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PREDICTIVE CONTROL OF MULTI-LEVEL INVERTER FED THREE-PHASE INDUCTION MOTOR

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ABSTRACT

This paper presents a predictive control for multi-level inverter drive induction motor. Implementations of the control algorithm as well as, the multi-level inverter are presented. Also, the system is simulated and the speed, voltage, and current of an induction motor under normal and up-normal performance are obtained. The system is tested under a wide range of reference speed changes as well as different load conditions. Several simulation results using Matlab simulink software show the validity of the predictive control and multi level inverter scheme.

في هذا البحث يتم دراسة التحكم التنبؤي للمقاوم العاكس ذو المستويات المتعددة الذي يغذي محرك تأثيري ثلاثي الأوجه . يتم استعراض الأنواع المختلفة للتحكم التنبؤي و المقاوم العاكس ذو المستويات المتعددة. يتم دراسة الأداء للمحرك عند تغذيته من المقاوم العاكس ذو المستويات المتعددة ويتم تطبيق أحد طرق التحكم التنبؤي للنظام. يتم دراسة الأداء للنظام عند قيم مختلفة للسرعة و أيضا قيم مختلفة لعزم الحمل.

1. INTRODUCTION

For more than 20 years the field oriented control is state-of-the-art in industrial drive applications, though first ideas of predictive control have already been proposed [1]. After a "silent" period in the following decade, many fundamental predictive control systems such as Direct Torque Control (DTC) [2], Predictive Current Control [3] or Generalized Predictive Control (GPC) [4].

During the last decade a lot of publications on predictive control have been announced. Some of them are improvements or enhancements of control methods [5], whereas other authors have proposed new ideas, [6,7], but even these in most cases are further developments or combinations of fundamental predictive control algorithms.

All these papers show that behind the simple expression "predictive control" there is a very wide variety of different control methods. Having a closer look, it is clear, that in spite of their individual developments there are many similarities between the se algorithms. Since the multi-level inverter has got its importance in applications with induction motors more and more, this paper only deals with predictive control structures concerning multi-level inverter supplied induction motors. At first the general idea of predictive control will be explained. Afterwards the different classes of predictive control as well as different levels number of multi-level inverter will be illustrated. Finally the simulation results will be given for different step changes in speed change in motor load, and motor reference speed.

2. OVERVIEW ON PREDICTIVE CONTROL STRATEGIES

The predictive control algorithm can be grouped in three main groups based on the operating principle of these strategies. They are hysteresis based, trajectory based, and model-based strategies. These groups are not separated too much from each other and sometimes the cross coupling is rather clear.

2.1 Hysteresis Based Predictive Control [3]

In this group of the predictive control keeps the controlled system variables between the boundaries of a hysteresis area or space. The simplest form of such controller is known as hysteresis or bang-bang controllers. Although the bang-bang controllers are not considered as predictive controllers in literature, they clearly show their predictive behavior.

Using predictive current control, the switching instants are determined by suitable error boundaries Figure (1) which shows a circular boundary. The boundary location is controlled by the current reference vector (is□□. When the current vector (is) touches the boundary line, the next switching state vector is determined by prediction and optimization.

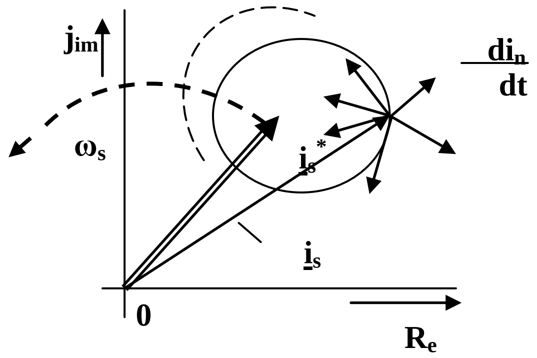

Fig. 1 Boundary circle and space vectors

Higher frequencies can be handled by employing the double prediction method: Well before the boundary is reached, the actual current trajectory is predicted in order to identify the time instant at which the boundary transition is likely to occur. The back EMF vector (in) at this time instant is predicted, then it is used for the optimal selection of the next switching state vector (ωs) using the earlier described procedure. The predictions are made at the respective time intervals required to reach the error boundary again.

It must be always ensured that the hysteresis controller reacts fast enough when the reference signal has gone outside of the hysteresis band. This is a major problem when the hysteresis controller is implemented in a digital processor, as the detection of the reference signal crossing the hysteresis band will be done only at the next sampling instant. It may happen that the error has grown to large value by this time. Hence, hysteresis based predictive control are more suitable when their realization is done using analogue operational amplifiers rather than micro-controllers.

2.2 Trajectory Based Predictive Control [2&9]

The trajectory based predictive controller is one of the predictive control group. The trajectory based control method works on the basic principle to force the system variables on pre-calculated trajectory. Once the system is on one these trajectory until a change is enforced from outside.

