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Review of overvoltage and resonance problems and reduction of in a DTC-controlled five-level flying capacitor drive

***Abstract**. The overvoltage and resonance problems that cause early defects in the stator winding insulation are well known in the low voltage drives. This paper investigates these problems the medium voltage drives and offers the necessary measures to prevent these problems in a DTC-controlled five-level flying capacitor drive. With properly designed switching tables and using a fixed switching frequency, occurrence of overvoltage is prevented. Also, using a fixed switching frequency of occurrence of resonance is prevented. Simulation results and implementing a 3kVA samples using direct torque control strategy has been presented confirming the proposed solutions.*

***Abstract**. Problemy przepięć i rezonansów powodujących uszkodzenia izolacji stojana są dobrze znanym problemem napedów niskonapięciowych. W artykule zbada no podobne zjawiska występujące w napędach średniego napięcia i zaproponowano metody zapobiegania tym problemom na przykładzie pięciopoziomowego napędu ze sterowaną pojemnością. Dzięki prawidłowemu zaprojektowaniu systemu przełączania zapobiega się przepięciom. Rezultaty symulacji i zastosowanie w układzie 3 kVA potwierdziły założenia pracy. (**Problem przepięć i rezonansów w wielopoziomowych napędach typu DTC ze sterowana pojemnością**)*

Keywords: voltage reflection, resonance phenomena, flying capacitor inverter.
Słowa kluczowe: przepięcia, rezonans.

Introduction

Invention of IGBT with rise time in the range of 50ns has a large share in development of PWM drives. Using this advantage, the switching frequency can be increased to get the motor sinusoidal current and reduced torque ripple. However, the fast rise time may cause the overvoltage in the motor terminal, even several times the DC supply voltage especially with long cables, and a non-uniform voltage distribution in stator winding. Exposed to this overvoltage, stator insulation to ground and insulation between turns will be stressed. This leads to the premature motor failure primarily because the motor insulations are designed to work in rated voltage and frequency. Factors that affect the overvoltage include cables, motors and cable impedance matching, inverter output dv/dt and modulation strategy [1]-[2]. So far several solutions to overcome these problems in low voltage drives is presented but until 2005, special researches on the overvoltage in multilevel drives and its effect on medium voltage motors was not done or practical results not provided. In recent years researchers have paid to this issue and recommended to reform the structure of medium voltage motors. Today Several structures of medium voltage inverters for these medium voltage motors are provided that among them three structures of diode-clamped, H-bridge and flying capacitor finds more application and are commercially available [3]-[5]. Among the above structures, flying capacitor inverter as shown in Fig. 1 has been interested because that does not require the transformer as H-bridge inverter and it does not generate distortion as diode-clamped. It is more attractive in high switching frequencies where leads to low capacitor values. Among the methods of induction motor speed control, direct torque control method or DTC strategy with a high performance level in the low-voltage drives, also been implemented in multilevel drives [6]-[9]. DTC strategy in [9] has been implemented on a flying capacitor inverter, but problems such as the overvoltage and resonance have not been addressed. With this introduction, to prevent premature engine failure due to resonance and voltage, the need for reforms in the medium voltage motors and measures in the inverter, which in this paper necessary reforms in the motor is fully expressed and necessary measures have been implemented in the inverter. According to a good understanding of problems in low voltage, first to describe problems and solutions in the case of low voltage drive presented and then paid for a similar review in the medium voltage drive is done. Finally modifying the switching table and using a fixed switching frequency to overcome these problems is presented.

