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Performance Analysis of Non Linear Field Oriented Controlled Induction Motor Drive for Improved Performance - Effect of Intermittent Loading

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Abstract: Attempt has been made in previous works to improve the steady state and dynamic performances of the vector controlled induction motor drives. The Input-output (I/O) linearization and decoupling technique which are based on the concepts of differential geometry and vector control has been used in the decoupling of speed or torque from the flux of induction motor drives. This paper investigates the effects of non-linearity on the performance of field oriented control of induction motor drive at intermittent loading, Nonlinear control are better seen implemented in large dynamic systems invoking non linearity. the effects of intermittent loading at no load, full, 10%, 20%, 50% and 80% loading where checked on the speed and electromagnetic torque of the induction motor being controlled, stator current and rotor current were also important parameters affected by non-linearity in control under intermittent loading. The results obtained gave a detailed comparison of the distortions present in motor control when not properly controlled. A comparative study of the system under loading conditions were checked under control for linear and non-linearity. Matlab/Simulink was used to model the induction motor drive and also simulate the dynamic performance of the system as load is being varied. The robustness of Matlab/Simulink was used to enable efficient intermittent loading at various points of the simulation, the data logout tool of Matlab/Simulink were also used for data collection analysis and comparison.

Keywords: Intermittent Loading FOC, Induction Motor Drive, DQ Axis, Space Pulse Width Modulation

1. Introduction

Real world systems are inherently non-linear, at least when considered over a wide operating range, although many of the systems are believed to behave as linear near a certain operating point at low speeds under certain assumptions. Many physical processes are represented by nonlinear models. Examples include; Coulomb friction, gravitation and electrostatic attraction, voltage-current characteristics of most electronic systems, and drag on a moving vehicle [1]. Recently, many researchers from fields as broad as process control, biomedical engineering, robotics, aircraft and spacecraft control have shown an active interest in the design and analysis of nonlinear control strategies. Therefore, most real problems inevitably require encountering nonlinearities [1].

The main reasons for the growing interest in nonlinear control include the improvement of linear control systems, the analysis of hard nonlinearities; have to deal with model uncertainties and simple construction [2]. Nonlinear strategies improve on trivial approaches by accounting for dynamic forces such as centripetal and Coriolis forces that vary proportionally to the square of velocity. So the linear control laws severely limit the speed of movement to achieve a certain accuracy. However, a simple nonlinear controller can adequately compensate for the nonlinear forces, thus achieving high speed over a wide working range. Also hard non-linearities such as dead zones; Hysteresis, Coulomb friction, static friction, backlash and saturation do not allow a linear approximation to real systems. After predicting these nonlinearities, nonlinear approaches properly compensate for them to achieve unmatched performance. In addition, real systems often exhibit uncertainties in the model parameters, as a result of sudden or slow change in the values of these parameters. A non-linear controller can deal with the consequences through robustness or adaptability model uncertainties [3].

The systems that are nonlinearly controllable or observable may be controllable/observable in a nonlinear sense. Considering a manipulator with six (6) degrees of freedom (DOF), the overperformance of a nonlinear strategy, especially in the presence of a perturbation, is evident in Figure 1, where a finite matched perturbation (Figure 1) is injected into the manipulator and tracking performance (Figure 1b) a non-linear approach of Sliding Mode Control (SMC) is compared with a linear strategy, d. H. Computed Torque Control with Proportional Integral Derivative (CTC - PID).