Some time later, control scheme similar to this scheme like the Direct Mean Torque Control (DMTC). Some more schemes, like Sliding Mode Control or Direct Torque Control (DTC) are the combination hysteresis based and trajectory based scheme, while the Direct Speed Control (DSPC) can be identified as a pure trajectory based control scheme even if some hysteresis based aspects with including in it. DSPC is explained further as an example of a trajectory based predictive control [2].

The switching states of inverter supplied drives are classified into the groups as “torque increasing “, “Slower torque-decreasing “, and “faster torque-decreasing “. For short time intervals, the inertia of the system as well as the derivatives of the load torque and the machine torque are assumed constant.

The behavior of the system leads to a set of parabolas as function in the speed error vs. acceleration area as shown in Fig. (2).The initial state of the system is assumed being ek/ak (error "e" at speed "a"). In this state, a “torque increasing” voltage vector has to be reduced by the inverter and therefore the switching state Sk is chosen. The state now travels along the dotted parabola until the point ek+1/ak+1 is reached. This is the intersection with another parabola for a “torque decreasing” switching state Sk+1, which will pass through the point “+Hy”. The intersection ek+1/ak+1 has been precalculated as the optimal switching instant to reach the desired state point “+Hy” as fast as possible. So, in ek+1/ak+1 the inverter is commutated into the switching state Sk+1. Then the state of the system travels along the new parabola until the point ek+2/ak+2 is reached. At this point the inverter is switched again into a “torque increasing” state, Sk+2. The corresponding trajectory passes the point “-Hy”. In steady state, the state moves along the path +Hy–ek+2/ak+2–-Hy– ek+3/ak+3–+Hy. Hence the speed error e is kept in the hysteresis band between -Hy and +Hy. This is the hysteresis aspect of this strategy mentioned above. Of course, the optimal steady-state point would be the point of origin. Since the switching frequency of the inverter is limited, the drive state cannot be fixed to that point. So the hysteresis band is defined to keep the switching frequency in an acceptable range.

Note: that the trajectory based predictive control is based on a very precise prediction of the future control system behavior. Foreknowledge of the drive system is used to precalculate the optimal switching states instead of trying to linearize the nonlinear parts of the system and then control them by PI Speed-controllers. The speed can be controlled directly without a cascade structure.

2.3. Model Based Predictive Control [4]

There is a kind of relationship between hysteresis based and trajectory based predictive control strategies. The model-based predictive control or model predictive control was introduced for industrial control application. model based predictive control (MBPC) is founded on totally different ideas. Both hysteresis as well as trajectory based predictive controllers use the actual system state to pre-calculate the value of the controlled variable for the next sampling step. The past history is not explicitly taken into consideration as it is exclusive in the actual system state.

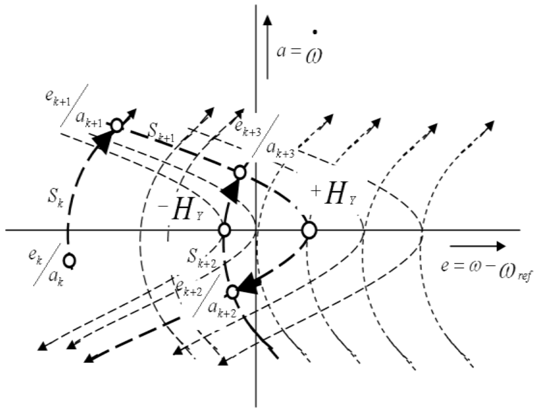

Fig. 2 DSPC: Trajectories in the speed error versus acceleration-state plane

Model-based Predictive Control takes into consideration the past, and optimizes the future switching state not only for the next cycle, but up to a specified future horizon or control horizon. Fig. (3) shows the typical structure of Model Based Predictive Control MBC. Its central part is a model, which is used to predict the future behavior of the system. The prediction has two main components.

- The free response, being the expected behavior of the output y(t+j) assuming zero future actuating values input = zero.
- The forced response, being the additional component of output due to the precalulated set of future actuating values u(t+j).

The main advantages of these controllers are:

- Multivariable structures are too easily represented able.
- The system restrictions (constraints) can be handled in systematic manner and be taken into consideration in the model.
- The phase displacement of the reference signal can be integrated without further expenditure.
- Automatic identification of model parameters is possible.

MBPC here is in contrast to trajectory or hysteresis based predictive control strategies, which are especially suited for nonlinear systems. Nevertheless some papers show that a good performance controlling inverter supplied drives can be achieved [8].

