CONTRIBUTION TO THE DIRECT CONTROL OF TORQUE APPLICATION UTILISING DOUBLE STAR INDUCTION MOTOR TO MEET WITH RESCUE MODES REQUIREMENTS

M.HECHELEF AEK.MEROUFEL
Testing and Commissioning manager at ''Construcciones y Auxiliar de Ferrocarriles'' CAF.SA
hmed14@yahoo.fr

Abstract: *During the recent years, one of the major topics in railway traction system research is the degraded operating mode. This paper deals with application of a new proposal known as Contribution to the direct control of torque utilising dual starts induction motor to meet with rescue mode requirements, The research discussed consists of how to manage the rescue mode of applications using the AC motor for traction system when part of the winding is defective or one semiconductor switch in the inverter is short-circuited by using a backup software and switching mechanism. The proposed solution uses the conventional direct control of torque with double star induction motor with a series of modifications.*

Keywords: *DTC, degraded mode, inverter, traction system. DSIM*

1. Introduction

This paper relates to providing a traction system to public transport vehicles and concerns more particularly when the traction system face some difficulties to meet with the constraints of the transport public where the objective is avoiding stopping on mainline in a failure mode, Which raises the following question how can we improve the existing traction system design and accommodate the degraded mode operation in these extremes conditions as desert, tunnels..?

Nowadays the degraded operational mode of the traction system when used in railway system as trains, or trams), is one solution since it allows to operators to cover the rescue of failures cases.

Our proposal in this paper to use double start induction motor which provide the end user with another option to produce a positive torque on the output shaft by supplying the two-star windings in normal mode or only one star winding in the degraded mode when there are problems in part of the winding or in the inverter switches, by using selectively a backup software by the train control unit.

2. Railway traction system

Since 1898 when the world's first AC locomotive has-been manufactured the AC machine played a significant role in the development of the traction system performances, it is the main component in the railway traction system.

Figure (2.1) shows traction chain when used in railway application.

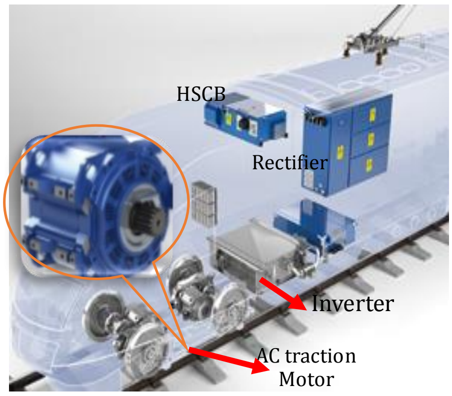


Fig.2.1. AC traction system for a railway application

Usually In the railway electrical traction system we can find the following main devices:

-Pantograph to link the AC/DC electrical network to the train;

-HSCB: High-speed circuit barker;

-Rectifier & inverter (DC/AC);
-Traction motor.

This paper will discuss and analyse the factors to explore and find more alternatives in order to improve the design of the traction system for these Railway locomotive application to be used for rescue mode in normal and extreme environments.

This is based upon the experience in rolling stock maintenance in more than one country that are subject to and characterized by harsh climatic conditions. We propose to use double start induction motor with two inverter instead of one star induction machine with one converter. In this paper we will demonstrate with more details our proposal to solve the problem descripted above.

3. The proposal architecture

The figure (3.1) represents the architecturale proposal when we use double start induction motor powered by two inverters.

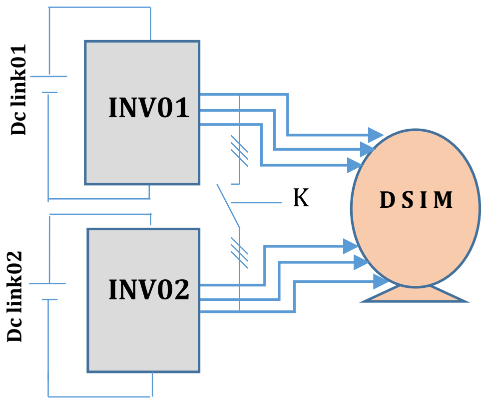


Fig.3.1 .DSIM powered by two inverters

The traction system continue providing a positive torque even when one converter broken down or part of the winding of one star is defective. We include in the solution also the option of switching between the two converters by using (K) contactor base on the following [T] formula:

$T = (\sum_1^N C_n + \prod_1^N C_n) * (\sum_1^N S_n + \prod_1^N S_n)$

With:

Cn: number of inverters (Two traction inverter modules (INV01 and INV02) in order to supply the power to the traction motors)

Sn: number of the start windings

In our case which is a double star induction motor N=2.

