VOLTAGE SAG INDEPENDENT OPERATION OF INDUCTION MOTOR BASED ON Z-SOURCE INVERTER

Uroš Flisar, Danjel Vončina, Peter Zajec

University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia

Key words: Z-Source inverter, space vector modulation, field oriented control, field weakening

Abstract: This paper describes an adjustable speed drive system for driving an induction motor beyond its nominal speed, even in the presence of input voltage sags. The system is based on the Z-Source inverter, which offers several advantages over traditional current or voltage source inverters as it can operate in both buck or boost mode. The boost operation is achieved with controlled short-circuiting of the inverter phase legs that is otherwise forbidden in traditional inverters. This shoot through states are accomplished with the modification of the space vector modulation which is thoroughly explained. In order to assure the required output voltage and ride-through ability during voltage sags, the method for selecting the proper inverter voltage is introduced. The control of the induction motor is carried out with the field oriented control coupled with the field weakening regime of the induction motor. The experimental setup is based on a prototype with a DSP control system to verify the operation of the proposed system.

Nemoteno obratovanje asinhronskega motorja na osnovi pretvornika z impedančnim prilagodilnim vezjem

Kjučne besede: pretvornik z impedančno prilagodilnim vezjem, modulacija s prostorskim vektorjem, vektorska regulacija polja, slabljenje polja

Izvleček: Članek opisuje izvedbo nemotenega obratovanja asinhronskega motorja, ki temelji na trifaznem razsmerniku z impedančnim prilagodilnim vezjem. Razsmernik s prilagodilnim vezjem omogoča vrsto prednosti v primerjavi s klasičnimi napetostno ali tokovno napajanimi razsmerniki, saj poleg pretvorbe napetosti navzdol, hkrati omogoča tudi pretvorbo napetosti navzgor. Dvig vhodne napetosti dosežemo z reguliranim proženjem kratkih stikov v vejah razsmernika, kar je sicer prepovedano v omenjenih klasičnih razsmernikih. Tak način proženja kratkih stikov smo dosegli s prilagoditvijo pulzno-širinske modulacije napetosti na podlagi prostorskih vektorjev. Prav tako je prikazan izračun napetosti razsmerniškega mostiča, s katero zagotovimo zahtevano izhodno napetost za nemoteno obratovanje pri upadih vhodne napetosti. Regulacija vrtenja asinhronskega motorja je izvedena s pomočjo vektorske regulacije na osnovi polja, ki omogoča preprosto nadgradnjo za vključitev slabljenja magnetnega polja v rotorju, s katerim ga zavrtimo preko nazivne hitrosti. Eksperimentalni sistem, ki ga sestavljajo napetostni vir, impedančno prilagodilno vezje, trifazni razsmernik s priključenim asinhronskim motorjem in DSP nadzornim vezjem, je uporabljen za verifikacijo predlaganih rešitev.

1 Introduction

The traditional power converters used for the control of motor drives are voltage source inverter (VSI) and current source inverter (CSI). However, both have limitation in their operation. Because the ac output voltage of the VSI is limited below the dc bus, the VSI usually requires an additional boost converter. Similarly the buck converter is often added to the CSI. This additional converter stage increases cost and complexity and lowers the overall efficiency of the power conversion system.

The Z-Source inverter (ZSI) overcomes the restrictions of the previously mentioned topologies /1/. Its structure is comprised of two capacitors and inductors connected in a unique impedance network that is usually coupled with a voltage source and Inverter Bridge. The modus operandi of the ZSI includes a controlled short circuiting (also called shoot through) of the inverter phase legs. This enables the boost operation, whereas without it, the Z-Source inverter acts as a traditional voltage source inverter. The Z-Source inverter was originally intended for power systems with fuel cells /2-4/, due to their distinctive operating curve. As their output voltage dramatically decreases with the increased current demand, the need for the boost operation becomes essential. A similar conclusion can be drawn in conjunction with solar cells, since their output voltage changes according to the change in temperature and sun radiation. Another demanding power conversion process takes place in wind turbines, where the wind energy is transformed into the electrical energy. Because the output of the wind turbine is directly proportional to the change in wind speed, the uninterrupted power delivery to the electrical grid is essential.