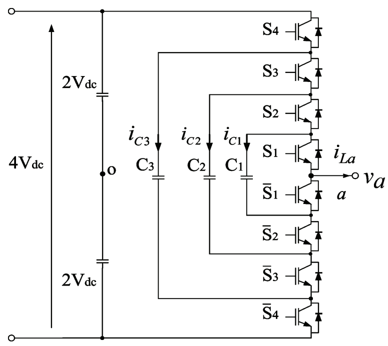

Fig. 1. One leg of a five-level flying capacitor inverter

Reviewing the issue of low voltage drives

Overvoltage problem in inverter fed motors is investigated based on distributed models or lumped models that each of them has advantages and disadvantages. Distributed model has high accuracy but its response is general. On the other hand although the lumped model is less accurate but gives an analytical response and possibility that determine voltage anywhere in cable and motor and also is suitable for purposes of filter design [10]-[11]. Increasing the number of sections in lumped model, its accuracy approaches to the distributed model [12]. Rapid pulses have a high-frequency spectrum and therefore exact prediction of overvoltage needs to cable and motor models that are valid up to MHz range. The overvoltage problem in the early analysis is considered using the simple RL model for the motor and a lossless model was used for cable. At high frequencies due to reduction of the stray capacitors impedances, the motor transfer function differs from a simple RL circuit. However, if the filter is used, the RL model is adequate. For more accurate overvoltage analysis, the lossy-model or distortion model for cable should be used. In recent years many efforts has been done to model motor and the cable at high-frequencies, led to more accurate responses. To obtain the cable characteristic, instead of using the equations related to geometric structure of the cable which does not consider frequency dependency, Open circuit Z_{oc} and short circuit Z_{sc} characteristics can be calculated and then using (7) the characteristic impedance will be calculated.

(1) $$Z_o = \sqrt{Z_{sc} \cdot Z_{oc}}$$

In this model, first the impedance measurements was carried out and then model and its parameters to match these values are determined. Comprehensive model presented in [13] is a development of IEEE112 model suitable for studying various phenomena such as overvoltage, common mode voltage and bearing currents. In [14] a systematic method for determining the parameters of this comprehensive model is presented. In [15], descriptive mathematical relations for the transient voltage and current in the cable provided in the frequency domain which using inverse Laplace transform gives the time domain equations to calculate voltage at motor terminals and at every point of the cable. Advantage is that these models no need complex and costly measurement with the LCR meter. In [16] two methods of modeling through the impedance measurements and the mathematical relations is presented and compared. The advantage of measurement-based approach is its simplicity and also the satisfactory results. Mathematical method is more complicated but the parameters will be calculated systematically. The model in [17] considers details such as skin effect in determining the parameters of the cable, and the frequency dependence for the earth path is considered which to calculate the zero sequence currents is required.

Overvoltage peak value created at motor terminals using the long cables or high dv/dt is equal to [18]:

(2) $$V_r = (1+\Gamma)V_{bus}$$

where Γ is called reflection coefficient and is calculated from the following equation:

(3) $$\Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

where Z_L is the motor impedance and Z_o is the cable characteristic impedance at high frequencies:

(4) $$Z_o = \sqrt{L_o / C_o}$$

Parameters of L_o and C_o are respectively inductance and capacitance per unit length of cable. If the simple RL model for the motor to be assumed, the impedance at high frequencies is very high and it can be considered open circuit. Thus according to the characteristic impedance of small cables generally less than 1000 ohms, the reflection coefficient will be equal to 1 leads to almost a maximum motor terminal voltage to $2V_{dc}$. In [11] an expression to calculate the reflection coefficient is extracted:

(5) $$\Gamma = sin(\theta_v)/\theta_v$$
$$\theta_v = vt_r / 2l_c$$

where v is the speed of pulse propagation in the cable depends on the cable characteristics and is within 32% to 70% speed of light in vacuum [2], l_c is cable length and t_r is the pulse rise time. Overvoltage magnitude versus the cable length and the pulse rise time is shown in Fig.2 and Fig.3.

Oscillation frequency of overvoltage f_o depends on the cable characteristics and its length l_c, and overvoltage amplitude decreases with time constant τ:

(6) $$f_o = \frac{1}{4l_c\sqrt{L_o C_o}}$$

(7) $$\tau = \frac{2L_o}{r_s}$$

where r_s is the effective series resistance per unit length of cable and its value at high frequencies due to skin effect is significant. Researches indicate that if a new pulse is applied before damping of oscillations, the stator overvoltage may be three or four times the DC supply voltage is reached. To prevent this phenomenon, each pulse width must be at least 3τ [2].