3.1.The double start induction machine

When there is a need to increase system performance, particularly when facing limits on the power ratings of power supplies and semiconductors level constraints, the dual start induction motor shall motivate the use of phase number other than three, new motor design criteria and the use of harmonic current and flux components. In a multi-phase system, it shall be assumed a system that comprises more than the conventional three phases; the motor output power can be divided into two or more solid-state inverters.

The dual star asynchronous motor. Whose figure (3.2) expresses the windings of the double star induction motor and the offset angle between the two stars windings.

- A1,B1,C1: stator winding01.
- A2,B2,C2: stator winding02
- Ar, Br, Cr: rotor winding
- α: offset angle between two stators.
- θ: offset angle between the rotating part and the stators

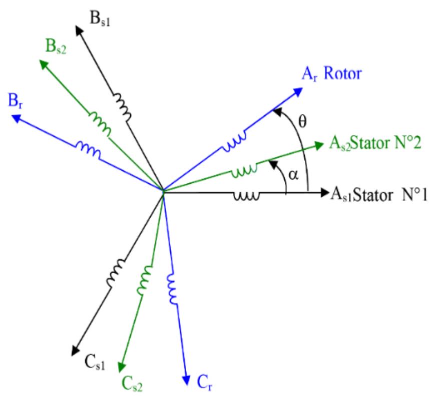


Fig.3.2. winding and offset angles

3.1.1. Modelling of the double star induction motor

The mathematical model of the machine is can be expressed by the following set of electrical/mechanical equations

The first star:

$$[\mathrm{Vabc}, s_1] = [\mathrm{Rs}_1][\mathrm{abc}, s_1] + \frac{d[\varphi \mathrm{abc}, s_1]}{dt} \qquad (3.1)$$

For the rotating part:

$$[\mathrm{Vabc}, r] = [\mathrm{Rr}][\mathrm{abc}, r] + \frac{d[\varphi \mathrm{abc}, r]}{dt} \qquad (3.2)$$

The mechanical equation:

$$J\frac{d\Omega}{dt} = Tem - Tr - kf\Omega \qquad (3.3)$$

Where J is the moment inertia of the rotating parts, K_f is the friction coefficient related to the engine bearings, and T_{em} represents the torque loading [4].

The electrical state variables in "αβ" system are the electrical flux, and the input variable in the system "αβ" expressed by the vector [U] then the state space representation of the machine can be modeled and expressed in the form:

$$\dot{X} = \frac{dX}{dt} = AX + BU \qquad (3.4)$$

With X: state variables

$$X = [\varphi_{salph1} \quad \varphi_{Sbeta1} \quad \varphi_{Salph2} \quad \varphi_{Sbita2} \quad \varphi_{ralpha} \quad \varphi_{rbita}]$$

A: system evolution matrix

$$A = \begin{bmatrix} A11 & A12 & A13 & A14 & A15 & A16 \\ A21 & A22 & A23 & A24 & A25 & A26 \\ A31 & A32 & A33 & A34 & A35 & A36 \\ A41 & A42 & A43 & A44 & A45 & A46 \\ A51 & A52 & A53 & A54 & A55 & A56 \\ A61 & A62 & A63 & A64 & A65 & A66 \end{bmatrix} \qquad (3.5)$$

B: control Vector

$$B = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (3.6)$$

U: input vector it is represented by the tension vector

$$U = [V_{Salph1} \quad V_{Sbeta1} \quad V_{Sa\,lph2} \quad V_{Sabeta2}\ ] \qquad (3.7)$$

3.2. Direct control of torque

In order control the inverter switches we propose to use the direct control of torque technique, it is particularly appropriate for solving the problems of dynamic performance of a three-phase AC drive in railway traction systems because of their short response times. Nowadays, the Direct Torque Control method (DTC) is already widely applied, especially in the field of electrical traction. DTC, which is a true competitor of Field Oriented Control, is characterised by its fast torque response and its simple implementation. Furthermore, the algorithm takes care of a low switching frequency, which is still desired in high power applications exactly when the application require an important torque stable with low speed. As it showed in the figure (3.3).