Recently, the use of the ZSI is advancing into the motor drive applications /5/, because it offers several advantages over traditional solutions. The nature of ZSI's operation makes it less sensitive to EMI which could short-circuit inverter phase legs that would normally destroy the switching devices. Because this kind of shoot through is allowed, the insertion of dead time is not necessary anymore. Consequently, this reduces the current and voltage harmonics. Controlling the short-circuiting of inverter phase legs can theoretically step up the input voltage to any value up to the infinity. The practical values are however limited with the device voltage ratings. Nevertheless, with controlled boost of the input voltage an important benefit of the ZSI is gained - the ability to provide ride-through during voltage sags.

The ac output of the VSI is usually controlled with sinusoidal pulse-width modulation (SPWM) or with a computational more intensive space vector modulation (SVM). Regarding the utilization of the inverter voltage, the SVM is preferable as it is capable to utilize the inverter voltage of about 15 percent more than the SPWM. Both strategies have to be modified in order to include the shoot through states, needed for the ZSI's boost operation /6-8/. Another factor that favors the use of the SVM is the compatibility with Field Oriented Control (FOC) of the induction motor (IM). This type of control is frequently used with the operation in the extended speed range, where the field weakening enables the motor operation with the constant power above base speed.

2 Configuration and control of the zsi for motor drives

The voltage source PWM inverter is the common choice for powering the induction motor drives. The preferred PWM method for voltage source inverter is SVM, where the concept of space vectors (representing the states of the inverter switches) is used to control the ac output of the inverter bridge. Figure 1 depicts how the output voltage vector *V* can be expressed as a linear combination of adjacent space vectors V_1 and V_2

$$V = V_1 + V_2 = V_{100}\frac{T_1}{T_S} + V_{110}\frac{T_2}{T_S} + (V_{000} + V_{111})\frac{T_0}{T_S} \quad (1)$$

T_0 is time duration of zero state V_{000} and V_{111}, T_1 and T_2 are time durations for any of the neighboring active states and T_S is the switching period. In the linear or undermodulation region the output voltage vector *V* always remains within the inscribed circle in the hexagon formed by the six space vectors. The pulse pattern of SVM for three phase inverter is illustrated in Fig. 2. The state sequence begins with the zero state where the V_{000} is impressed (all upper transistors are open). This is followed by the two active states and ends with another zero state V_{111}, where all upper transistors are closed. After half of the switching period T_S, this sequence repeats in reverse order. The SVM with the symmetrical pulse pattern has the two zero states distributed equally on both ends of the active states as illustrated in Figure 2.

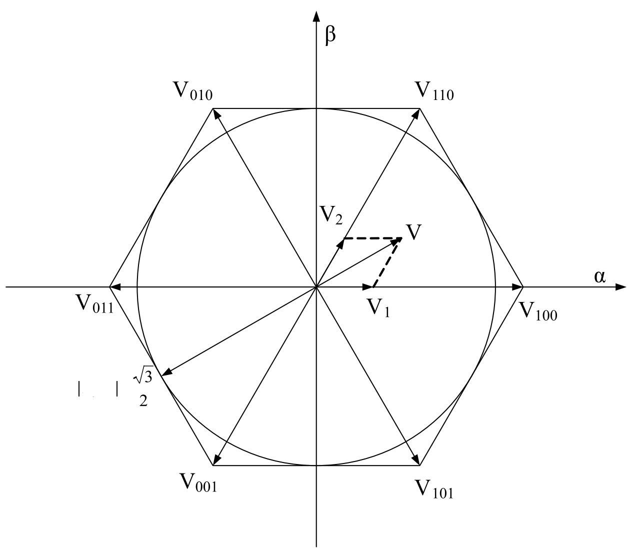

Fig. 1: Space vectors of three phase bridge inverter showing voltage trajectory and voltage vector limit