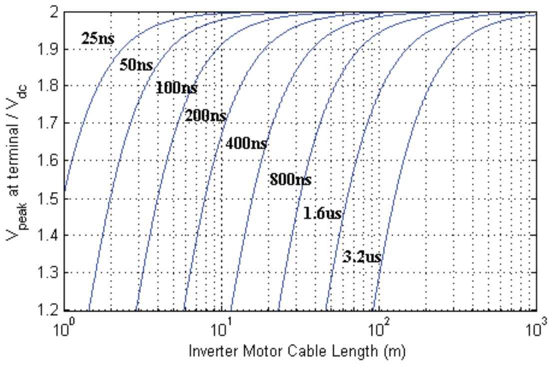

Fig. 2. overvoltage versus cable length

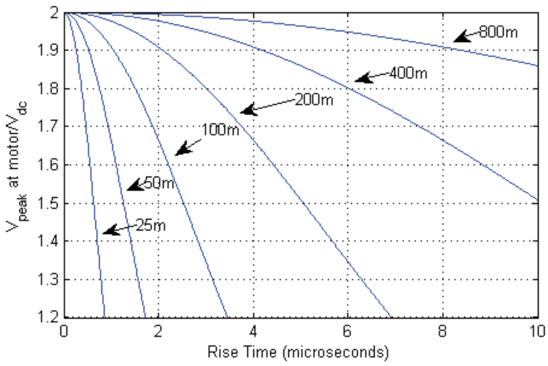

Fig. 3. overvoltage versus pulse rise time

If the cable length is less or t_r be high so that $t_r / l_c \geq 12.5(ns/m)$, the reflected voltage is low and overvoltage will be less than twice the DC supply voltage [19]. Critical cable length is defined as length of cable that causes the overvoltage to be twice the DC supply voltage:

(8) $$L_1 = \frac{v \cdot t_r}{2}$$

Numerous Solutions in researches dealing with the problem of overvoltage is provided which can be divided into five categories: increasing the rise time to 5us, installation of inverter output filter or impedance matching circuit on the motor terminals, using the appropriate cable, modifying the modulation and increasing tolerance of the motor.

1 - Increasing the rise time: Although as one of the first solutions to deal with the problem of voltage was presented, but due to a significant increase in switch loss is not used today. In this case due to reduced dv/dt, damaging overvoltage will not be created.

2- RC filter at the motor input or RLC circuit and choke at the inverter output: RC circuit in the motor terminal, called the motor input filter, has low impedance at high frequencies that improves high frequency impedance matching and reduces the reflection coefficient. RLC filter installed in the inverter output can reduce dv/dt and prevents the premature failure due to stator winding overvoltage [20]. Although both circuits are effective in the overvoltage reduction but RLC filter is recommended because it has a fewer losses and on the other hand installing RC circuit is not always possible, for example in underwater pumps [21]. Using the choke is obsolete because the damping is low and the voltage drop at fundamental frequency was noticeable that the torque is reduced. In [22], an optimal method for determining the filter parameters is presented which according to cable length, cable characteristic impedance and reflection coefficient at the inverter side determines values of R, L and C such that the overvoltage be acceptable. Filter designing researches trend to unify filter in a way that in addition to reducing dv/dt, also reduce the common mode voltage or current bearings and electromagnetic disturbance [23-27]. However, the filter may cost about the cost of inverter and occupy a large space [28]. In applications such as warship which the weight and dimensions are extremely important and the inverter is used to remove the gearbox, the filter eliminates these benefits.

3 - Using the appropriate cable: knowing the overvoltage problem in inverter fed motors, selection of cable connecting the inverter and motor also became important [18],[28]-[29]. According to [18], three-conductor cable with earth and aluminum sheath with thick walls to connect the inverter and motor is suitable. From an insulation point of view, XPLE and EPR cables has been suggested with insulation strengths higher than PVC. Due to the high frequency energy in EPR cable is absorbed, the rise time of pulses to reach the motor increases and the overvoltage kept in the acceptable range. In addition regarding to dielectric losses and aging due to high frequencies, the EPE cable is better than XPEL [30].

4 –Modifying the modulation algorithm: As stated in the introduction, short pulses can lead to overvoltage to 3 or 4 times of DC supply voltage. Control strategy should prevent these short pulses from reaching to the motor by removing them.

5- Increasing motor tolerance: If the motor voltage is higher than partial discharge inception voltage, partial discharge be initiated and motor insulation will be stressed and finally be destroyed. In addition, the voltage gradient in the first turn makes 95% of voltage on the first turn and increases the local stress [28]. Longevity of insulation against corona can be improved by strengthening of stator insulation, but it leads to reduced conductor cross section, which would reduce the efficiency or motor must be used with larger size [31].