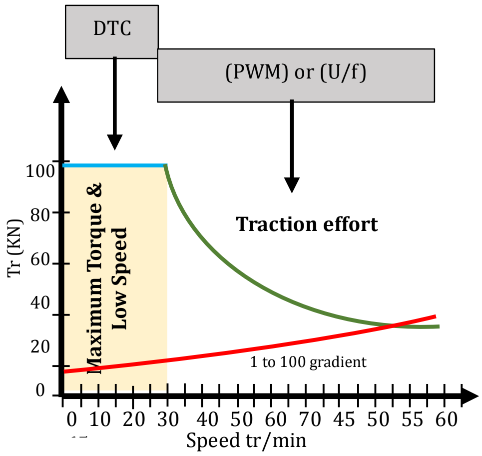


Fig.3.3. traction effort in railway system application

3.2.1. Principle of direct control of torque

If we consider the first start and the equations used for vectorial representation of the stator characteristics of the machine, which binds to the stator reference.

$$\begin{cases} \overline{V_{salph1}} = R_{s1}\overline{I_{salpah1}} + \dfrac{d\overline{\emptyset_{salph1}}}{dt} \\ \overline{V_r} = \overline{0} = R_r\overline{I_r} + \dfrac{d\overline{\emptyset_r}}{dt} - jw\overline{\emptyset_r} \end{cases} \qquad (3.2.1)$$

From the electrical flux expression, the rotor current can be expressed as:

$$\overline{I_r} = \frac{1}{\sigma}\left(\frac{\overline{\emptyset_r}}{L_r} - \frac{L_m}{L_r L_s}\overline{\emptyset_{salph1}}\right) \qquad (3.2.2)$$

With the dispersion coefficient

$$\sigma = 1 - \frac{{L_m}^2}{L_s L_r}$$

The expressions (3.1) become

$$\begin{cases} \overline{V_{salph1}} = R_{s1}\overline{I_{salpah1}} + \dfrac{d\overline{\emptyset_{salph1}}}{dt} \\ \dfrac{d\overline{\emptyset_r}}{dt} + \left(\dfrac{1}{\sigma\tau_\tau} - jw\right)\overline{\emptyset_r} = \dfrac{L_m}{L_s}\dfrac{1}{\sigma\tau_\tau}\overline{\emptyset_{salph1}} \end{cases} \qquad (3.2.3)$$

Relation (3.2.3) shows that:

It is possible to control the vector $\emptyset_{salph1}$ from the vector $\overrightarrow{Vs}$ to the voltage drop near |RsIs|

The vector follow the variation of $\emptyset_{salph1}$ with as a time term constant, the rotor act as a filter (time constant $\sigma\tau_\tau$) between the flux $\emptyset_{salph1}$ and $\emptyset_r$.

Moreover, $\emptyset_r$reach in the steady state value;

$$\overline{\emptyset_r} = \frac{L_m}{L_s}\frac{\overline{\emptyset_{salph1}}}{1 + jwr\sigma\tau} \qquad (3.2.4)$$

By putting $\gamma = \left(\overline{\varphi_s}\,\overline{\varphi_r}\right)$the representation of torque, expression becomes.

$$\Gamma_{elm} = p\frac{L_m}{\sigma L_r L_s}\phi_{salpha1} * \phi_r \sin\gamma \qquad (3.2.5)$$

Relation (3.2.5) shows that

*It is possible to control the flux vector $\emptyset_{salph1}$ by acting on the voltage vector $\overrightarrow{Vs}$ as we can consider the voltage drop |RsIs| so small when comparing it with voltage vector value $|\overrightarrow{Vs}|$ in the period [0 T_e]

*The rotor act as a filter with (time constant $\sigma\tau_\tau$) between the flux $\emptyset_{salph1}$ and $\emptyset_r$. Moreover, $\emptyset_r$ reach his steady state value as follow:

$$\overline{\emptyset_r} = \frac{L_m}{L_s}\frac{\overline{\emptyset_{salph1}}}{1 + jwr\sigma\tau} \qquad (3.2.6)$$