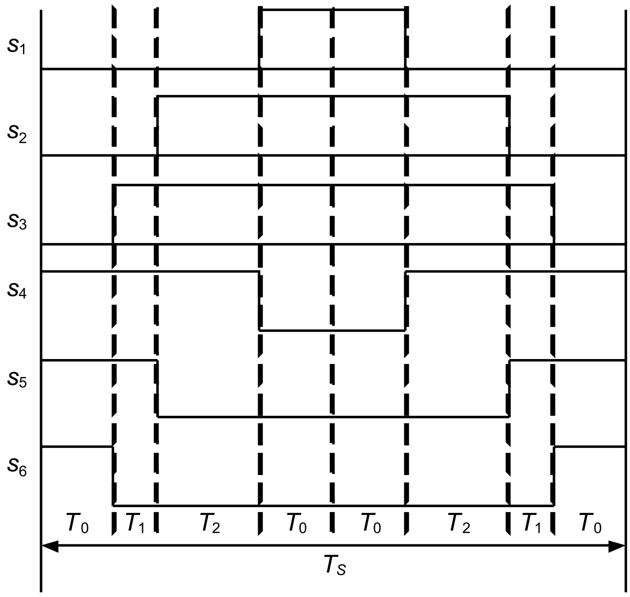

Fig. 2: Symmetrical pulse pattern of SVM for three phase Inverter Bridge

The maximum line-to-line rms voltage (U_{ab}) that can be utilized with the SVM from the inverter voltage u_i of the VSI is

$$U_{ab} = \frac{u_i}{\sqrt{2}}. \quad (2)$$

When using an induction motor with the nominal line-to-line rms voltage of 177 V as an example, it requires a minimum inverter voltage of 250 V. This value needs to be further increased if the compensation of voltage sags is required. Although the VSI usually includes input capacitor for such occurrences, it is a low energy storage element and is inefficient in case of severe voltage sags. Furthermore, increasing the input voltage is not always a viable solution. Often an additional converter stage is inevitable, which can be an additional boost converter or an addition of the Z Source impedance network.

2.1 Z-Source inverter operation

If the impedance network is added to existing VSI, the later is transformed into a Z-Source inverter shown in Figure 3. It can be separated into four major parts: the voltage source U_{DC} and diode D_1 to block the input voltage during shoot through; the symmetrical Z-Source impedance network, with capacitors $C_1 = C_2$ and inductors $L_1 = L_2$; a three phase inverter bridge and the induction motor as the load.

The basic operating principle and control of the ZSI have been detailed in /1/. The summary of the ZSI main operating modes are:

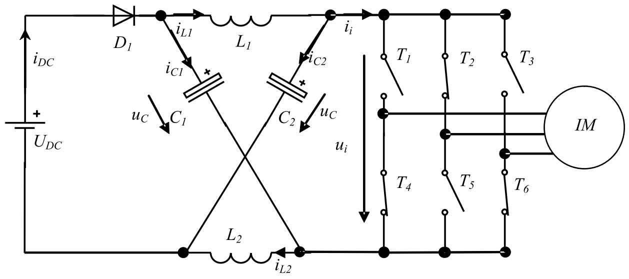

Fig. 3: Z-Source Inverter with induction motor

Mode 1): The inverter bridge is operating in one of the six active states and diode D_1 is conducting. From the load point of view, the inverter bridge behaves as a current source as depicted in Figure 4. The voltage and current relationships are

$$u_L = U_{DC} - u_C;\ u_i = 2u_C - U_{DC} \quad (3)$$

$$i_{DC} = i_L + i_C; i_i = i_L - i_C \rightarrow i_{DC} = 2i_L - i_i. \quad (4)$$