The stator overvoltage in medium voltage drive

Standard IEC60034-18-41 and IEC60034-18-42 has assigned to evaluate and qualify insulation in rotating machines fed by the inverter and two kinds of insulation system of the type I and type II are defined. Type I allocated to the low voltage motors with a random wound coil and it is assumed that the partial discharge activity does not taking place. So the insulation material can't withstand partial discharge. In type II dedicated to high-voltage motors above 690-volt with a form-wound coil, the partial discharge problem is more serious and insulation material must be resistance against partial discharge and the Corona-resistant layer is added. Although in the medium voltage motors the insulation materials are resistant against the partial discharge, reviews in [32] has shown that SG-layer (Stress Grading) in the face of rapid and repeated pulses with a magnitude greater than 1.6Vdc, has not a good performance and finally the partial discharge will destroy firstly SG-layer and ultimately the wall insulation. The purpose of SG-layer is smoothing out voltage variations of the winding insulation to semiconductor coating to prevent adverse field intensity level in winding. If rapid pulse is applied to the motor, voltage stress due to the capacitor effect of SG-layer is applied the first on semiconductor coating and after a few microseconds on SG layer [33]. To avoid this problem, materials that are treated as varistor for SG layer and materials with high conductivity for semiconductor coating is recommended. In [34], properties of materials and coatings designed to reduce the destructive effects of rapid pulses is presented. SG using two layers to reduce temperature and increase the resistance to rapid pulses has been proposed.

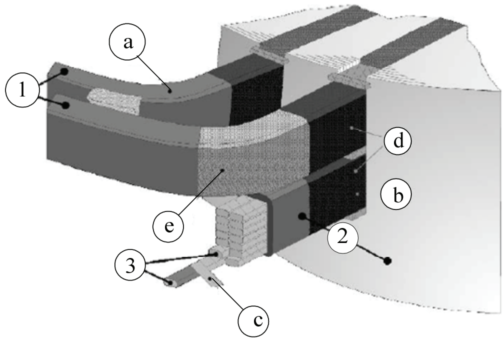

Fig. 1. Form-Wound winding in medium-voltage motors [28]
a. phase insulation/overhang insulation,
b. ground insulation
c. turn insulation, **d**. corona protection
e. stress grading region,**1.** phase to phase
2. phase to ground, **3**. turn to turn

Research results in [35] recommend *VPI* (vacuum-pressure-impregnated) process improvements and using better insulating materials for medium-voltage motors fed by inverters. In [36] to reduce eddy losses due to inverter high-frequencies, the reformations such as magnetic-grooves installation is proposed.

One advantage of multilevel converters is that the input voltage divided by the number of levels and in every moment a fraction of the DC supply voltage is switched. Thus the voltage reflection will be corresponding to the same changes. In other words, dv/dt decreases and the motor overvoltage divided by the number of levels in multilevel inverter. One the other hand medium voltage drives using high-voltage IGBT with a rise-time much bigger than the low voltage IGBT and although it is undesired (generally larger than 0.4us) in terms of loss, but reduces *dv/dt* [37]-[39]. With reduced *dv* and increased *dt*, overvoltage problem caused by reflected voltage in multilevel drives with a long cable is less than two-level drives. However, the control strategy requires that at any moment makes only one level of size variation in the output voltage otherwise this advantage will be removed. The applied dv/dt is more important when the output voltage leads to the voltage level 4 because (for example) changing the voltage level from 2 to 4 will cause the motor voltage to be 1.5 times rated voltage and is far more important than changing the level from 1 to 3, which causes 1.25 times rated voltage. Voltage-level changing from the 0 level to the 2 level will not lead to any detrimental overvoltage.

Another issue in PWM-drives is the resonance phenomena that can cause premature failure [40]-[41]. In [40], a 13.8kV motor insulation defects when fed through 800-meter cable by low voltage inverter connected to step-up transformer. Failure is due to resonant frequencies that exist between motor and transformer inductance with the cable capacitance. To solve the problem, a low pass filter (LCR filter) is used. Due to the resonant frequency is about *3kHz*, there is no need to use high-frequency model or distributed model for cable and a compact model will suffice. However, modeling the motor capacitor in this frequency range is important. In [41] with increasing switching frequency above the resonant frequency of occurrence of overvoltage is prevented. Accordingly DTC strategy should be based on a fixed frequency so as to prevent the occurrence of resonance. Damping of the oscillations with time constant $\tau = 2Lo/rs$ will be guaranteed if dead-time will be set greater than 3τ. Considering the turn-off time in high-voltage IGBT reaches to *10us*, dead-time will comply with the above conditions. In [42][42]-[43] method to keep constant the switching frequency is presented.