By putting: $\gamma = (\overline{\emptyset_s}\,\overline{\emptyset_r})$: The representation of torque expression becomes:

$$\Gamma_{elm} = p\frac{L_m}{\sigma L_r L_s}\phi_{salpha1} * \phi_r \sin(\gamma) \qquad (3.2.7)$$

The expression (3.2.7) shows that:

*The torques value is dependents of the amplitude of two vectors $\overrightarrow{\phi_{salpha1}}$ and $\overrightarrow{\phi_r}$ with relative position.

* If we manage well the control of the flux vector $\overrightarrow{\phi_{salpha1}}$ by acting on the module and the voltage vector position, therefore it is possible to control the amplitude and the relative position of $\overrightarrow{\phi_r}$,

*This is possible only if the control period Te of the voltage $\overrightarrow{Vs}$ satisfies this condition.

$T_e \ll \sigma\tau_\tau$

III.2.2.Setting of the stator flux

The expression of the stator flux with the reference associated to the stator is obtained from the following equation

$$\emptyset_{sj} = \int_0^t (Vsj + RsjIsj)dt \quad j=1,2 \qquad (3.2.8)$$

Using interval [0, Te] corresponding to a sampling period (Te), the switch state (Sa Sb Sc) are fixed, and if we consider the value, |RsIs| to be negligible when compared with voltage $|\overrightarrow{Vs}|$ we can assume:

$$\emptyset sj(t) \approx \emptyset_{S0} + V_{Sj}T_E \quad j=1,2 \qquad (3.2.9)$$

With φ_{S0} being the flux vector at Time t=0

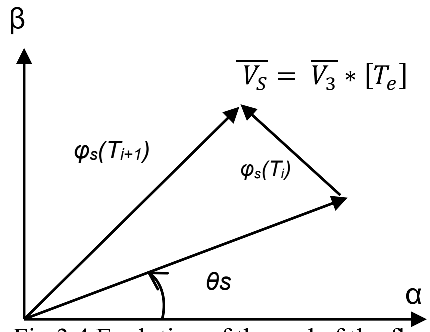


Fig.3.4.Evolution of the end of the flux i.e. ($\overline{V_S}=\overline{V_3}$)

This relation shows that if we apply a non-zero voltage vector, the end of the stator flux vector moves on a straight line whose direction the applied voltage gives vector. Figure (3.4) illustrates this principle, taking as example the voltage vector (V3).

3.2.3. Control of the electromagnetic torque

In a steady state, we can assume for simplicity that the stator flux vector $\overrightarrow{\emptyset_s}$ rotates with a constant amplitude $|\emptyset_{s0}|$, and with an average speed W_{s0s} . It can also be assumed that the rotor flux vector maintains constant amplitude and rotates with same pulsation ω_{s0} as the vector $\overrightarrow{\emptyset_s}$. We put at t_0 ;

$$\begin{cases}\overline{\emptyset_s} = \emptyset_{so}e^{j\theta_{so}} \\ \overline{\emptyset_r} = \emptyset_{ro}e^{j\theta_{ro}}\end{cases} \qquad (3.3.1)$$

Based on the flux, current and electromagnetic torque mentioned above, the electromagnetic torque equation could be transformed to a sinusoidal form as follows:

$$\Gamma_{elm} = P\frac{L_m}{\sigma L_s L_r}\emptyset_{so}\emptyset_{ro}\sin(\gamma_0) \qquad (3.3.2)$$

Where γ_0 is the angle between the stator and the flux rotor vector.