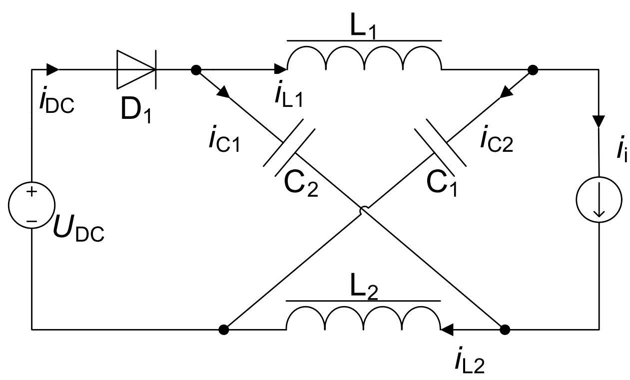

Fig. 4: ZSI operating in active mode

Mode 2): The input diode is still conducting and the inverter bridge is operating in the zero state. The upper or the lower transistors are closed and the inverter bridge acts as an open circuit viewed from the Z-Source network. The voltage relationships are the same as in (3) while the currents are

$$i_{L1} = i_{L2} = i_{C1} = i_{C2} = \frac{i_{DC}}{2} \rightarrow i_{DC} = 2i_L \quad (5)$$

Mode 3): Figure 5 illustrates the shoot through mode, where the input diode is reverse biased because the sum of the capacitor voltage is higher than the input voltage. The shoot through can be done in one phase leg, two or in all three phase legs. The voltage and current relationships in the shoot through mode are

$$u_L = u_C,\ u_i = 0 \quad (6)$$

$$i_{DC} = 0;\ i_{L1} = -i_{C1};\ i_{L2} = -i_{C2}. \quad (7)$$

The duration of the shoot through (T_{sh}) depends on the required boost ratio (B) and can be calculated with

$$T_{sh} = \frac{B-1}{2 \cdot B} \cdot T_S, \quad (8)$$

where B is

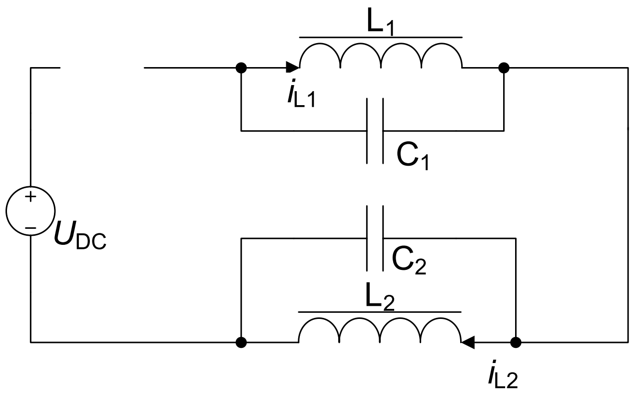

Fig. 5: ZSI operating in shoot through state

$$B = \frac{u_i}{U_{DC}} = \frac{1}{1 - 2 \cdot \dfrac{T_{sh}}{T_S}} \quad (9)$$

The maximum duration of the shoot through is limited to half of the switching period, where the resulting inverter voltage is theoretically boosted to infinity. However in practical application the maximal boost or the maximal inverter voltage is limited with the device voltage ratings.

To summarize, the ZSI behaves in a similar way as a traditional VSI, however it also introduces a new operating state, called shoot through state that boosts the inverter voltage. This enables the ZSI to produce any output voltage, provided the inverter voltage stays within device voltage ratings.

