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Autotransformer Connected 24 Pulse AC-DC Converter for Vector Controlled Induction Motor Drive: A Matlab Simulation

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Abstract*: This paper deals with the steady state performance analysis of an autotransformer based 24- pulse ac-dc converter feeding variable frequency vector controlled squirrel cage induction motor drives at different mechanical load and constant reference speed. These variable frequency induction motor drives are generally operated in vector controlled mode due to their inherent advantages. There are three new elements which are added in the proposed model, first is three single phase autotransformers for phase shifting of 3-phase supply, second one is 24-pulse converter to eliminate the harmonics injected to the source and third one is interphase transformers to ensure the independent operation of the rectifier circuits. The feedback closed loop control system is used to control the speed of the induction motor, which has highly nonlinear torque-speed characteristics. This simulation is done to analyse the parameters of ac electric drive in terms of settling time, steady state error and overshoot. The simulation results show that the speed control performance reduces the steady state error and maximum overshoot under different load conditions.

Index Terms: Vector Controlled Induction Motor, PWM Inverter, Autotransformer, Interphase Transformers, FOC.

I. INTRODUCTION

The control of high performance asynchronous motor drives for general industry application and production automation has received wide spread research interest. Many schemes have been suggested for the control of induction motor drives, among which the field oriented control or vector control, is accepted as one of the most effective method.

In many applications where high performance variable speed operation is required, only dc motors were mostly used due to the ease speed control. Initially separately excited dc motors were particularly popular in applications where quick torque response was needed. However, dc motors have some generic drawbacks like, requirement of maintenance within an interval of time, unusable in explosive or corrosive environments due to sparking problem etc. There is difficulty in commutation problem at high currents and voltages, hence its use is limited to low power and low speed motors These problems can be overcome by using induction motors, which have a simple and rugged structure. The field and the armature currents respectively can control the flux and torque, independently in the case of dc motor. It is because of this inherent decoupling between the field flux and the armature current; one is able to achieve very good torque dynamic from dc machines.

Unlike a dc machine, there is no inherent decoupling between flux and torque producing components of the stator currents in the induction machine. Hence achieving good torque dynamics in ac machines is not easy. However, these days, for induction motors, vector control or field oriented control method is used for good torque dynamics [1].

With the appearance of the scene of power electronics, new focus was applied on both DC and AC machines for variable speed applications. The DC drive uses thyristor controlled rectifiers for providing high performance torque, speed and flux control. For variable speed induction motor drives, generally PWM techniques are used to generate polyphaser supply at a particular frequency [2]. The induction motor drives use the concept of keeping voltage/frequency (V/f) ratio constant so that the flux in the machine remains constant. Since the method to control V/f drives are simple but it will result in poor dynamic performance of torque and flux in the drive. As a result, for industrial applications where good torque, speed or position control are main important considerations, DC drives is preferred [3]. A 12-pulse AC-DC converter for induction apparatus which uses zigzag secondary winding with inter phase reactors and isolated and non-isolated AC-DC converters for improve power quality is described in [4], [5].

The fork connections are described by Paice in [7] which provides 12-pulse and 18-pulse ac to dc converter for drives applications. The 28-step current wave shape for harmonic reduction is described by Chen and Horng in [8]. A fork connection based 24- pulse AC-DC converter is also illustrated by Singh et al in [9], for the improvement in direct torque controlled induction motor drives. The principle of FOC is that it controls the flux and torque independently i.e. controlling of one parameter is not affecting the other parameter, which is similar as in the working of separately excited DC machine. The direct axis component of current is used to produced the flux which is obtained by transforming the stator current into rotating reference frame which is along the stator and rotor flux. The q-axis component of current is used to produce the torque.

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II. AUTOTRANSFORMER CONNECTED VECTOR CONTROLLED INDUCTION MOTOR

In variable speed drives, the supply is mainly an inverter which consist of power switches for generating sinusoidal waveforms of voltage and current whose magnitude and frequency are controllable [11]. In Vector control method there is an independent control of flux and torque and it is done by converting ac drive into equivalent dc drive. Due to the independent control of flux and torque the dynamic performance of drive improves. These developments positioned the ac drives. Vector control schemes are classified on the basis of how the field angle is acquired. If the field angle is considered by using terminal voltages and the current or hall sensors or flux sensing windings, then it is known as direct vector control. The field can also be obtained by using rotor position measurement and partial estimation with only machine parameters but not any other variables, such as voltages and currents; using this field angle, it leads to a class of control schemes which is known as indirect vector control [12], [13].