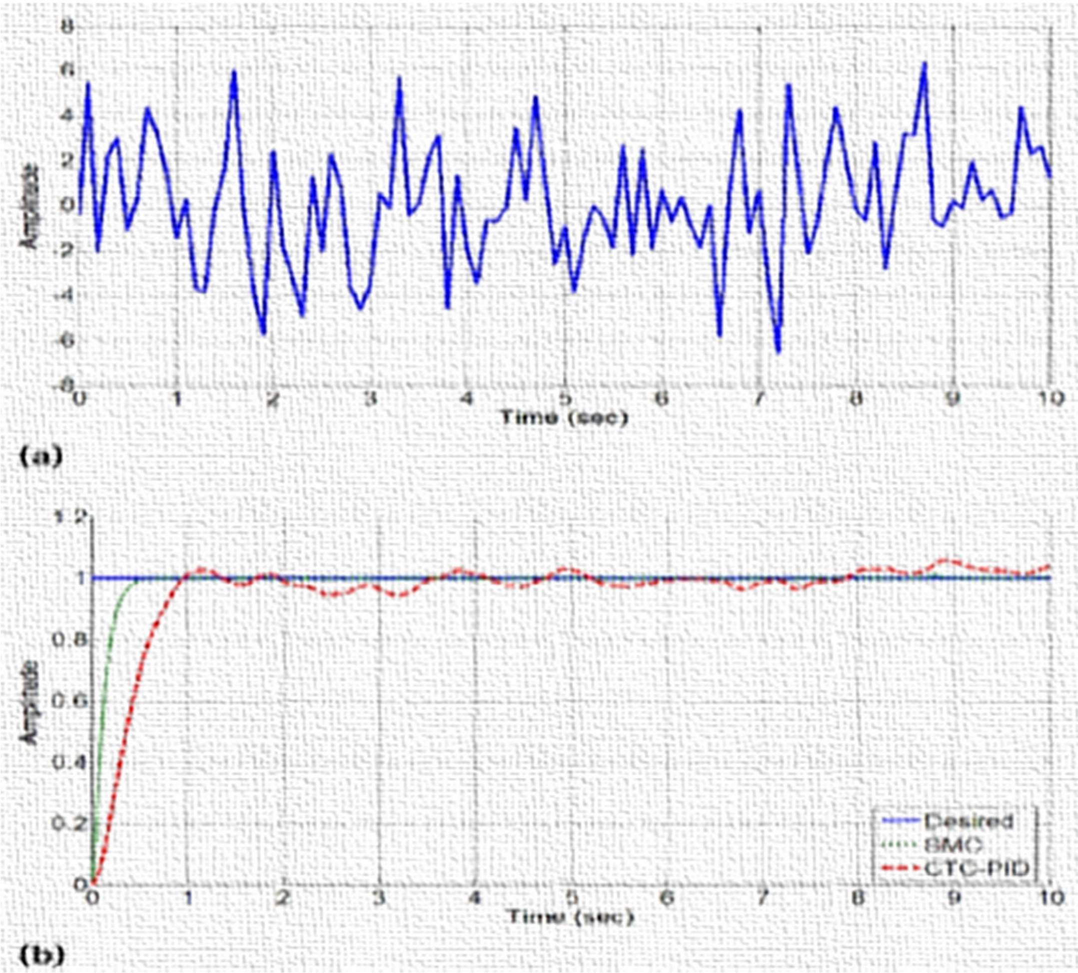

Figure 1. *Robustness comparison of linear and nonlinear control strategies (a) Disturbance (b) Tracking performance [2].*

The non-applicability of superposition and homogeneity in nonlinear systems leads to significant implications for the analysis and design of the control systems [4]. The simple relationship between the zero(s) and pole(s) of the transfer function and the time behavior does not hold in general. An unconstrained nonlinear system can have limit cycles that are not speculated by linear theory. Controllability and observability cannot simply be determined using rank tests. Furthermore, the stability of a system is no longer just a simple function of eigenvalue positions, as nonlinear systems can have multiple stable/unstable equilibrium points. Because of the relevance of nonlinear control in a wide range of recent applications, this article includes a brief commentary on the topic. Interested readers are encouraged to refer to the original literature cited for fuller details.

2. Nonlinear Dynamical Systems

Dynamics can be defined as a science of change, and dynamical systems abound in nature [5]. These include the movement of planets, the movement of liquids, the flow of current in electrical circuits, heat dissipation in solids, the propagation and acquisition of seismic waves, and the increase and decrease in human or animal population. Virtually all dynamical systems consist of: A set of independent state variables that evolve over time and can be used to fully describe the behavior of the system [6].

Nonlinear control systems include: robotics, ground vehicles, propulsion systems, electrical power systems, aerospace vehicles, autonomous vehicles, manufacturing processes, chemical and materials processing, all modern control problems require it. Linearization of a drive system with an induction motor with non-linear feedback generally requires access to all state variables. Figure 2 summarizes the idea of system linearization using nonlinear feedback. Combining nonlinear feedback with the nonlinear model and then performing variable transformations converts the highly nonlinear dynamic system, such as an induction motor, into a linear object [7].