2.2 Modified SVM

In order to include the shoot through states, we must modify the SVM (MSVM). We do this by positioning the shoot

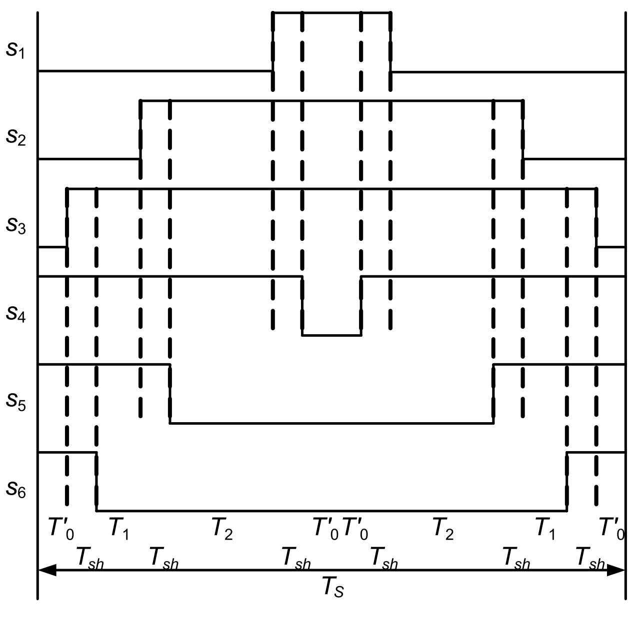

Fig. 6: Modified SVM switching pattern showing the uniform distribution of T_{sh}

through states at the transients of the switching states so that upper and lower transistors on-time is overlapping as illustrated in Figure 6. The shoot through states are distributed equally among all three phase legs and they utilize the zero states symmetrically. This kind of placement allows them to leave the existing active states (T_1 and T_2) uncompromised and more importantly, the number of switchings remains unchanged, however, at the cost of reduced duration of zero state (T'_0).

It can be evident from (9) and Fig. 6 that the boost ratio depends on the available duration of the zero state. If the required T_{sh} is greater than the available T_0, the required voltage boost can not be achieved. Because the voltage boost has a higher priority, the duration of the active states has to be reduced. Figure 7 illustrates the clamped maximum voltage vector (V'_{max}), which is reduced according to the required T_{sh} in order to assure the required voltage boost of inverter voltage

$$|V'_{\max}| = \frac{\sqrt{3}}{2} \cdot \left(1 - \frac{T_{sh}}{T_S}\right). \tag{10}$$

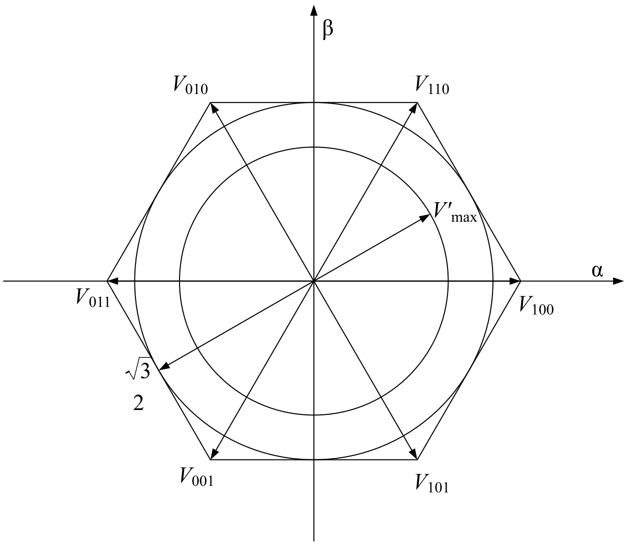

Fig. 7: Modified trajectory of the clamped voltage vector V'_{max}

The total voltage gain G_U is the combination of output voltage vector and the boost ratio. The relationship between G_U and T_{sh} is illustrated in Fig. 8 and can be calculated with

$$G_U = B \cdot |V'_{\max}| \tag{11}$$

The choice of the optimal G_U depends on the requirements for the intended application. However in general, we should maximize V and minimize B to reduce the voltage stress of the switching devices. The line-to-line rms voltage of the ZSI with MSVM is

$$U_{ab} = \sqrt{\frac{2}{3}} \cdot G_U \cdot U_{DC}. \tag{12}$$

Operating an induction motor with a ZSI requires careful control of the voltage gain to guarantee the proper operation during voltage sags. Usually the inverter voltage is kept constant and the boost ratio is adapting according to the change in input voltage. The inverter voltage that will enable uninterrupted motor operation during voltage sag can be calculated by solving the (11) and (12) for u_i