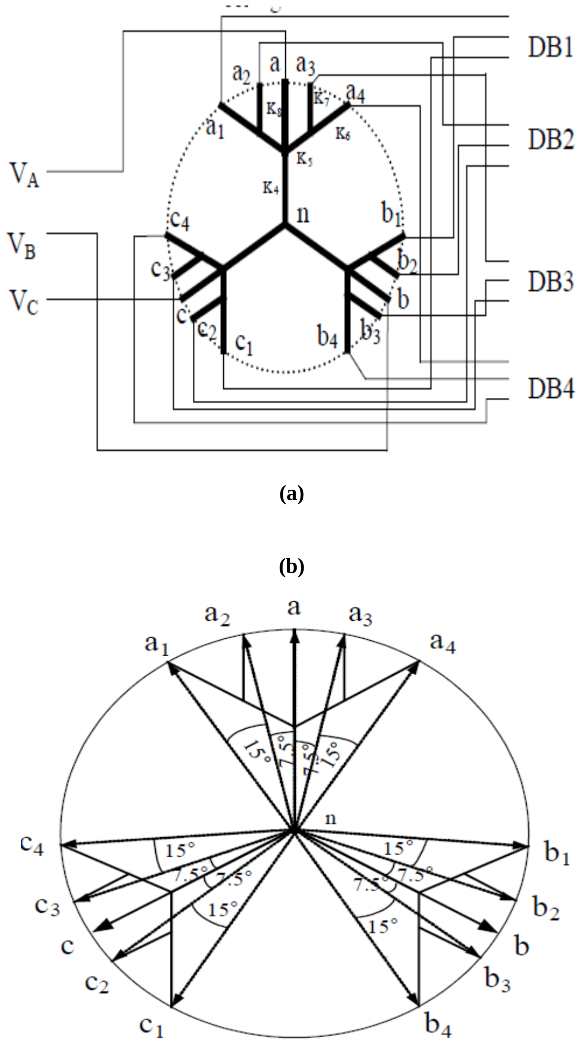
The concept of autotransformer-based n-pulse ac-dc converter functions on the concept of harmonic eliminating technique. The least order of harmonic is $nK \pm 1$, where K denotes a positive integer and n denotes the number of rectification pulses per cycle of the fundamental voltages. The elimination of harmonic content is explained in following manner. The harmonic reduction is possible if minimum phase difference is expressed as [5]

Phase Difference = 600 / Number of Six-Pulse Converters

For a phase-shifting transformer, the fundamental output current is transposed by an angle ϕ when it is allowed to pass through the transformer. The content of harmonics in current are shifted by an angle + ϕ or - ϕ and it depends on the required phase pattern. There are positive and negative harmonic components which shows a phase displacement as they pass through the transformer. The positive sequence consists of 7th,11th,17th harmonics while negative sequence consists of 5th,13th,19th harmonics and they show the phase opposition with each other. The sequence current shows a phase shift with fundamental current and it can be obtained from expression (ϕf-ϕh), where ϕf is angle of fundamental component of current and ϕh is angle of harmonic component of current. Now let us consider 5th harmonic current which is a negative sequence current, therefore the angle displacement between fundamental component and 5th harmonic is given by equation (ϕf-(-ϕf)/5) = 6ϕf/5, that is the negative sequence current component is phase displaced by 6ϕ with respect to fundamental component. Now for eliminating this harmonic current angle ϕ must be equal to 30º. Now for 7th harmonic current which is a positive sequence current, the angle displacement between fundamental component and 7th harmonic is given by equation (ϕf-ϕf//7) = 6ϕf/7, that is the positive sequence current component is phase displaced by 6ϕ with respect to fundamental component. Now for eliminating this harmonic current, angle ϕ must be equal to 30º. This result is for 12-pulse converter based rectifier [10]. Now for 24 pulse converter for eliminating the harmonic current component the angle is equal to 15º.

