf_{\alpha\beta})\,dt = \int (\mathbf{v}_{1\alpha\beta} - R_1\mathbf{i}_{1\alpha\beta})\,dt \tag{23}$$

where the subscript $\alpha\beta$ represents the stationary reference frame.

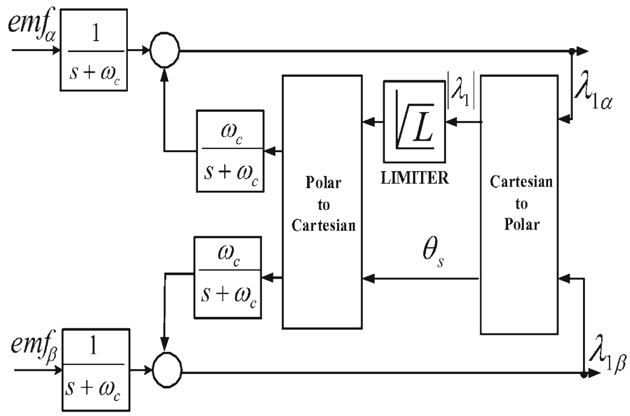

Fig. 2 Block diagram for estimating stator flux

The spatial position of the stator flux is found from estimated components in Eq. (23), and is given by:

$$\delta_s = tg^{-1}\left(\frac{\lambda_{1\beta}}{\lambda_{1\alpha}}\right) \tag{24}$$

For estimation of the stator flux vector at multiple points of IM's speed operation using Eq. (23), the integration method used by [29,30] and presented in Eq. (25) may be used.

$$y = \frac{1}{s+\omega_c}x + \frac{\omega_c}{s+\omega_c}z \tag{25}$$

The stator flux estimation presented by Eq. (25) has low performance at low speed, due to the low-pass filter behavior of its implementation. To solve this problem, it is implemented as presented in Fig. 2. In this way, the IM can operate at low speed.

4 Experimental results

The proposed deadbeat controller was implemented in a wound-rotor induction motor with short-circuited rotor and having the nominal data presented in Table 1. IM is linked to a 3 kW direct current machine (DCM) which will operate as a generator to test the application of the load torque. The controller was implemented on a Texas Instruments TMS320F335 digital signal processor, using electronic boards built in the laboratory for signal conditioning, and encoder with 3600 pulses per revolution. The vector modulation used a 10 kHz switching frequency. This setup is shown in Fig. 3.

First, the tests were conducted with no load. The first test was an input in degree of the torque reversal reference resulting in 5 N m and −5 N m values. The reference to the flux magnitude was kept constant at 0.4 Wb. The test results are shown in Fig. 4 where it can be noted that the references were perfectly reached.

The speed-reversing test at ramp from −500 to 500 rpm is the second test. The results are presented in Fig. 5, where we can also observe the way stator flux magnitude behaves. It is clearly observed that the speed reference was reached.

Table 1 IM data used in the tests

Nominal values		
Nominal active power of the stator	P_N	3.5 kW
Voltage per phase	V_N	220 V
Stator frequency	f	60 Hz
Number of poles	NP	4
Parameters		
Stator resistance	R_s	1 Ω
Rotor resistance	R_r	3.13 Ω
Magnetizing inductance	L_m	192 mH
Stator inductance	L_s	200 mH
Rotor inductance	L_r	200 mH
Moment of inertia	J	0.45 kg m^2