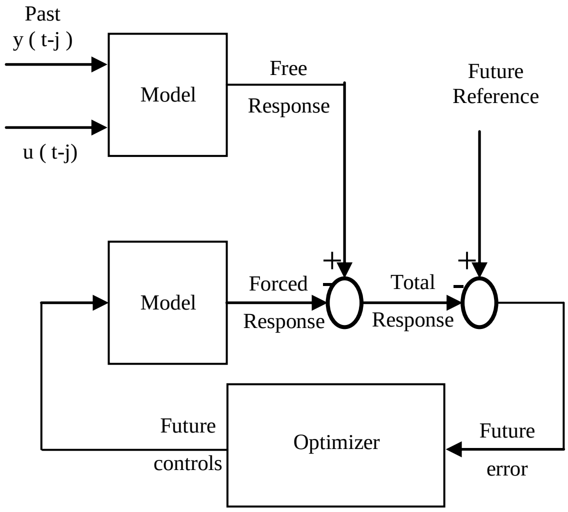

Fig. 3 typical structure of MBPC

3. MULTILEVEL INVERTER SYSTEMS

3.1. Diode-clamped multilevel inverter [2,10,&11]

The diode-clamped inverter provides multiple voltage levels through connection of the phases to a series bank of capacitors. According to the original invention the concept can be extended to any number of levels by increasing the number of capacitors. For example, three-levels inverter; there are two capacitors are connected across the dc bus resulting in one additional level.

Figure (4) shows a full-bridge single phase three-level diode-clamped converter. It should be noticed that each switch is turned on only once per half cycle and there are four complementary switch pairs in each phase. These pairs for one leg of the inverter are (S11,S13) (S12 , S14).

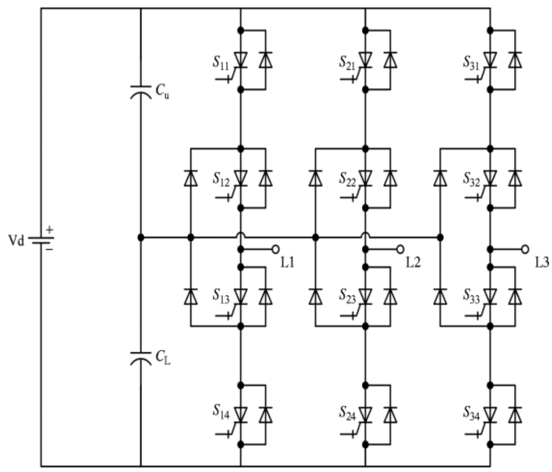

Fig. 4 Diode-clamped three-level multi-level inverter

The major advantages of the diode-clamped inverter can be summarized as follows:

- When the number of levels is high enough, the harmonic content is low enough to avoid the need for filters.
- Inverter efficiency is high because all devices are switched at the fundamental frequency.
- The control method is simple.

The major disadvantages of the diode –clamped inverter can be summarized as follows:

- Excessive clamping diodes are required when the number of levels is high..

3.2. Flying capacitor structure [12]

Another fundamental multilevel topology is the flying capacitor which involves series connection of capacitor clamped switching cells [12]. This topology has several unique and attractive features when compared to the diode-clamped inverter. One feature is that added clamping diodes are not needed.

Figure 5 shows the three-level flying capacitor inverter. The general concept of operation is that each flying capacitor is charged to one-half of the dc voltage and can be connected in series with the phase to add or subtract this voltage.

The major advantages of the flying-capacitors inverter can be summarized as follows:

- Large amounts of storage capacitors can provide capabilities during power outages.

Like the diode-clamp inverter with more levels, the harmonic content is low enough to avoid the need for filters.

The major disadvantages of the flying-capacitors inverter can be summarized as follows:

- An excessive number of storage capacitors is required when the number of levels is high. High level inverters are more difficult to package with bulky power capacitors and are more expensive too.
- The inverter control can be very complicated

3.3. Cascade H-bridge multilevel inverter [13,14,&16]

The series H-bridge inverter appeared in 1975 [13], but several recent patents have been obtained for this topology as well [14-16]. Since this topology consist of series power conversion cells, the voltage and power level may be easily scaled. An apparent disadvantage of this topology is the large number of isolated voltages required to supply each cell.