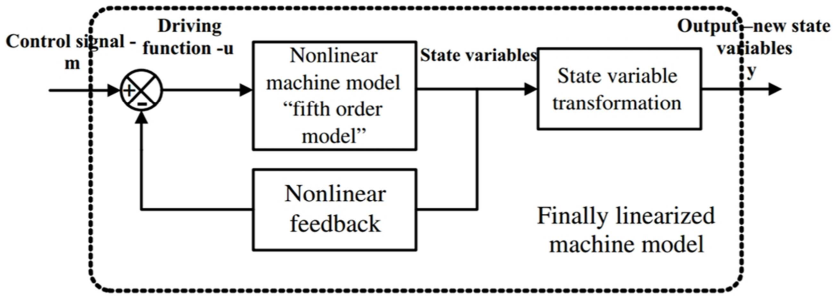

Figure 2. *Linearization of dynamic system using non-linear feedback: m-driving function of the Linearized system; y-state variable of the Linearized system; u-driving function of the non-linear system x – state variable of the non-linear system.*

2.1. Nonlinear Adaptive Control Schemes

The most effective and advanced nonlinear control schemes are the adaptive controls. The basic idea of an adaptive controller is to estimate uncertain parameters and tune the controller online to adapt to the dynamic situation where the variations in the system parameters or the environment are significant. Adaptive control grew in popularity in the aerospace control community in the 1950s. However, it lost its charm due to the lack of well-understood stability tools and proper hardware. Another particular reason for this loss of interest was the plane crash incident controlled by an adaptive law [8]. Nevertheless, interest in adaptive control has been revived, particularly in social robotics due to its suitability for a highly nonlinear, unstructured, and dynamic human environment compared to controlled and well-ordered industrial workcells. In general, there are two main types of adaptive control schemes viz. H. Model Reference Adaptive Control (MRAC) (Figure 3) and Self Tuning Adaptive Control (STAC) (Figure 4). In MRAC, the adaptation mechanism estimates appropriate parameters to make the system behave like the reference model. In STAC, the slowly changing parameters or unknown constants are optimized to minimize/maximize an objective function, typically error minimization or efficiency maximization.

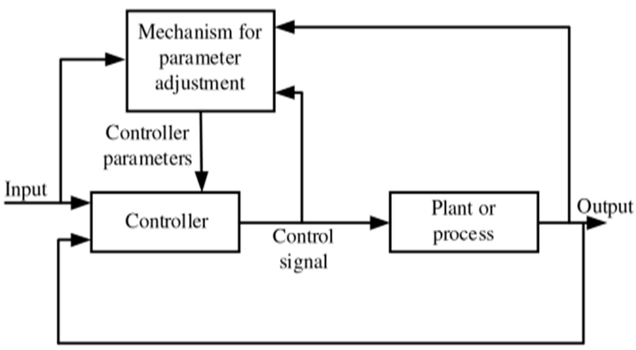

Figure 3. *Block diagram adaptive control [5].*

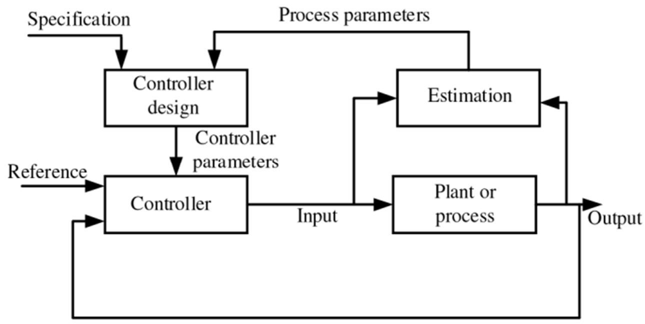

Figure 4. *Self tuning adaptive control [5].*

Adaptive controllers can use a dynamic model and estimate the uncertain parameters (Lewis, 2003) or they can be free of dynamic models. Model-based adaptive controllers can be easily tuned and their performance is usually better, as observed by Tety et al [8]. However, the dynamic model becomes very cumbersome as the DOF increases. This can lead to computational and communication problems, making the implementation of dynamic model-based adaptive schemes more difficult. Therefore, adaptive controllers without dynamic models can be the best choice for a high DOF plant since no dynamic model is required.