$$u_i = 2\sqrt{2} \cdot U_{ab} - U_{DC\_\min}. \tag{13}$$

The resulting u_i is valid for SVM based Z-Source inverter. If a different PWM technique is used, such as the SPWM, the (12) should be modified accordingly. It should also be noted, that the (13) considers the voltage vector is maximal and boost ratio is minimal. If a different voltage gain strategy is preferred, the (10) should be taken into consideration when choosing the desired inverter voltage.

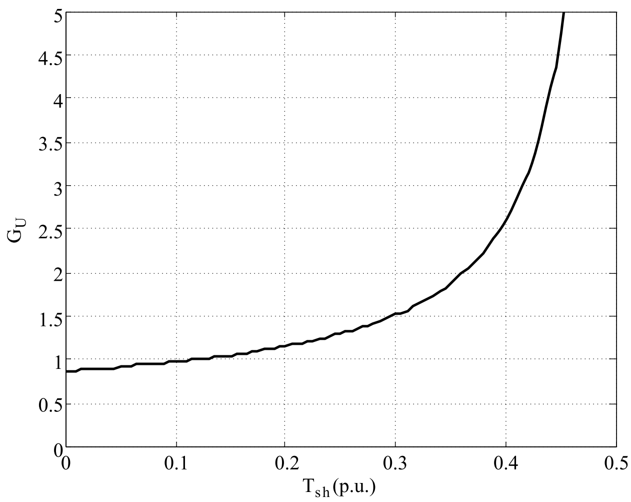

Fig. 8: Maximum voltage gain of ZSI with MSVM

3 Experimental results

The experimental verification has been carried out on the proposed system with the following parameters:

- Input line voltage: 100 – 300 V DC
- Z-Source network: $L_1 = L_2 = 165$ μH; $C_1 = C_2 = 1000$ μF
- Switching frequency: $f_S = 10$ kHz
- Load: Induction motor ($U_n = 177$ V, $I_n = 14{,}8$ A, $n_n = 1456$ rpm, $M_n = 20$ Nm, $f_n = 50$ Hz, $cos(\varphi) = 0{,}785$)
- Position sensor: 1024-lines incremental encoder
- Control system: DSP TMS320F2808

The IM was controlled with the field oriented control which is often used for adjustable speed drive applications, where the field weakening is applied to extend the speed range. The principle of field weakening was achieved by decreasing the flux producing current i_d according to the "$1/\omega_r$" method, while increasing the torque producing current i_q.

A typical functional diagram of the indirect FOC for the induction motor can be seen on Figure 9. The implementation of the existing FOC for VSI based induction motor requires minor modifications. These are mostly related to the chosen PWM method and to the control of the voltage boost. The measuring of the inverter voltage u_i is somewhat cumbersome because the u_i is zero at the time of the shoot through. A more elegant solution is measuring the capacitor voltage u_C and calculating the inverter voltage u_i from

$$u_i = \frac{u_C}{1 - \frac{T_{sh}}{T_s}} . \tag{14}$$

From here forth, the control of the u_i is performed with a PI regulator, which outputs the required B. The T_{sh} is calculated with (8).

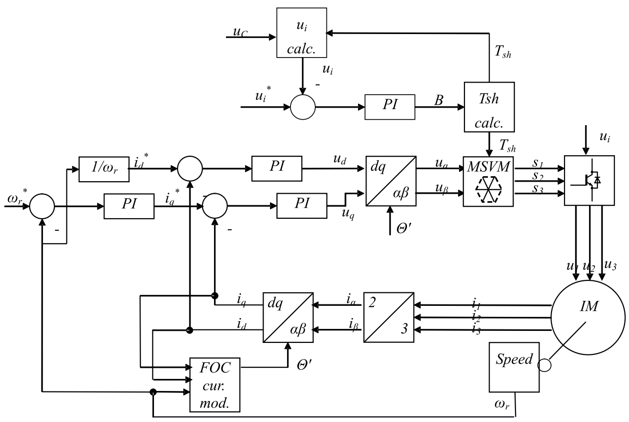

Fig. 9: Functional diagram for FOC with the MSVM and control of the inverter voltage