DTC Switching table designed to reduce overvoltage in Multilevel Drives

In a three-phase symmetrical induction motor, electromagnetic torque relation is:

$$T_e = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \left|\overline{\psi}_s\right| \left|\overline{\psi}_r\right| Sin\delta_\psi \quad (9)$$

Where $\left|\overline{\psi}_s\right|$ and $\left|\overline{\psi}_r\right|$, are the stator and rotor flux amplitude respectively and δ_ψ, the angle between two flux vectors, is called the torque angle. L_m, L_s and L_r are the magnetizing, stator and rotor inductances, respectively and σ is the total leakage factor of the motor defined by:

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (10)$$

In DTC, flux amplitude is maintained at about nominal value and the torque is set with the torque angle. Obviously maximum torque is achieved with $\delta_\psi = \pi/2$. As we will see, the torque angle and consequently the torque is adjustable using the stator voltage vector. Stator voltage equation is:

$$\overline{u}_s = r_s \overline{i}_s + \frac{d\overline{\psi}_s}{dt} \quad (11)$$

Although an accurate model should use the (11), only to a simple description of DTC strategy by neglecting the first term (which is a valid approximation especially at high speeds):

$$\frac{d\overline{\psi}_s}{dt} \approx \overline{u}_s \Rightarrow \overline{\psi}_s \approx \overline{\psi}_{s0} + \overline{u}_s \Delta t \quad (12)$$

Compared with two-level inverters, there are a large number of vectors with different sizes in multilevel inverters that they can control the flux vector with different speeds and in different directions. Thus the multilevel drives have a faster and more precise control on the flux and torque. Stator voltage vector in a multilevel drive is as follow:

$$\overline{u}_s = u_a e^{j0} + u_b e^{j2\pi/3} + u_c e^{j4\pi/3}$$

This space vector can be indicated as number cba in which a, b and c, respectively, show the size of the voltage levels in each phase. All the space voltage vectors other than the redundant vectors for a five-level drive are shown in Fig. 5. According to Fig. 5, vectors are inscribed in four hexagonal. In, the α-β plane has been divided into 12 sectors as shown in Fig. 6. Given the four hexagonal, zero speed to nominal speed is divided to four ranges and at each interval the proper vectors will be used. Switching table 1 for high speeds has been developed. According to this switching table when the flux index, torque index or sector changes, the applied voltage step size is 2Vdc or 3Vdc but it should be limited to Vdc to prevent harmful overvoltage at stator terminal . In this paper the α-β plane has been divided into 24 sectors as shown in Fig. 7 and a 24-sector table as table-2 proposed to limit dv/dt and the stator overvoltage.

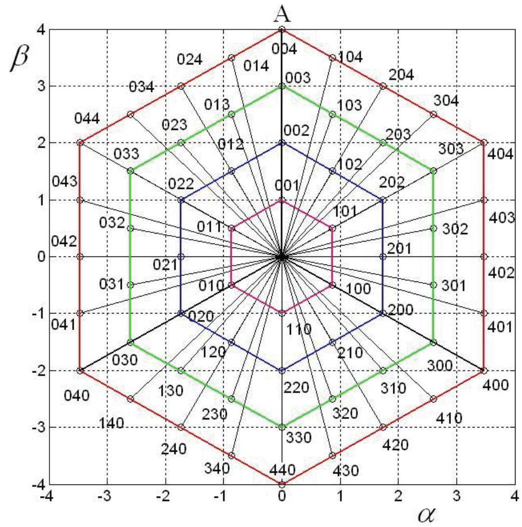

Fig. 5. voltage space vectors without redundancy in a five-level inverter

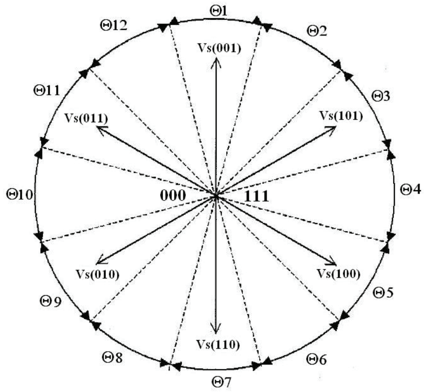

Fig. 6.: Multilevel DTC Sector division [9].