On the basis of connections, auto-transformers configurations are of following types:

a) Star Connected Autotransformer
b) Delta Connected Autotransformer
c) Polygon Connected Autotransformer
d) Delta-Polygon Connected Autotransformer
e) Hexagon Connected Autotransformer
f) T- Connected Autotransformer
g) Zigzag Autotransformer



(a)

(b)

Figure 1: (a) Winding arrangement of transformer for 24-pulse AC-DC converter having fork connected windings. (b) Phasor Representation

In this work, a fork autotransformer is used whose phasor diagram is depicted in Figure 1. The output of the four sets of the generated 3-phase voltages are shifted through an angle of 15°. The two of these output voltages are shifted through an angle of ±7.5° as compared to the input phase voltage while the other two sets are shifted by ±22.5°. Figure 1 shows the schematic diagram of the fork arrangement and its graphical representation shows the angular position of various phasors. The input phase voltage Va, acts as a basic component to determine the number of turns for autotransformer windings.

III. MATHEMATICAL PRELIMINARIES

Under this heading the different performance parameters of the three phase induction motors are calculated which is used for the MATLAB SIMULINK model in this paper:

(I) A 10Hp (7.5Kw), 415V, 50Hz,1440rpm, 4 pole, 3-phase squirrel-cage induction motor has following parameters referred to the stator:

Stator Resistance Rs = 1Ω,
Stator Inductance Ls = 0.77Ω,
Rotor Resistance Rr′ = 0.76Ω,
Rotor Inductance Lr′ = 0.77Ω,
Mutual Inductance Lm = 18.84Ω,
Moment of Inertia J = 0.1JK-gm^2,
Friction Coefficient = 0.009541 Nm-S
Number of Poles P = 4

Synchronous speed, $Ns = \frac{120f}{P}$ ……….(1)

$Ns = \frac{120 \times 50}{4}$

Ns = 1500 rpm

Rotor speed (Nr) = 1400 rpm

Slip (S) = $\frac{Ns-N}{Ns}$ ……….(2)

Slip (S) = $\frac{1500-1440}{1500}$

S=0.04 ………. (3)

Full Load Phase Current (I_p)

$I_p = \frac{V}{\sqrt{(Rs+\frac{Rr'}{s})^2+(Xs+Xr')^2}}$ ……….(4)

∴ $I_p = \frac{415/\sqrt{3}}{\sqrt{(1+.76/0.04)^2+(1.54)^2}}$

I_p =11.9446Amp ………..(5)

Full Load Line Current = I_p (since star connected Stator)

I_L = 11.9446 Amp ………. (6)

Now $\omega_{ms} = \frac{4\times\pi\times f}{P}$. ……….(7)

ω_{ms} = 157.1 rad/sec ………..(8)

Torque developed by the rotor $T_L = \frac{3Ip2\,\frac{Rr}{s}}{\omega ms}$ ……(9)

$= \frac{3\times(11.9446)^2\frac{(0.76)}{0.04}}{157.1}$

T_L = 51 N-m (Rated torque) ..……..(10)

Maximum line current during starting (I_{max})

$I_{max} = \frac{Vp}{\sqrt{(Rs+Rr')^2+(Xs+Xr')^2}}$ ……..(11)

$I_{max} = \frac{415/\sqrt{3}}{\sqrt{(1+0.76)^2+(0.77+0.77)^2}}$

I_{max} = 102.45 Amp

Starting Torque (T_{st}) = $\frac{(3\times(I_{max})^2\times R_r')}{\omega_{ms}}$ ……….(12)

$T_{st} = \frac{(3\times(102.45)^2\times 0.76)}{157.1}$

T_{st} = 152.33 Nm ………. (13)

$\frac{T_{st}}{T_L} = \frac{152.33}{51.7656}$ = 2.943 ……….(14)

$\frac{T_{st}}{T_L}$ =2.943

Maximum torque is given by-

$T_{max} = \frac{3}{2\times\omega_{ms}}[\frac{(V_L/\sqrt{3})^2}{R_S \pm \sqrt{R_S{}^2+(X_S+X'_r)^2}}]$ ……….(15)

$T_{max} = \frac{3}{2\times157.1}[\frac{(415/\sqrt{3})^2}{1.0+\sqrt{(1)^2+(0.77+0.77)^2}}]$

T_{max} = 193.27 Nm ………. (16)

$\frac{T_{max}}{T_L} = \frac{193.27}{51.765}$ = 3.7336 ..……….(17)

$\frac{T_{max}}{T_L}$ = 3.7336 ………. (18)