2.2. Non Linear Control of Induction Motors (IM)

This is widely used in industrial application due to its robustness, size, efficiency, reliability and cost. Asynchronous motors driven by static converters are generally used in industrial applications because of its advances in power electronics. On the other hand, the induction motor is a highly non-linear system and requires a complex control algorithm. One of these algorithms is called field oriented control (FOC) or vector control algorithm. Vector control algorithms use induction motor dynamic equivalent circuit and convert the three-phase stator currents into two DC currents, then calculation of the motor speed and torque are similar to DC motor [9]. The vector control algorithm implements two primary famous transforms, the first is called Clark transform which transforms the three stator currents into two dc currents in a stationary frame (DQ) and then into two dc currents in any rotating frame (dq) using Park transform [9].

3. Materials and Methods

3.1. Modeling the Three Phase Induction Motor

3.1.1. Mathematical Modeling of Three Phase Induction Motor

Symmetric structure, three-phase balance and linearity of rotor and stator magnetic core are assumed during any derivation of dynamic modeling of IM. The modeling of IM is usually derived from flux linkage, voltage and motion equations in a synchronously rotating reference frame of stator and rotor.

3.1.2. D-Q Reference Frame

The d-q equivalent flux linkage, voltage and motion equations can be easily achieved from space vector model by the decoupling of the real and imaginary part of their respective equations as shown in the following equations:

3.1.3. Voltage Equation in d-q-axis

Rotor and stator d-q-axis voltages in terms of corresponding flux linkages are specified as:

$$v_{ds} = R_s I_{ds} + \frac{d\psi_{ds}}{d_t} - \omega\psi_{qs} \quad (1)$$

$$v_{qs} = R_s I_{ds} + \frac{d\psi_{qs}}{d_t} + \omega\psi_{ds} \quad (2)$$

$$v_{dr} = R_r I_{dr} + \frac{d\psi_{dr}}{d_t} - (\omega - \omega_r)\psi_{qr} \quad (3)$$

$$v_{qr} = R_r I_{qr} + \frac{d\psi_{qr}}{d_t} + (\omega - \omega_r)\psi_{qr} \quad (4)$$

v_{ds} , v_{qs} represents stator $dq - axis$ voltages, respectively, v_{dr} , v_{qr} demonstrates rotor $dq\ axis$ voltages. Rotor and stator resistances are represented by R_s and R_r, respectively. I_{ds}, I_{qs} and I_{dr}, I_{qr} define the d-q-axis stator and rotor currents, respectively. ψ_{ds} , ψ_{qs} and ψ_{dr} , ψ_{qr} represents stator and rotor d-q-axis flux linkages. ω is the speed of rotation of arbitrary reference frame and ω_r is electrical speed of rotation [10].

3.1.4. Flux Linkage Equation in d-q-axis

The flux linkage equations in the respective d-q-axis equivalent equations are described as:

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \quad (5)$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (6)$$

$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \quad (7)$$

$$\psi_{qr} = L_r i_{dr} + L_m i_{qs} \quad (8)$$

L_s , L_r and L_{is} , L_{ir} are self-inductance and leakage inductance of stator and rotor, respectively, while Lm represents magnetizing inductances which are measured in Henry (H). Moreover, $L_s = L_{is} + L_m$ and $L_r = L_{ir} + L_m$.

3.1.5. d-q-axis Model of Stator and Rotor

Substituting values of flux linkages in terms of inductances into voltage equations of stator and rotor, we have:

$$v_{ds} = R_s I_{ds} - \omega\psi_{ds} + L_{is}\frac{d}{dt}i_{ds} + L_m\frac{d}{dt}(I_{ds} + i_{dr}) \quad (9)$$

$$v_{qs} = R_s I_{qs} + \omega\psi_{ds} + L_{Is}\frac{d}{dt}i_{qs} + L_m\frac{d}{dt}(I_{qs} + i_{qr}) \quad (10)$$

$$v_{dr} = R_r I_{dr} - (\omega - \omega_r)\psi_{qr} + L_{ir}\frac{d}{dt}i_{dr} + L_m\frac{d}{dt}(I_{ds} + i_{dr}) \quad (11)$$

$$v_{qr} = R_r I_{qr} + (\omega - \omega_r)\psi_{dr} + L_{ir}\frac{d}{dt}i_{qr} + L_m\frac{d}{dt}(I_{qs} + i_{qr}) \quad (12)$$

Figure 5 shows the d-q-axis equivalent model of induction motor.