Table 1. 12-Sector switching table for high speed range [9]

TI	FI	Θ1	Θ2	Θ3	Θ4	Θ5	Θ6	Θ7	Θ8	Θ9	Θ10	Θ11	Θ12
0	1	301	310	320	230	130	031	032	023	013	103	203	302
0	-1	302	301	310	320	230	130	031	032	023	013	103	203
1	1	200	210	220	120	020	021	022	012	002	102	202	201
1	-1	202	201	200	210	220	120	020	021	022	012	002	102
-1	1	401	410	430	340	140	041	043	034	014	104	304	403
-1	-1	403	401	410	430	340	140	041	043	034	014	104	304

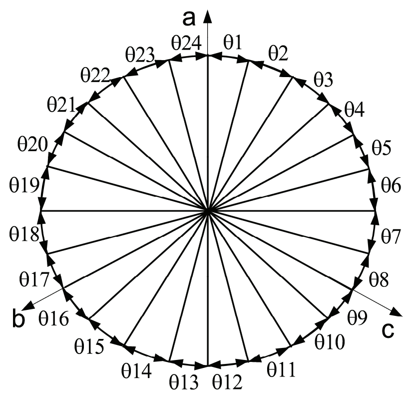

Fig. 7. 24 sectors in a multilevel inverter

According to the Table 2 column 3(from the left related to sector1) when vector changes from 200 to 401 (TI = 1 to TI =- 1), a two-steps change will be applied to the stator. Therefore the overvoltage will be corresponding to the reflection from the two-steps change. These changes can be reduced using redundancy of the vectors because adding one step to any component of a vector does not affect the differential mode voltage, but the common mode changes. For example, vector 200 has a redundant vector 311 which is the same in differential mode but changing from 311 to aforementioned vector 401 will be subjected to only one step change in each phase. So, other two steps changes can to be replaced with exception that vectors leading to the outer hexagonal have not redundancy. Finally, Table 3 is obtained.

Simulation results

DTC strategy on a small scale sample using a 400V, 3 kW motor is simulated and implemented. DTC and motor parameters are presented in Appendix. Multi-level structure of the DTC is shown in Fig. 8. To verify DTC performance with different tables, the motor is accelerated of zero to 90% nominal speed. The stator current, rotor speed and electromagnetic torque using table 1 shown in Fig. 9. The applied voltages in the motor terminals in Fig.10 show voltage Step-Sizes of $2Vdc$ or $3Vdc$. The stator current, rotor speed and electromagnetic torque using table 3 shown in Fig. 11. There is no significant difference as compared with Fig. 9. It means the drive performance is not reduced using new table. The applied voltages in the motor terminals using table 3 in Fig.12 show only the voltage Step-Size of Vdc.