If we Apply at t_0 an adequate voltage vector $\overrightarrow{V_s}$, and we impose along with a pulse ΔW_{s1} as rotational speed and Immediately after t_0, we can note that there is a changes on stator and rotor flux:

$$\begin{cases}\emptyset_s = \emptyset_{so}e^{j(\theta_{so}+\Delta\theta_s)} \\ \emptyset_r = (\emptyset_{so} + \Delta\emptyset_r)e^{j(\theta_{ro}+\Delta\theta_r)}\end{cases} \qquad (3.3.3)$$

With: $\Delta\theta_s = (w_{so} + \Delta w_{s1})(t - t_o)$

From the flux rotor (3.2.3) expression, we can deduce the value derivative of this quantity:

$$\frac{d\emptyset_r}{dt} = \frac{d\Delta\emptyset_r}{dt} e^{j\theta_r} + j\frac{d\Delta\theta_r}{dt} \emptyset_{r0} \qquad (3.3.4)$$

With: $\Delta\theta_r = \Delta\theta_s - \Delta\gamma$

With the same way, we can prove that: the Rotor flux vector keep turning with the same pulsation ΔW_{s0} and maintaining the same amplitude $\overline{\emptyset_{r0}}$ [2]. So after t_0 the torque equation can be expressed as:

$$\Gamma_{elm} = P\frac{L_m}{\sigma L_s L_r} \emptyset_{so}\emptyset_{so} \sin(\gamma_0 + \Delta\gamma) \qquad (3.3.5)$$

3.2.4. Selection of the voltage vector

Basically The DTC idea consist in controlling directly the opening or closing the inverter switches from the computed values of stator flux and torque. The state's changes of the switches are related to the evolution of the electromagnetic state of the motor.

The position of the flux vector is determined from its components $\emptyset_{salph}$ and $\emptyset_{sbeta}$.Both the flux and the torque control are ensured by selecting one of those four non-zero vectors or one of the two null vectors:

•If Vi+1 is selected, the flux amplitude will increase and the torque will increase.

•If Vi-1 is selected, the flux amplitude will decrease and the torque will increase.

•If Vi+2 is selected, the flux amplitude will increase and the torque will decrease.

•If Vi-2 is selected, the flux amplitude will decrease and the Torque will decrease.

•If V0 or V7 is selected, the vector flux will maintain its value and the torque will decrease if the speed is positive and will increase if the speed is negative.

4. The proposal solution

Within the paper, a small power dual start induction motor was used for the simulation when a series of tests shows the effectiveness of the proposed solution. The figure (4.1) present the proposal idea which is: direct control of torque application use the DSIM with a switching mechanism (K), motor winding status detection system and inverter switches detection system.

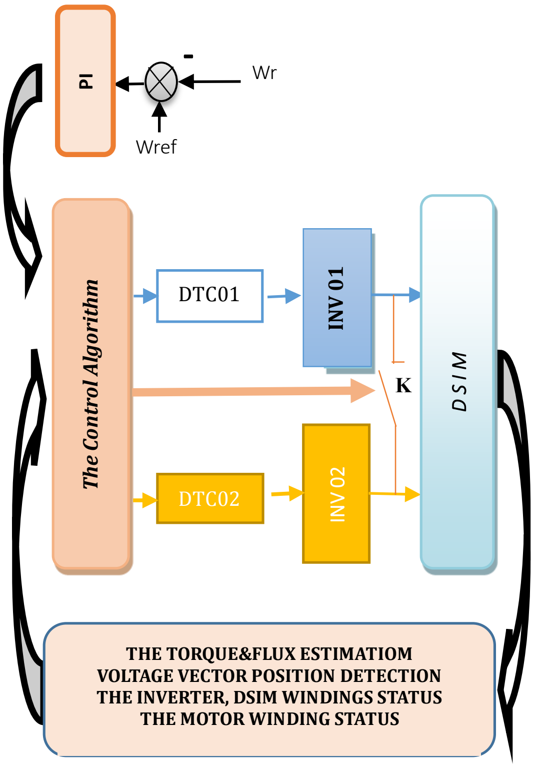


Fig.4.1 Proposal. Block diagram of the direct control of torque Application on the DSIM

5. The degraded mode

Depend to the status of the inverts and also the motor windings the controller switch to the adequate mode. If **one switch inverter** or **part of the motor winding** is defective the system switch directly to the degraded mode. In this paper we will study by simulation and demonstrate the effectiveness of our proposal

5.1 Simulations results and analysis

The modeling and simulation of the control method used to drive the double stars induction machine in this paper contain the state-space formulation in MATLAB/Simulink,Version.7.10.

The proposed method has been successfully implemented in a simulation package use OD4 (range-kutta) as solver.