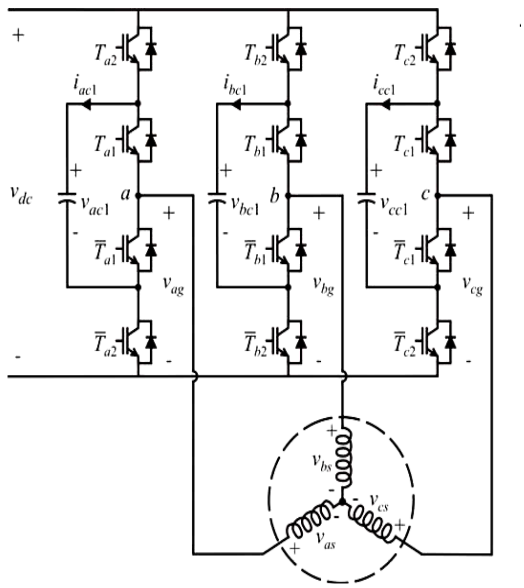

Fig. 5 Three-level flying capacitor inverter

Figure 6 shows the basic structure of a single-phase cascaded inverter with separate DC sources. Each SDCS is connected to an H-bridge inverter. The ac terminal voltages of different level inverter are connected in series. The phase out-put voltage is synthezed by the sum of four inverter output, VAB =V1 + V2 +V3.Using the top level as the example, turning on S1 and S4 yields V1 = + Vdc. Turning on S2 and S3 yields V1 = - Vdc. Turning off all switches yields V1 = 0. Similarly, the ac output voltage each level can be obtained in the same manner. if Ns is the number of dc sources, the output phase voltage level is m = Ns + 1.

The major advantages of the cascaded inverter can be summarized as follows:

- Compared with the diode-clamped and flying-capacitors inverters, it requires the least number of components to achieve the same number of voltage levels.
- Optimized circuit layout is possible because each level has the same structure and there are no extra clamping diodes or voltage-balancing capacitors.
- Soft-switching technique can be used to reduce switching losses and device stresses.

The major disadvantages of the cascaded inverter can be summarized as follows:

- It needs separate dc source for real power conversion, thereby limiting its applications

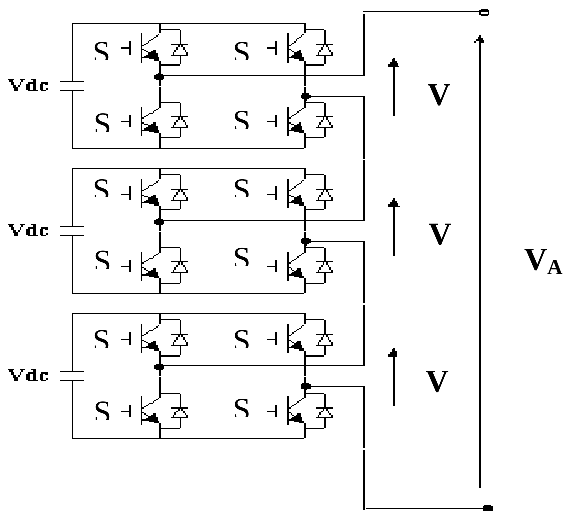

Fig. 6 Single-phase cascaded H-bridge inverter

4. NN-BASED PREDICTIVE CONTROLLER FOR MULTI-LEVEL INVERTER FEED AN INDUCTION MOTOR

This controller uses a neural network model to predict future plant responses to potential control signals. An optimization algorithm then computes the control signals that optimize future plant performance. The neural network plant model is trained offline, in batch form, using any of the training algorithms .The controller, however, requires a significant amount of online computation, because an optimization algorithm is performed at each sample time to compute the optimal control input.

4.1 Predictive Control law

The model predictive control method is based on the receding horizon technique [4]. The neural network model predicts the plant response over a specified time horizon.

The predictions are used by a numerical optimization program to determine the control signal that minimizes the following performance criterion over the specified horizon.

$$u = \sum_{j=N_1}^{N_2} (y_r(t+j) - y_m(t+j))^2 + P\sum_{j=1}^{N_u}(u'(t+j-1) - u'(t+j-2)) \qquad (1)$$

where N1, N2, and Nu are define the horizons over which the tracking error. The u' variable is the tentative control signal, yr is the desired response, and ym is the network model response. The block diagram showen in figure (7) illustrates the model predictive control process. The controller consists of the neural network plant model and the optimization block. The optimization block determines the values of u' that minimize J, and then the optimal u is input to the plant. The Neuron Network output (yhat,yhat1) are inputs to the optimizer which also, reference speed and feed back speed as another two inputs. The output of optimizer go to the input (u) of Neuron Network and control signal.

The first stage of model predictive control is to train a neural network to represent the forward dynamics of the plant. As shown in fig. (8) the prediction error between the plant output and the neural network output is used as the neural network training signal.