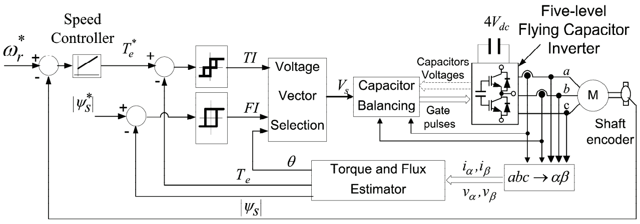

Fig. 8. DTC structure in a flying capacitor inverter

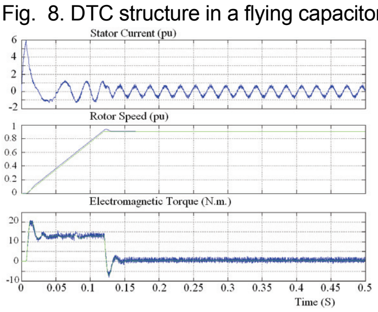

Fig. 9. Waveforms using Table 1

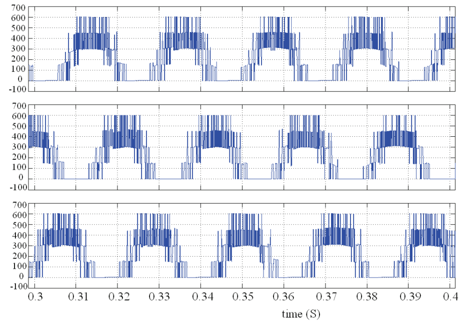

Fig. 10. Voltages applied to the three-phase motor with table 1

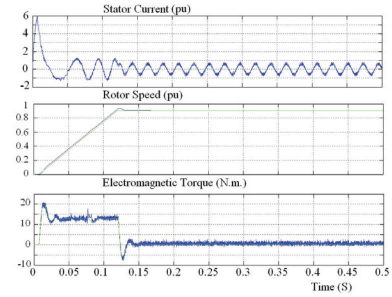

Fig. 11. Waveforms using Table 3

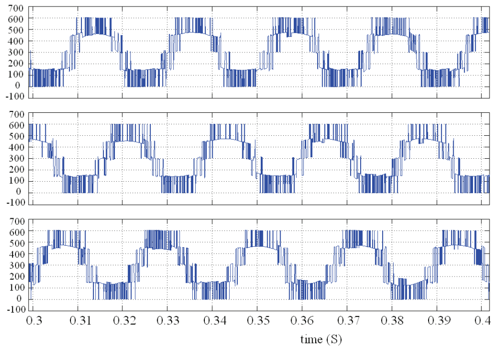

Fig. 12. Voltages applied to the three-phase motor with table 3

Table 2. 24-Sector Switching Table For High Speed Range In 5-Level Drive

TI	FI	θ1	θ2	θ3	θ4	θ5	θ6	θ7	θ8	θ9	θ10	θ11	θ12	θ13	θ14	θ15	θ16	θ17	θ18	θ19	θ20	θ21	θ22	θ23	θ24
0	1	301	300	310	310	320	330	230	230	130	030	031	031	032	033	023	023	013	003	103	103	203	303	302	302
0	-1	302	301	300	300	310	320	330	330	230	130	030	030	031	032	033	033	023	013	003	003	103	203	303	303
1	1	200	200	210	210	220	220	120	120	020	020	021	021	022	022	012	012	002	002	102	102	202	202	201	201
1	-1	201	201	200	200	210	210	220	220	120	120	020	020	021	021	022	022	012	012	002	002	102	102	202	202
-1	1	401	400	410	420	430	440	340	240	140	040	041	042	043	044	034	024	014	004	104	204	304	404	403	402
-1	-1	402	401	400	410	420	430	440	340	240	140	040	041	042	043	044	034	024	014	004	104	204	304	404	403

Table 3. Modified 24-Sector Switching Table For High Speed Range In 5-Level Drive

TI	FI	θ1	θ2	θ3	θ4	θ5	θ6	θ7	θ8	θ9	θ10	θ11	θ12	θ13	θ14	θ15	θ16	θ17	θ18	θ19	θ20	θ21	θ22	θ23	θ24
0	1	301	300	310	310	320	330	230	230	130	030	031	031	032	033	023	023	013	003	103	103	203	303	302	302
0	-1	302	301	300	300	310	320	330	330	230	130	030	030	031	032	033	033	023	013	003	003	103	203	303	303
1	1	311	311	321	321	331	331	231	231	131	131	132	132	133	133	123	123	113	113	213	213	313	313	312	312
1	-1	312	312	311	311	321	321	331	331	231	231	131	131	132	132	133	133	123	123	113	113	213	213	313	313
-1	1	401	400	410	420	430	440	340	240	140	040	041	042	043	044	034	024	014	004	104	204	304	404	403	402
-1	-1	402	401	400	410	420	430	440	340	240	140	040	041	042	043	044	034	024	014	004	104	204	304	404	403

Practical results

Implemented five-level flying capacitor drive is shown in Fig. 13. Different parts of the system have been named including IGBTs and related drivers, flying capacitors, voltage transducers and DSP controller. The main processor board ezDSPF2812 with 150MIPS capability is suite for implementing DTC. The processor is equipped with 16 channel analog to digital converter which is used to measure nine floating-capacitor voltages, two phase current, three phase voltage and DC link voltage. Six I/O port with 56-pin provides commands to 24 IGBTs easily. Induction motor using Tables 1 and 3 is accelerated to 90%

of nominal speed and results are shown in Fig. 14 and 15. The applied voltage in Fig. 17 as compared with Fig. 16 confirms reduction of voltage step-size.