5.1.1 Inverter breakdown

Figure (5.1) present the inverter output voltage by using the direct control of torque with one semiconductor element defective (short circuited).

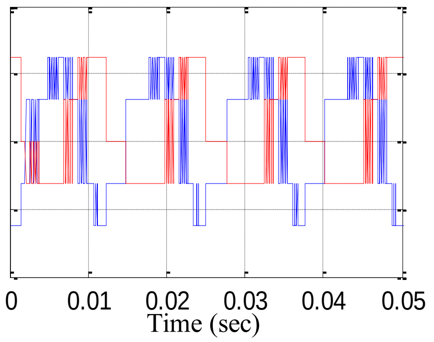


Fig.5.1. Inverter voltage output with element Semiconductor defective

The figure (5.2a,b) illustrates the motor behavior against an event of one semiconductor element in one line of the inverter is defective (short circuited) which can be summarised as:

-The solution can provide good dynamic performance, 1.1 (sec) as response time.

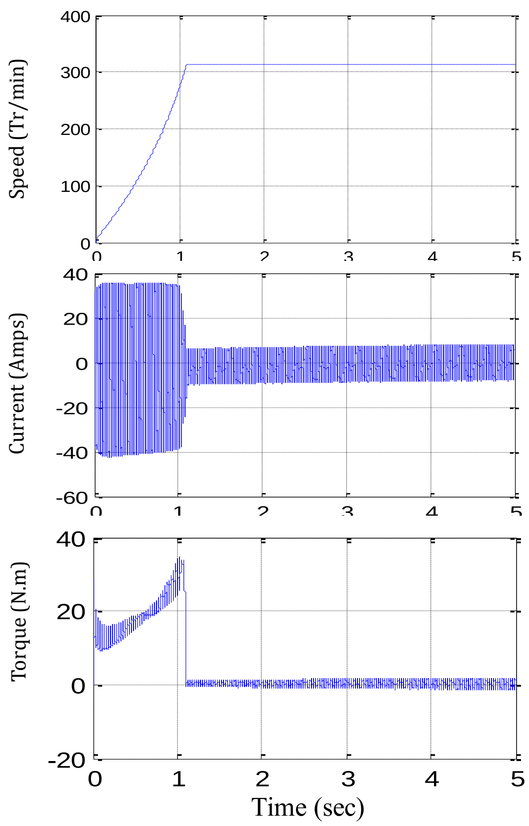


Fig.5.2.a. Inverter voltage output with one element Semiconductor is defective

In the event of load disturbance the DSIM present a good response of 1.1(sec) witch mean a delay of 0.5 (sec) if compared with classical method and normal form of torque ripple.

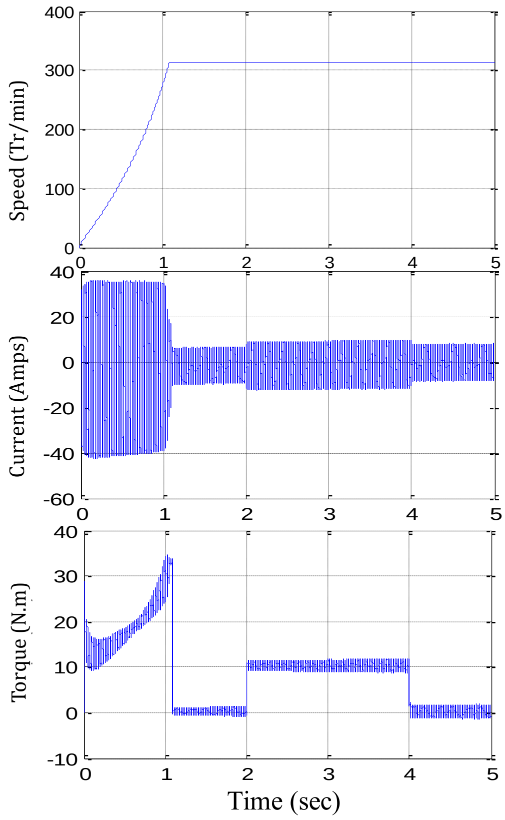


Fig.5.2.b. Inverter voltage output with element Semiconductor defective

5.1.2. Part of the motor winding is defective

In this part, we will simulate the double start induction motor controlled by direct control of torque when one phase winding is defective.