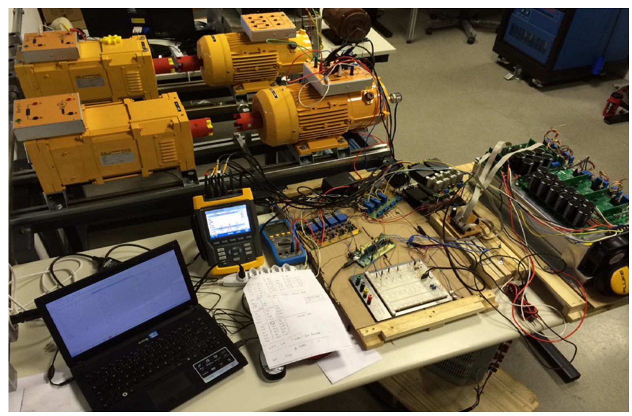

Fig. 3 Experimental setup

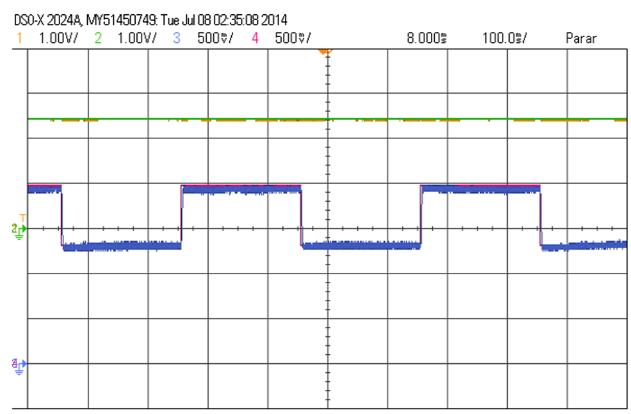

Fig. 4 Reversal test of reference torque (C1/C2: 0.82 Wb = 3.3 V and 0 Wb = 1.65 V and C3/C4: 25.27 N m = 3.3 V and 0 N m = 1.65 V)

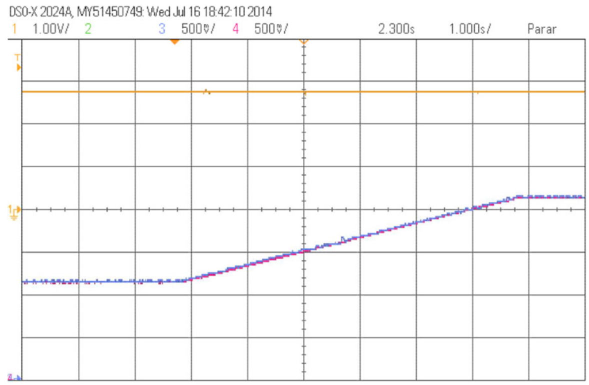

Fig. 5 Reversion speed test (C1: 0.82 Wb = 3.3 V and 0 Wb = 1.65 V; C3/C4: 1800 rpm = 3.3 V and 0 rpm = 1.65 V; C2: 25.27 N m = 3.3 V and 0 N m = 1.65 V)

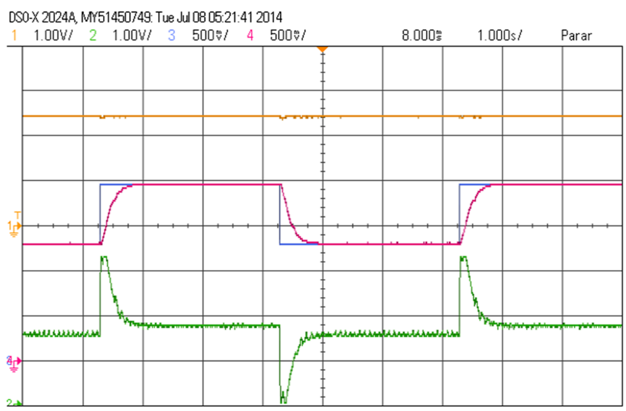

Fig. 6 Reversion speed test (C1: 0.82 Wb = 3.3 V and 0 Wb = 1.65 V; C3/C4: 1800 rpm = 3.3 V and 0 rpm = 1.65 V; C2: 25.27 N m = 3.3 V and 0 N m = 1.65 V)

The third test was regarding speed reversing from 300 to −300 rpm. Test results are presented in Fig. 6. We can also see the way torque and stator flux magnitudes behave. Once again, references were perfectly reached.

In low-speed test, the machine operates below 8 Hz. This test is the fourth one. The results (speed reversing from −90 to 90 rpm) can be seen in Fig. 7. In this figure, it is observed that the reference was reached, showing a satisfactory performance of the proposed controller at low-speed operation. This one is possible due to the flux estimation to use the Fig. 2 implementation. To complete this analysis, it is presented the behavior of the stator's phase a current and the stator flux magnitude.

As the fifth test, it is presented the response to the load input. In this test, IM operates with 500 rpm speed and a 3 N m torque load. At a given moment, a 5 N m load torque is applied on its axis. Figure 8 shows the results where we can observe the way torque and stator flux magnitudes behave. It can also be noted that the speed reference was reached.