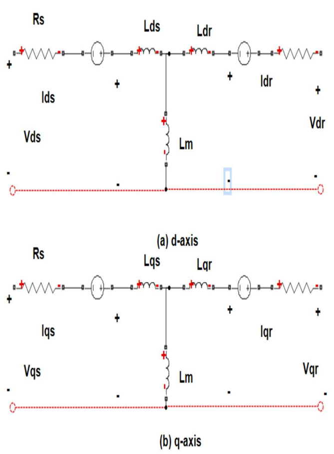

Figure 5. *d-q-axis equivalent model of induction motor.*

3.2. Non-linear Field Oriented Control

Non-linear field-oriented control based on rotor flux linkages is the most popularly used method, because it involves aligning the longitudinal and transverse axes of the stationary frame with the rotor flux frame [11]. Therefore, unit vectors are often used to transform the variables from a stationary frame to a synchronous frame. In this method, these unit vectors are generated in a rapid feed-forward manner, which is derived as follows: The rotor fluxes in the direct and quadrature axes are written as

$$\frac{d\psi_{dr}}{dt} + \frac{R_r}{L_r}\psi_{dr} - \frac{L_m}{L_r}R_r i_{ds} - (\omega_e - \omega_r)\psi_{qr} = 0 \quad (13)$$

$$\frac{d\psi_{qr}}{dt} + \frac{R_r}{L_r}\psi_{qr} - \frac{L_m}{L_r}R_r i_{qs} - (\omega_e - \omega_r)\psi_{dr} = 0 \quad (14)$$

For decoupling control,

$$\psi_{qr} = 0 \quad (15)$$

And hence

$$\frac{d\psi_{qr}}{dt} = 0 \tag{16}$$

So the entire flux is directed along d-axis. Substituting equation (16) and (17) in equation (13) and (14) we get,

$$(\omega_e - \omega_t) = \frac{L_m R_r}{\psi_{dr} L_t} i_{qs} \tag{17}$$

$$\omega_{st} = (\omega_e - \omega_r) \tag{18}$$

If rotor flux ψ_{qr} is constant, then $\psi_r^* = \psi_{dr}$

Hence slip speed can be calculated from $q - axis$ reference current and rotor reference flux as follows:

$$\omega_{st} = \frac{L_m R_r}{\psi_r^* L_r} i_{qs}^* \tag{19}$$

The synchronous reference frame speed is the addition of the angular slip speed and the angular rotor speed which can be given by equation (20)

$$\omega_e = (\omega_{st} + \omega_r) \tag{20}$$

The unit vector is generated by integrating the synchronous frame reference speed as

$$\theta_e = \int \omega_e \, dt \tag{21}$$

The controller scheme for field-oriented control can be implemented in Matlab/Simulink as shown in Figure 6, the control scheme requires three PI controllers, one to control torque and speed, the second to control d-q components of flux and rotation angle θ, the field-oriented control scheme is similar to the vector control scheme in that it calculates the steady-state reference components d and q of the motor's torque and speed before conversion to the abc rotary frame [12].

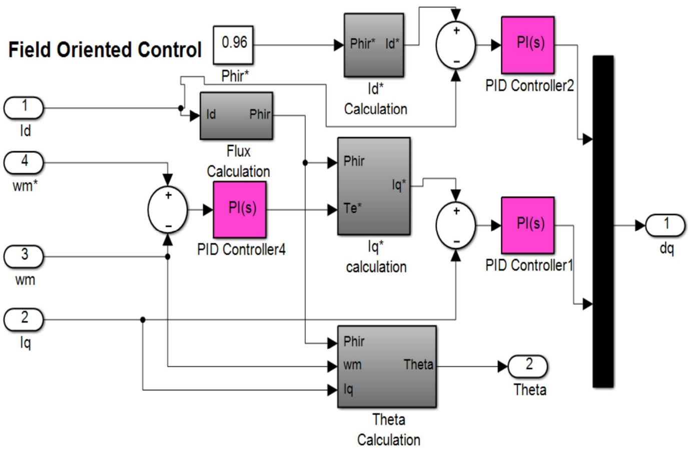

Figure 6. Simulink implementation of the field oriented controller.