The operation of the induction motor was first verified with the VSI without the Z-Source network. For the VSI, the minimal inverter voltage according to (2) is 250 V. Including a safe margin of 10 %, the u_i was set to 280 V. Figure 10 shows the ramp up of the rotor speed from nominal value up to 2400 rpm, together with the waveforms of i_d current. The motor was loaded with the 50 % of the nominal torque, because when the motor is operating at high speed, the required torque is normally low.

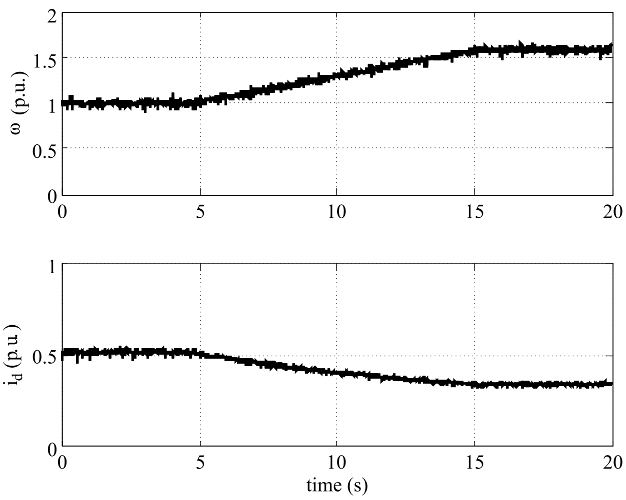

Fig. 10: Ramp up of the speed of IM with VSI (U_{DC} = 280 V)

The same measurements were repeated with a ZSource inverter and the results are shown in Fig. 11. The input voltage was decreased to 180 V to demonstrate the capabilities of the ZSI. The waveforms verify the proper operation of the ZSI where the rotor speed is again increased to 2400 rpm at the 50 % of nominal torque.

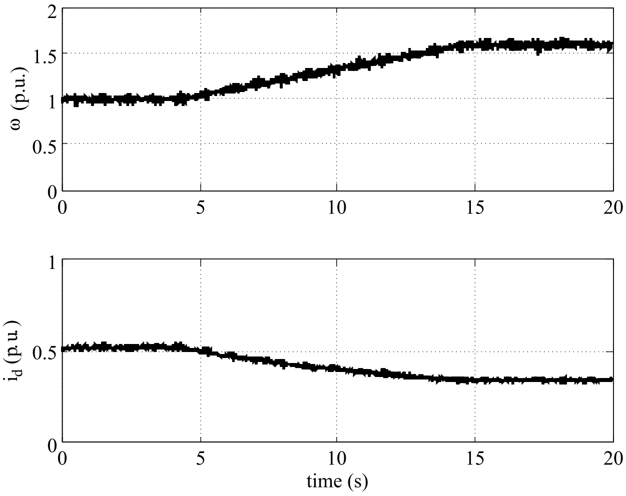

Fig. 11: Ramp up of the speed of IM with ZSI (U_{DC} = 180 V)

When operating the motor in the field weakening regime, voltage sags at the DC input present an even bigger problem, which can lead to rapid reduction of the rotor speed. Figure 12 illustrates the effect of simulated voltage sag of about 25 % of the input voltage for the VSI. Because the voltage sag is too severe, the rotor speed decreases below its nominal value. On the contrary, the flux producing current i_d greatly increases, which indicates the disrupted operation of the IM in the field weakening regime.