The figures (5.3a), (5.3b) illustrates the laden and unladen test results of simulation of the DSIM with part of the winding is defective (one phase is defective) which can be summarised:

1. The defective part in the wending generate a time delay of 1.5(sec) which is the result of the voltage trop.

2. The voltage drop related to the phase defective result an abnormal starting current to meet with the power demand (1.5) time more than the usual starting current in similar applications. This application should have a temperature protection system, as the temperature elevation is the one disadvantage in this proposal.

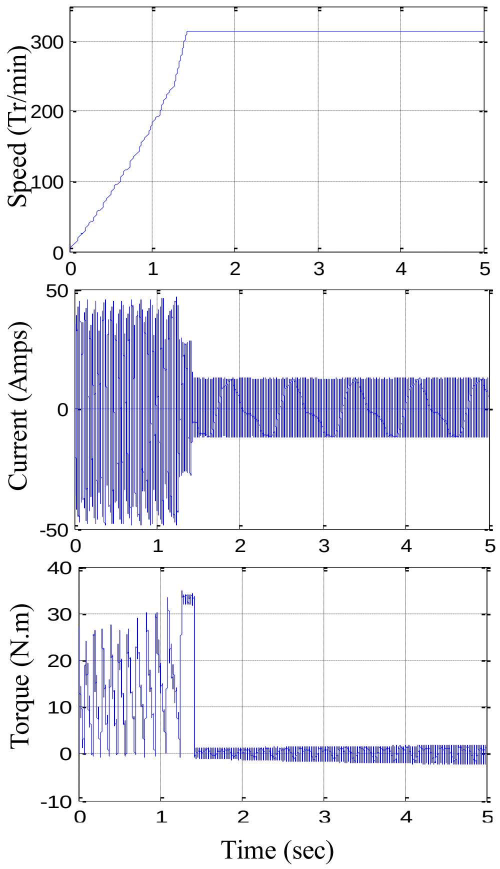
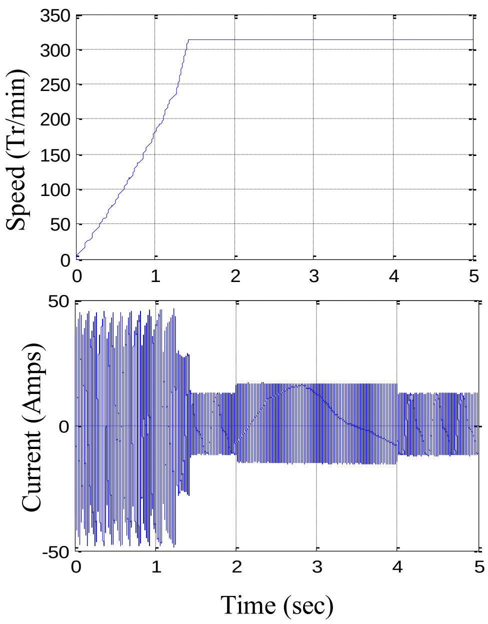


Fig.5.3.a. Unladen test results of simulation of the DSIM with part of the winding is defective



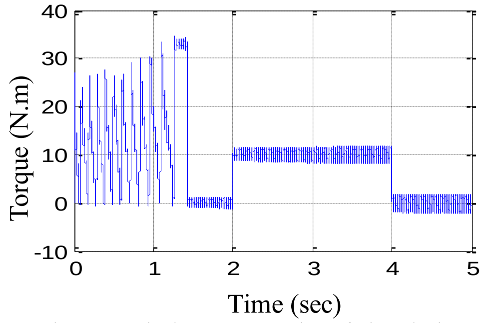


Fig.5.3.a. laden test results of simulation of the DSIM with part of the winding is

6.Conclusion

The direct control of torque application using DSIM method has been adapted to accommodate the degraded mode requirements, are results, proven by simulation, Which can be summarised:

1. The double star induction motor is an optimal solution to be used to meet with the degraded mode needs and exactly when a part of the winding is defected.

2. The direct control of torque method showed the high capacity to manage such kind of degraded mode situation.

3. The research results obtained in this paper can be implemented to solve the degraded mode traction railway system.

7. References

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