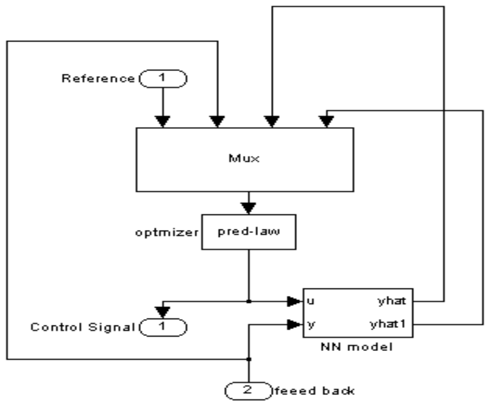

Fig. 7 the model predictive control process

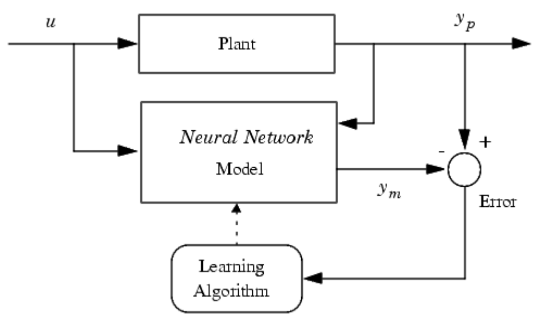

Fig. 8 training of NNP controller

The neural network plant model uses previous inputs and previous plant outputs to predict future values of the plant output. The structure of Neural Network is shown in fig. (9). The tansigmoint activation method will be fed the sum of the input patterns and connection weights, as previously discussed. This sum will be referred to as "u". The tansigmoint activation method simply returns the hyperbolic tangent of "u". The formula to calculate the hyperbolic tangent of the variable "u" is shown in equation (2).

$$\tanh(u) = \frac{e^{u} - e^{-u}}{e^{u} + e^{-u}} \qquad (2)$$

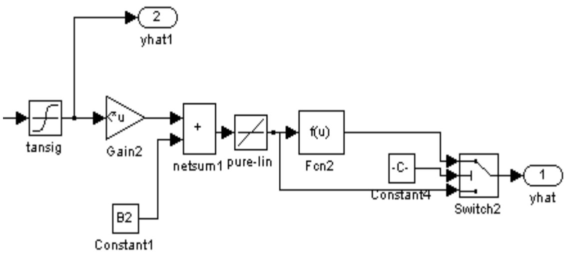

Fig. 9 The structure of Neural Network

4.2. Multi-level Inverter

H-Bridge Multilevel inverter is used. In this type, the phase output voltage is synthezed by the sum of the inverters output voltage.

The main law of this type is

$$VAB = V1 + V2 + V3 + \ldots\ldots.. + Vm \qquad (3)$$

Where m is the number of levels . For example where m=7, hence the number of levels is seven and Ns=6.

5. SIMULATION RESULTS

One of the model predictive controllers is used, with the system. The system runs with ANNP controller (Artificial Neural Network predictive controller).

The predictive controller is presented in the previous section I.V. The number of NN layers are three layers with eight Neuron in the hidden layers. the input layer has two Neuron, one for the predictor output (optimizer) and the other for the actual motor speed . The motor parameters are given in the appendix A. the motor modeling equations are taken in a stationary reference frame, which solved using matlabe simulink to obtain the motor response.

The H-Bridge multi-level inverter is used. In order to investigate the validity the computer program of multi-level inverter and also the effect of the levels of the multi-level inverter on the behavior of the motor. Two multi-level inverter topology are used. The first is three-level inverter and the second eleven-level. In the first time m in equation (3) will be taken equal three for three level inverter. In the second time m will be taken equal eleven for eleven-level inverter.

To train the NN, a collection of data is first obtained a ramp input command is applied to the system and, then, data is used to train NN off-line.

5.1. Simulation Results of Three-level inverter Fed Three-phase Induction motor

First three level inverter used with three phase induction motor Fig. (10) shows the simulation result waveforms of the speed output with reference speed at start is 1400 rpm decreased to 1000 rpm At starting load torque is 1 N.M, then load torque set up to 6N.M at time 2 Sec.

Figure (11) shows the simulation result waveforms of the inverter output voltage feeds an induction motor. The motor voltage wave form is shown in three-levels.

Figure (12) shows the simulation result waveforms of the motor stator current response with varying load torque and motor speed. At starting the load torque is applying 1 N.M., then the load torque step up to 6 N.M. at 2 sec. at last the load torque is 5.5 N.M at time 5 sec.

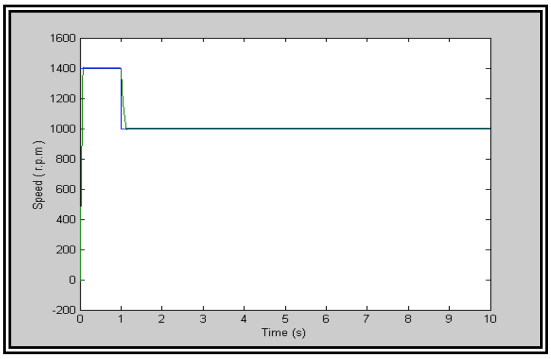

Fig. 10 Speed curve with reference speed of Three-level inverter drives induction motor