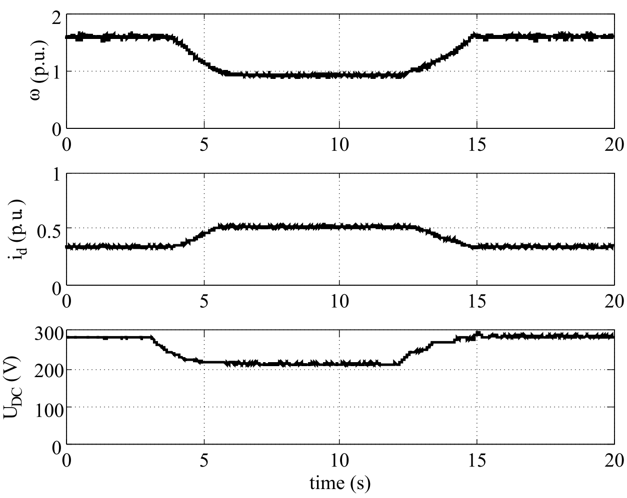

Fig. 12: Motor operation with VSI when exposed to voltage sag

For the ZSI to be able to endure the input voltage drop of 25%, the minimal inverter voltage has to be set according to (13). The resulting u_i is 365 V; however the inverter voltage was set 10 % higher, at 400 V. Figure 13 shows the IM operating at 2400 rpm and at 50 % of the nominal torque. The ZSI successfully adapts its boost ratio during the voltage sag and the operation of the IM remains uninterrupted. The waveforms clearly demonstrate that the inverter voltage is boosted without any negative influence on the flux current i_d, which is maintained at a desired level without any interruptions.

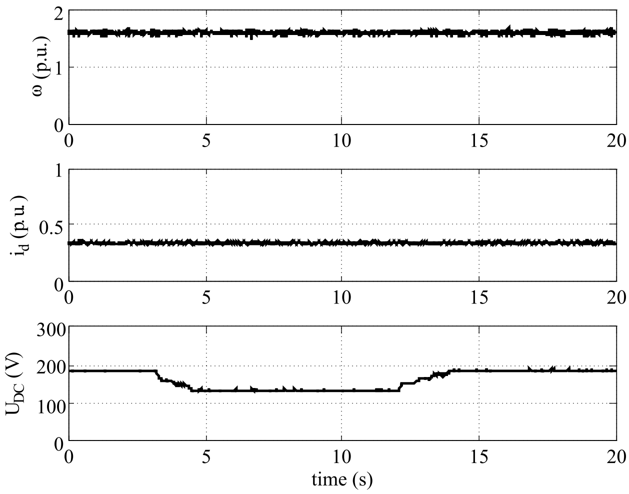

Fig. 13: Motor operation with ZSI when exposed to voltage sag

4 Conclusions

This paper has presented the motor drive system based on the Z-Source inverter and the induction motor. The field oriented control which is extensively used in high-performance drive applications was successfully adapted to the Z-Source inverter, where the modification of the SVM and control of the inverter voltage was explained. The operation of the system was verified with the practical use with the DSP control system together with the operation in the extended speed range. The use of the Z-Source based inverter is beneficial if the input voltage is limited, or if the voltage source is subjected to frequent voltage sags. The ZSI can easily adapt to such disturbances and keep the operation of the motor system reliable.

The findings of the performed experiments could also help when designing power converters with renewable energy sources in mind. In such cases, the changes in input voltage are seldom that sudden, nevertheless an insight into the behavior of the ZSI under comparable circumstances has been presented.

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U. Flisar
University of Ljubljana, Faculty of Electrical Engineering, SI-1000 Ljubljana, Slovenia
uros.flisar@fe.uni-lj.si

D. Vončina
University of Ljubljana, Faculty of Electrical Engineering, SI-1000 Ljubljana, Slovenia
voncina@fe.uni-lj.si

P. Zajec
University of Ljubljana, Faculty of Electrical Engineering, SI-1000 Ljubljana, Slovenia
peter.zajec@fe.uni-lj.si

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