IV. SIMULINK MODELLING: 24 PULSE AUTOTRANSFORMER CONNECTED VECTOR CONTROLLED INDUCTION MOTOR

The MATLAB/SIMULINK model is shown in figure1. This model is made on MATLAB R2011. This model is common to all of the result. In the proposed model there is 3-phase source which supply the power to the three single phase auto-transformer which are interconnected with each other and formed a 3-phase auto-transformer, the output of this 3-phase auto-transformer has 12 terminals which are the inputs of the four 6-pulse diode rectifiers (formed 24-pulse converter) and outputs of these rectifiers are connected to interphase transformers (IPTs). The outputs of these IPTs are connected to a LC-filter after that a PWM inverter is connected. The Induction motor is fed by a current controlled PWM inverter which is designed by using a universal bridge block. The simulation parameters of the motor and inverter circuit are as follows:

- AC supply: 3-ø, 415V, 50Hz supply
- Three-Phase auto-transformer :25kV/415V,2.21kVA
- Inter phase transformer (IPT): 0.66kVA
- Universal Power Converter: Diode bridge
- PWM IGBT Inverter.
- DC link capacitor of 2200 μF, Inductance =.002H.
- Squirrel Cage Induction Motor: 10HP – 415 V, 50 Hz,1440 rpm.

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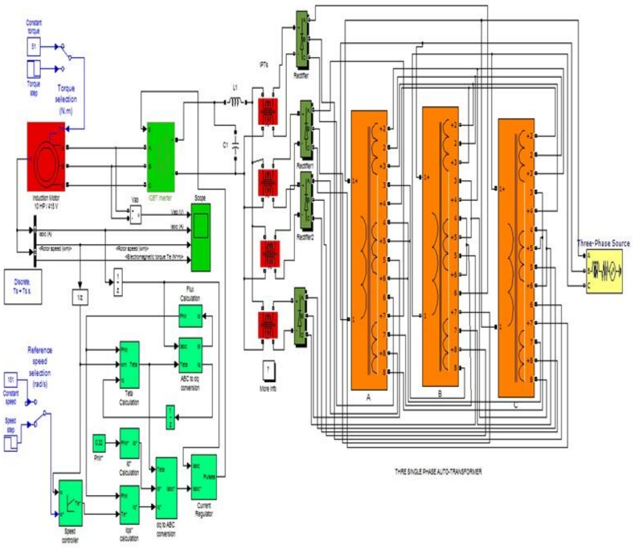

Figure 2: MATLAB/SIMULINK model of 24-pulse vector controlled induction motor

A. Case Study I: No Load Torque with Kp=7 AND Ki=.1

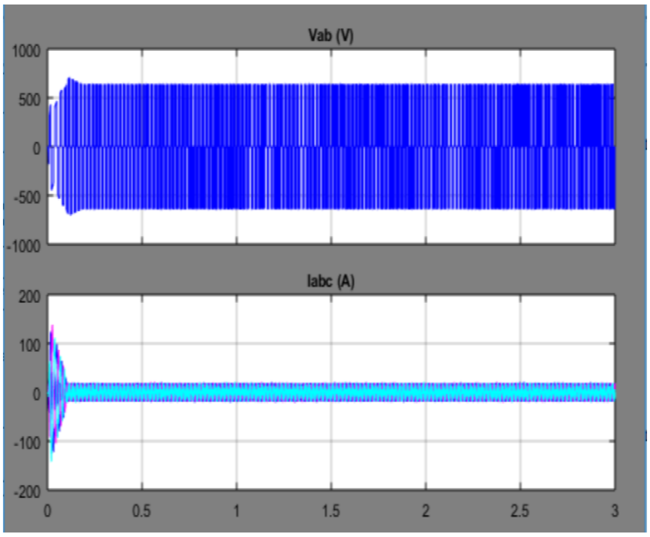

Figure 3: Response of Inverter Output Voltage (Vab) and Stator Current (Iabc).