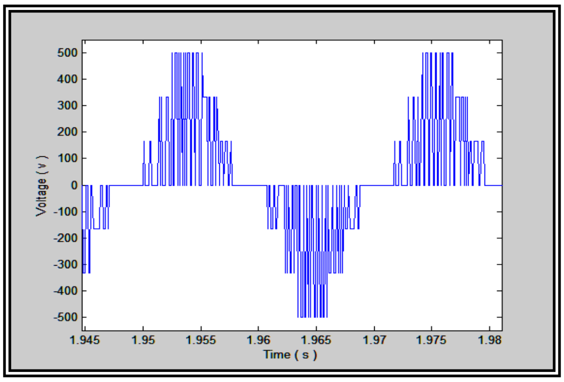

Fig. 11 Voltage wave-form of Three-level inverter drive induction motor

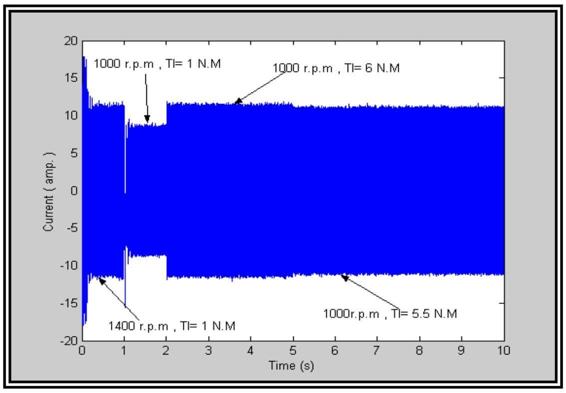

Fig. 12 Current wave form of Three-level inverter drive induction motor

Figure (13) shows the simulation result waveforms of the motor current wave form compared with reference current. The figure shows some of ripple in current wave.

Figure (14) shows the simulation result waveforms of the motor torque (Te) varying with time as varying of the load torque and speed. Load torque Tl equal to 1N.M at starting with speed 1400rpm, at time (1 sec) load torque still 1N.M but the speed slow down to 1000rpm, at time (2 sec) speed still 1000rpm but load torque raised up to 6N.M, at time (5 sec) speed still 1000rpm but load torque step down to 5.5 N.M. The motor torque shows ripple for all conditions

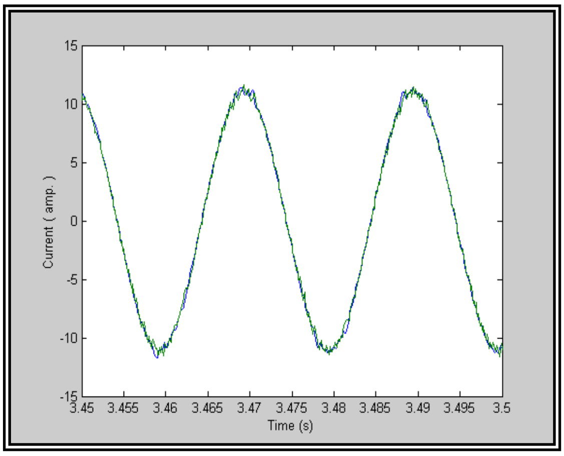

Fig. 13 Current wave form with reference current wave of Three-level inverter drive induction motor

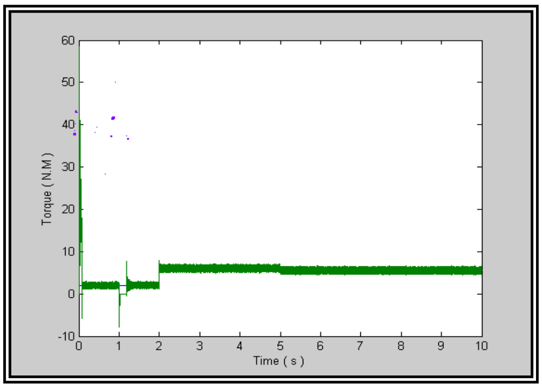

Fig. 14 Motor torque & load torque Three-level inverter drive induction motor

5. 2. Simulation Results of Eleven-level inverter Fed Three-phase Induction motor

AN eleven-level inverter is used to feed three phase induction motor. Figure (15) shows the simulation result waveforms of the motor speed with a step at time t=1sec. The reference at start is 1400 rpm. but the system take some of time to reach this value, then when the reference go to 1000 rpm. the motor speed step down to 1000 rpm with time. The system speed has no ripples and the response is so fast when it is compared with the previous three-level inverter system

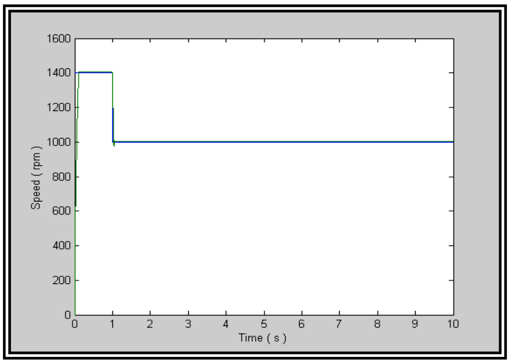

Fig. 15 Speed curve with reference speed of Eleven-level inverter drive induction motor

Figure (16) shows the simulation result waveforms of the inverter output voltage feeds an induction motor. An eleven-levels show the motor voltage wave form.