The simulink implementation of the subsystem the flux calculation is shown in figure 7, the implementation of the flux calculation is as given from equations (5) to (8).

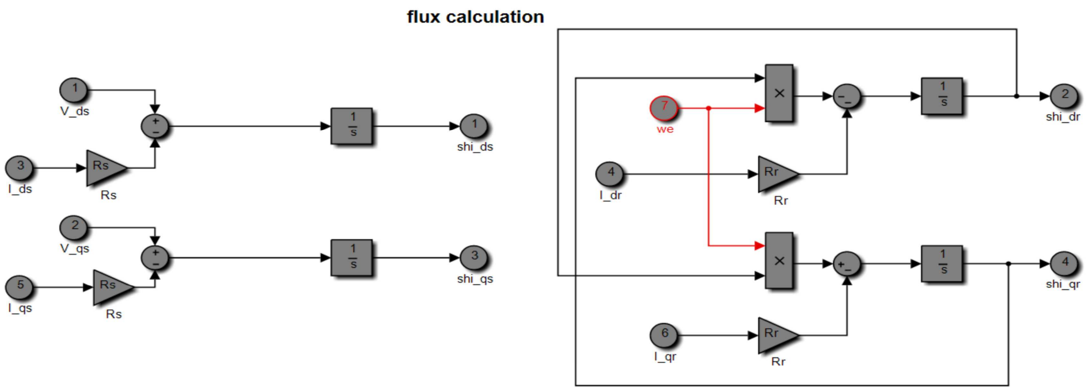

Figure 7. Simulink implementation of flux calculation in the FOC.

The d and q component calculation subsystem from figure can be implemented as shown in figure 8 and figure 9, the simulink implementation is as given from equation (5) to (12).