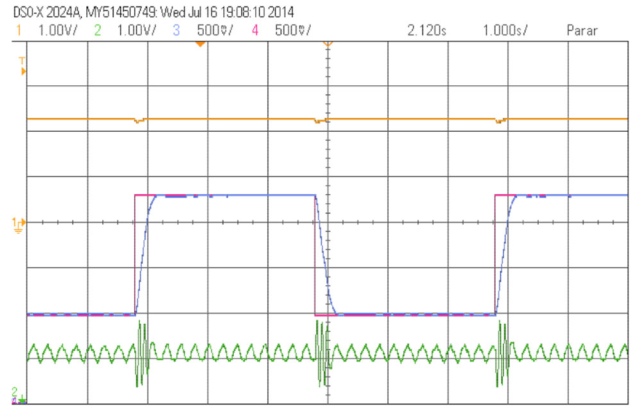

Fig. 7 Reversion speed test (C1: 0.82 Wb = 3.3 V and 0 Wb = 1.65 V; C3/C4: 450 rpm = 3.3 V and 0 rpm = 1.65 V; C2: 28.5 N m = 3.3 V and 0 N m = 1.65 V)

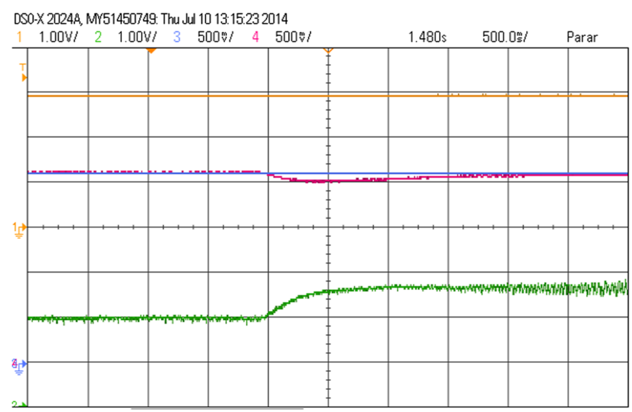

Fig. 8 Speed and flux response to load input (C1: 0.82 Wb = 3.3 V and 0 Wb = 1.65 V; C3/C4: 450 rpm = 3.3 V and 0 rpm = 1.65 V; C2: 10 A = 3.3 V and 0 A = 1.65 V)

The sixth test is the load application and removal at IM axle. In this test, IM is operating at 600 rpm speed and with 4 N m load due to DCM axle. At a given time, a 15 N m torque load is applied on its axis, and after a few moments, it is taken off to verify controller's performance. In Fig. 9, we see the satisfactory controller performance during the test due to the speed reference to be fully reached. We can also check the behavior of the torque and flux, demonstrating the operability of the proposed control.

5 Conclusions

This paper proposed a controller for deadbeat DTC as an alternative to DTCs already existing in the literature. To achieve this goal, we used the discretized dynamic mathematical model of IM using flux vectors and stator current, and deadbeat control theory. The space vector modulation was used due to its operation with fixed switching frequency, facilitating the design of filters and also allowing better use

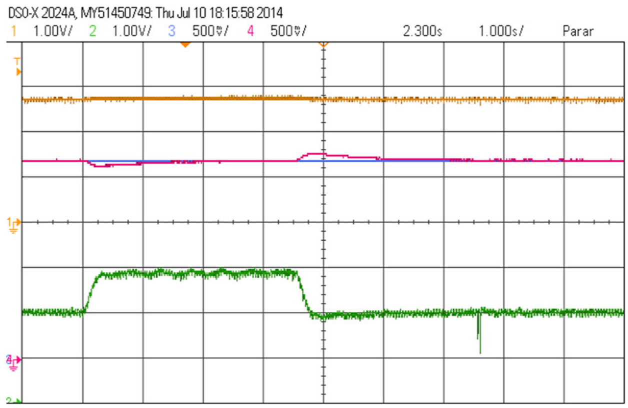

Fig. 9 Speed and flux response to load input and removal (C1: 0.82 Wb = 3.3 V and 0 Wb = 1.65 V; C3/C4: 1800 rpm = 3.3 V and 0 rpm = 1.65 V; C2: 25.27 N m = 3.3 V and 0 N m = 1.65 V)

of the voltage of the DC link inverter. This type of controller allows the system to achieve the fastest possible response with no errors for the system being controlled. The controller requires no adjustments of gains due to using IM discretized dynamic model, which makes it very attractive. Deadbeat DTC had satisfactory performance for the presented experimental results, including testing at low speed, which demonstrates the great potential of such proposal. Thus, this controller can be successfully used in IM operation.

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