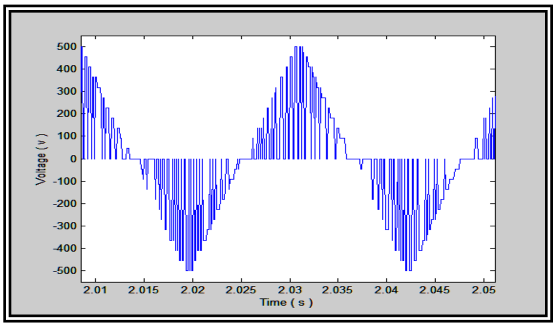

Fig. 16 Voltage wave form of Eleven-level inverter drive induction motor

The simulation result waveforms of the motor stator current response with varying load torque and motor speed is shown in fig. (17). At starting the load torque is applying 1 N.M., then the load torque step up to 6 N.M. at 2 sec. at last the load torque is 5.5 N.M at time 5 sec. Note that, the current value in this case decreases compared with fig.(12), because of decreasing in the total harmonic distortion (THD), and total power loss[17].

Figure (18) shows the simulation result waveforms of the motor current wave form compared with reference current. The figure shows almost free ripple in current wave, and the wave varying smoothly.

Figure (19) shows the simulation result waveforms of the motor torque (Te) varying with load torque (Tl) Load torque Tl equal to 1N.M at starting with speed 1000rpm, at time (1 sec) load torque still 1N.M but the speed slow down to 1000rpm, at time (

2 sec) speed still 1000rpm but load torque raised up to 6N.M, at time (5 sec) speed still 1000rpm but load torque step down to 5.5 N.M. The motor torque wave form can be obtained as very small ripple compared with the three-level inverter system. Also, fast response.

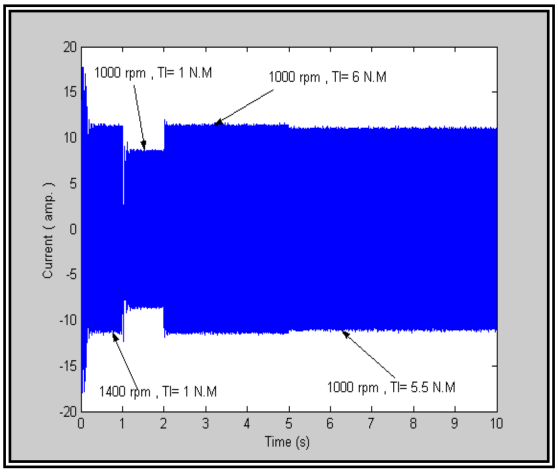

Fig. 17 Current wave form of Eleven-level inverter drive induction motor

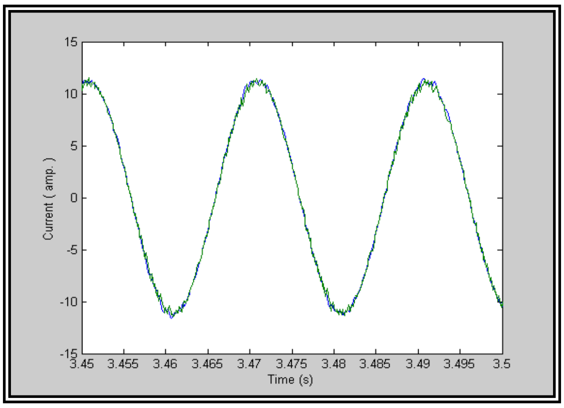

Fig. 18 Current wave form with reference current wave of Eleven-level inverter drive induction motor

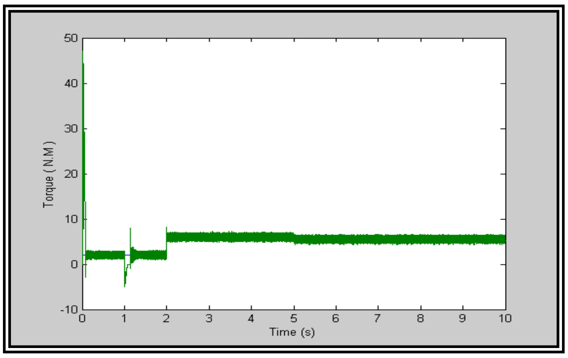

Fig. 19 Motor torque & load torque of Eleven-level inverter drive induction motor

6. CONCLUSION

Paper results show, that predictive control is a good alternative as speed control. Ripples in multi-level inverter are less than classic inverter. The system ripples can be reduced by increasing the number of levels. The harmonic content decreases as the number of levels increases and thus filtering requirements are reduced.