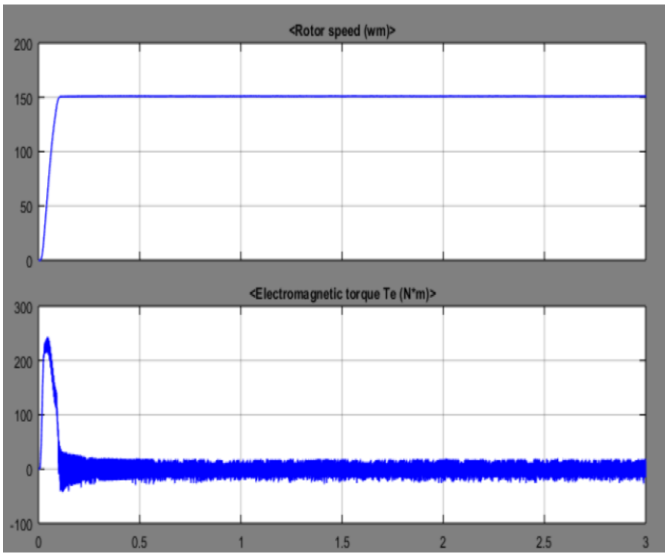

Figure 4: Response of Rotor Speed and Electromagnetic Torque at No Load Condition.

Table I: Performance Specifications for No Load

SPECIFICATIONS	PERFORMANCE VALUES FOR NO LOAD
Settling Time t_s(sec.)	0.101
Maximum Overshoot M_p (rad/sec.)	0.1
Steady State Value (rad/sec.)	150.93 to 151.00
Steady State Error (rad/sec.)	0.07

Under this no load condition, the settling time is 0.101 sec and steady state error is 0.07. The maximum overshoot is much reduced and it is 0.07.

B. Case Study II: Rated Load Torque of 51Nm with Kp=7 AND Ki=.1

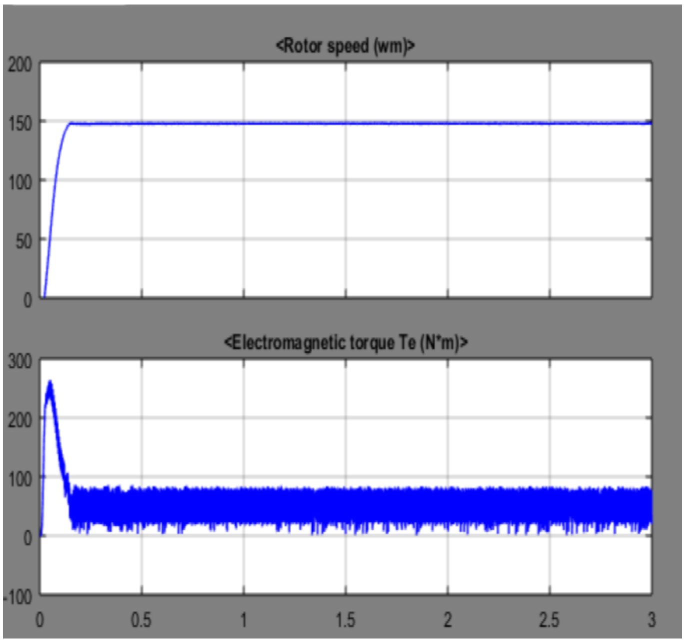

Figure 5: Response of Rotor Speed and Electromagnetic Torque at Rated Load Condition.

Table II: Performance Specifications for Rated Loading

SPECIFICATIONS	PERFORMANCE VALUES FOR RATED LOAD
Settling Time t_s(sec.)	0.149
Maximum Overshoot M_p (rad/sec.)	0.2
Steady State Value (rad/sec.)	148.08 to 147.94
Steady State Error (rad/sec.)	0.14

Under this rated-load condition the settling time is 0.149 and steady state error is 0.14 and maximum overshoot is 0.20.

C. Case Study III: Under Load Torque (45 Nm) with Kp=7 AND Ki=.1

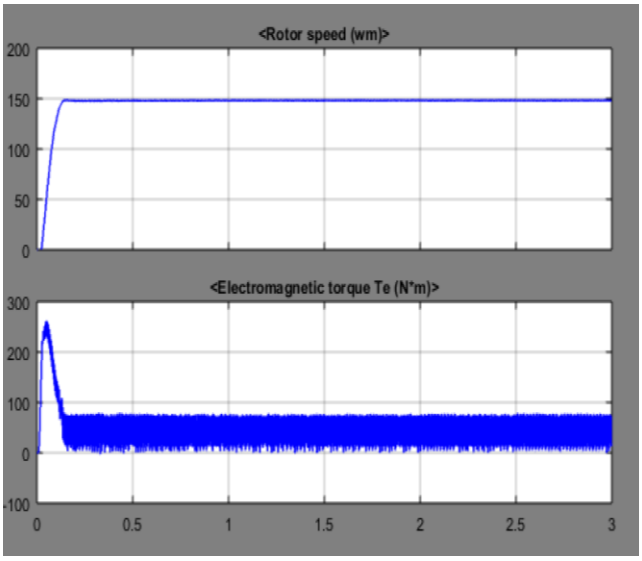

Figure 6: Response of Rotor Speed and Electromagnetic Torque at Under Load Condition.