Conclusion

In this paper, overvoltage and resonance problems that cause early defects in the stator winding insulation in the medium voltage motors has been investigated and the required modifications to retrofit the motor structure was presented. Then the table is modified to reduce the output *dv/dt*. Using constant switching frequency, the occurrence of resonance problem was avoided. Simulated and practical results obtained from direct torque control a 3kVA induction motor using TMS320F2812, confirm the the proposed solutions.

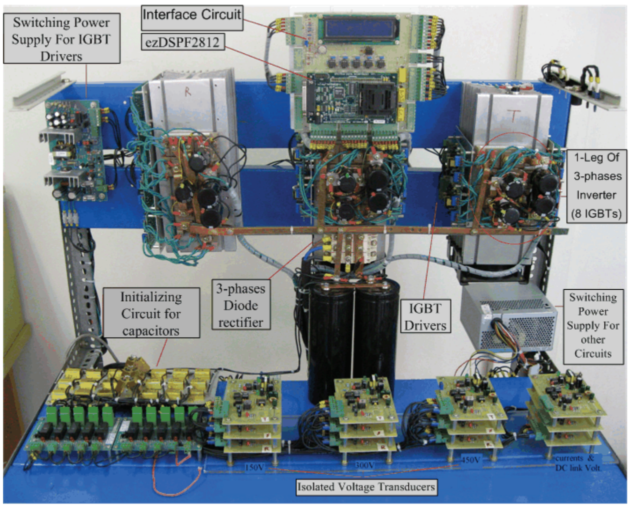

Fig. 13. Implemented system

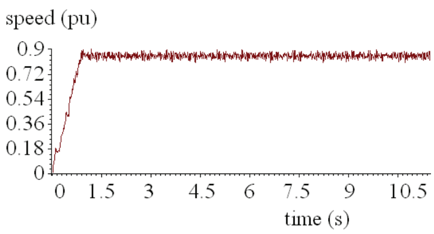

Fig. 14. Speed variation using Table 1

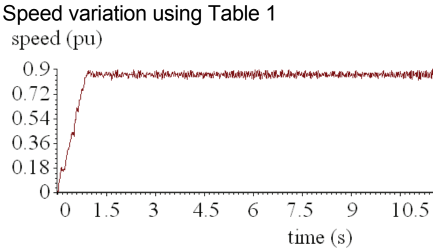

Fig. 15. Speed variation using Table 3

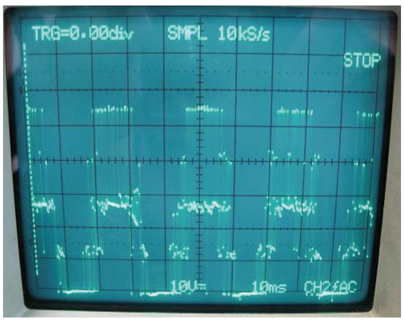

Fig. 16. Voltages applied to the three-phase motor with table1

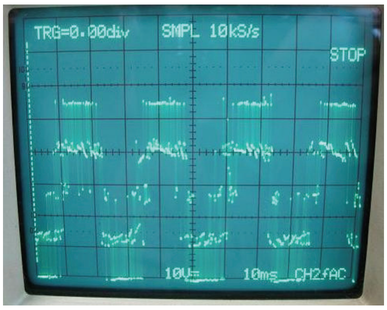

Fig. 17. Voltages applied to the three-phase motor with table 3

Appendix A

Induction motor specifications:

V=400V, Power=3 kW, p=2(4 pole), R_s*=1.873Ω,* R_r*=1.86Ω,* $L_{ls}=L_{lr}$*=7.54mH,* L_m*=210mH, J=0.01kg-m2.*

Direct torque control parameters:

Torque hysteresis bandwidth =0.2N.m,
Flux hysteresis bandwidth = 0.01Wb,
Initial and nominal machine flux=0.8Wb
Maximum switching frequency=5000Hz,
DTFC sampling=40uS

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