7. REFERENCE

[1] V. Emeljanov, Automatic control systems with variable structure (Automatische Regelsysteme mit veränderlicher Struktur),Munich, Vienna: R. Oldenbourg Verlag, 1969

[2] Takahashi, T. Noguchi, "A new quick response and high efficiency control strategy of an induction motor", in Conf. Record IEEE IAS Annual Meeting 1985, pp. 496-502.

[3] J. Holtz, S. Stadtfeld, "A predictive controller for the stator current vector of AC-machines fed from a switched voltage source", in Conf. Record IPEC Tokyo 1983, Vol. 2, pp. 1665-1675

[4] D. W. Clarke, C. Mohtadi, P. S. Tuffs, "Generalized Predictive Control. Part I. The basic algorithm", Automatica, Vol. 23, No. 2, pp. 137-148, 1987 and "Generalized Predictive Control. Part II. Extensions and interpretations", Automatica, Vol. 23, No. 2, pp. 149-160, 1987.

[5] Purcell, P. Acarnley, "Multilevel hysteresis comparator forms for direct torque control schemes", Electronic Letters, Vol. 34, No. 6, pp. 601-603, March 1998.

[6] E. Flach, R. Hoffmann, P. Mutschler, "Direct Mean Torque Control of an induction motor", in Conf. Record EPE'97, Vol. 3, pp. 672-677, Trondheim 1997.

[7] M. Trzynadlowski, M. M. Bech, F. Blaabjerg, J. K. Pedersen, "An integral space-vector PWM technique for DSP-controlled voltage-source-inverters", IEEE Transactions on Industry Applications, Vol. 35, No. 5, pp. 1091-1097, Sept./Oct. 1999.

[8] M. Tonnes, H. Rasmussen, "Robust self-tuning control of ACservo drive", in Conf. Record EPE'91, Vol. 3, pp. 48-49, Firenze 1991.

[9] M. Depenbrock, "Direct Self-Control (DSC) of an inverter-fed induction machine", IEEE Transactions on Power Electronics, Vol. 3, No. 4, pp. 420-429, Oct. 1988

[10] R.H. Baker, "High-Voltage Converter Circuit", U.S. Patent Number 4,203,151, May 1980.

[11] Nabae, I. Takahashi, and H. Akagi, "A New Neutral-Point Clamped PWM Inverter," Proceedings of the Industry Applications Society Conference, pages 761-766, September/October 1980.

[12] T.A. Meynard, H. Foch, "Multi-level Conversion: High Voltage Choppers and Voltage-source Inverters," Proceedings of the IEEE Power Electronics Specialist Conference, pages 397-403, 1992.

[13] R.H. Baker, "Electric Power Converter", U.S. Patent Number 3,867,643, February 1975.

[14] P.W. Hammond," Medium Voltage PWM Drive and Method", U.S. patent number 05,625,545, assigned to Halmar Robicon Group, April 1997.

[15] G.A. Duba, E.S. Thaxton, and J. Walter," Modular Static Power Converter Connected in a Multi-Level, Multi-Phase", Multi-Circuit Configuration, U.S. patent number 05,933,339, assigned to Electric Boat Corporation, August 1999.

[16] Y. Khersonsky, "Step Switched PWM Sine Generator", U.S. patent number 06,556,461, assigned to Power Paragon Incorporated, April 2003.

[17] Operation and design of Multilevel inverter Dr. Keitch Corzine, University of Missouri –Rolla , pages (3-11), December 2003

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The machine parameters are:-

Motor Power (P in KW) =30 KW
Motor Power (P in HP) =42.4 HP
Motor Rated Voltage (Vr in Volts = 500 Volts
Motor rated frequency (F in HZ) = 50 HZ
Number of Poles = 4 Poles
Rotor Resistance (Rr in Ω) = 4.87 Ω
Stator Resistance (Rs in Ω) = 7.25 Ω
Rotor Inductance (Lr in H) = 0.41 H
Stator Inductance (Lr in H) = 0.41 H
Mutual Inductance (lm in H) = 0.389 H
Motor Inertia (J in Kg.m2) = 0.01 Kg.m2
Motor Friction (D in N) = 0.01 N

The controller parameters:-

Cost horizone N2 = 10
Control horizone Nu = 3
Number of hidden layers = 8
Minimum system input = 12
Maximum system input = 40
Minimum system output = 800
Maximum system output = 1500