Table III: Performance Specifications for Under Load

SPECIFICATIONS	PERFORMANCE VALUES FOR UNDERLOAD
Settling Time t_s(sec.)	0.127
Maximum Overshoot M_p (rad/sec.)	0.134
Steady State Value (rad/sec.)	147.98 to 148.11
Steady State Error (rad/sec.)	0.13

Under this condition the settling time and steady state error is improved and maximum overshoot are reduced to a great extent.

D. Case Study IV: Over Load Torque (60 Nm) with Kp=7 AND Ki=.1

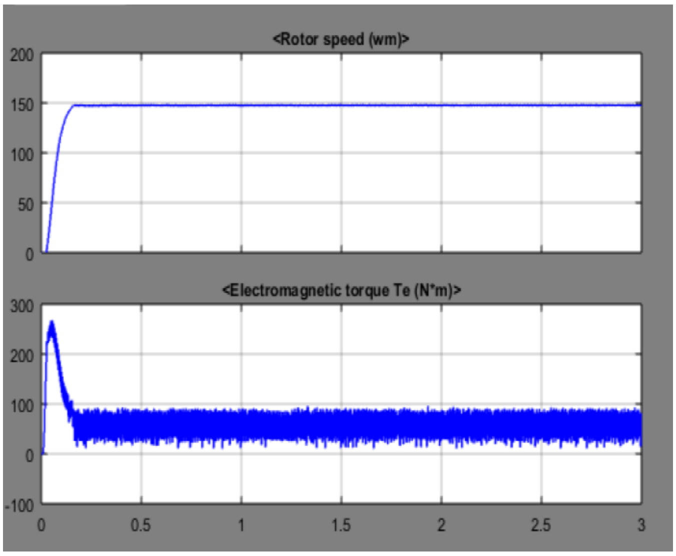

Figure 7: Response of Rotor Speed and Electromagnetic Torque at Overload Load Condition.

Table IV: Performance Specifications for Over Loading

SPECIFICATIONS	PERFORMANCE VALUES FOR OVER LOAD
Settling Time t_s(sec.)	0.157
Maximum Overshoot M_p (rad/sec.)	0.21
Steady State Value (rad/sec.)	147.72 to 147.4
Steady State Error (rad/sec.)	0.32

Table IV is for overloading condition and in this case, the steady state error and other parameters are increased drastically. The settling time is 0.157 sec, the steady state error is reached to 0.32 and maximum overshoot is increased to 0.21.

V. SIMULATION RESULTS ANALYSIS

The result analysis and discussion for different types of load torque of the 10 HP induction motor are as follows:

Table V: Result Comparison of Drive for different loading Conditions

Cases	Settling time (ts in sec.)	Maximum % Overshoot (%Mp)	Steady state error (Ess)	Kp	Ki	Reference Load / Speed
Case 1	0.101	0.1	0.07	7	0.1	No Load/Constant
Case 2	0.149	0.2	0.14	7	0.1	Rated Load/Constant
Case 3	0.127	0.134	0.13	7	0.1	Under Load/Constant
Case 4	0.157	0.21	0.32	7	0.1	Over Load/Constant

From table V, it is observed that excellent performance of the drive is obtained at underload condition. Overshoot and settling time is reduced to a great extent during no-load condition. The result obtained under different loading conditions shows that case 3 shows good response as compared to other cases. Case 3 for under load condition have much less settling time, less overshoot and less steady state error when compared to other loaded conditions. Hence better efficiency and good speed regulation is obtained for under-load condition.

VI. CONCLUSIONS

The 24-pulse transformer minimizes the harmonics which are injected to the source and this improves the power quality, which implies that the losses are decreased and the efficiency of the system increases. For different loading conditions; the settling time in case 3 (under loading case) is 0.127 sec which is the minimum settling time on loading cases except no-load condition whose settling time is 0.101 sec. It is concluded that when the drive is tested for different loading conditions, then under-load condition indicates better performance values for constant reference speed.

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