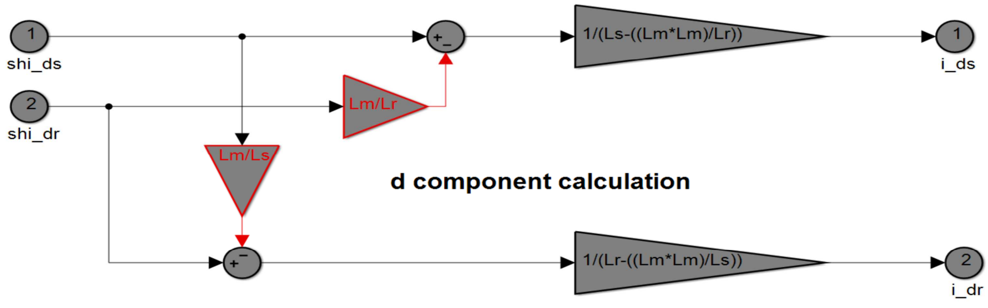

Figure 8. *Simulink implementation of d component estimation.*

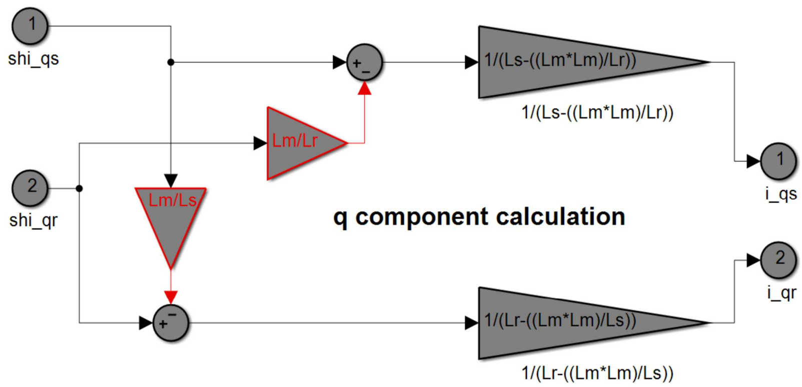

Figure 9. *Simulink implementation of q component estimation.*

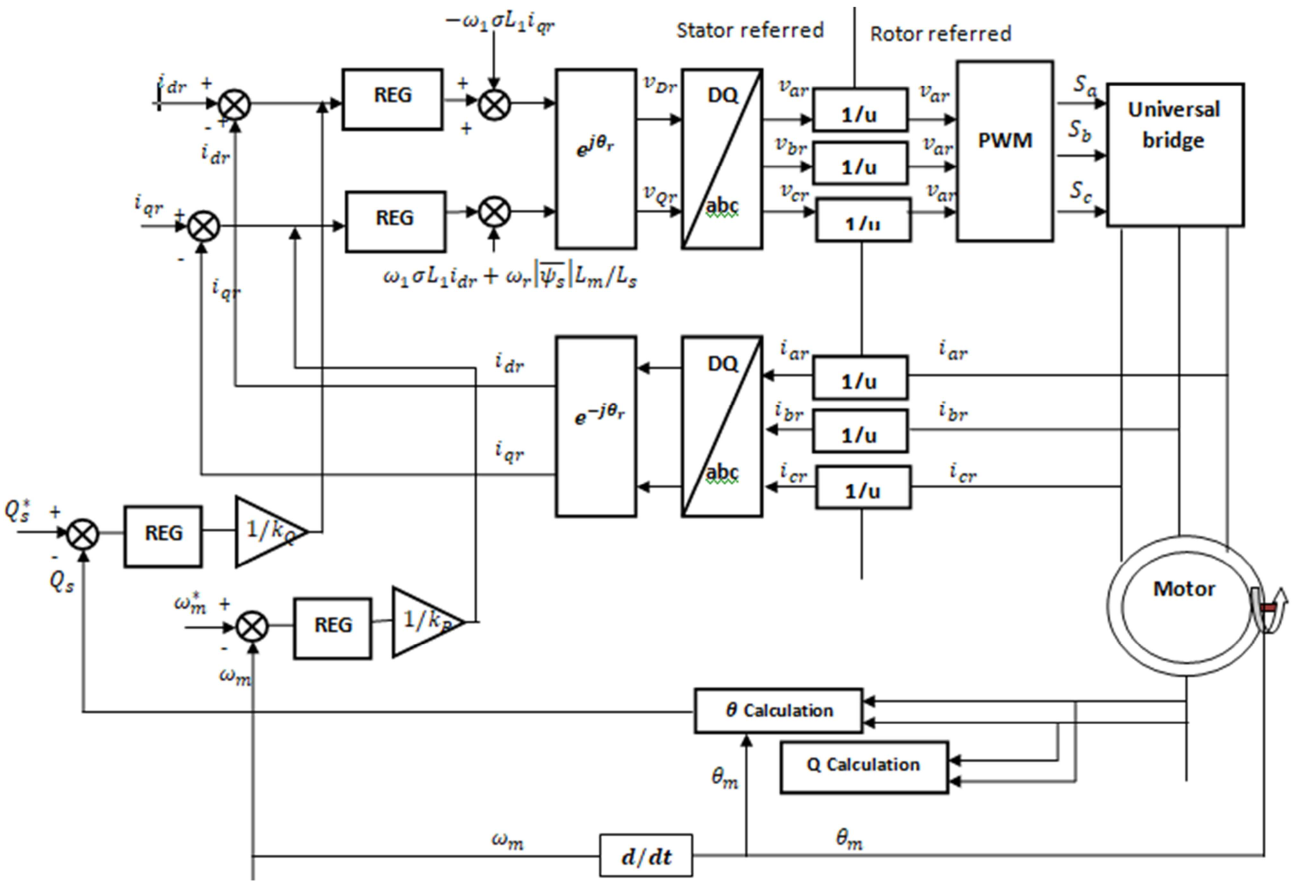

Figure 10. *Overall control diagram of the nonlinear FOC scheme.*

3.3. The Non Linear FOC Scheme

The indirect field-oriented control scheme has been explained in Figure 10. The three-phase currents i_a, i_b and i_c, are fed to the Clarkes transform module. The outputs of the transformation are denoted as i_{ds}^s *and* i_{qs}^s . These two components of the current are the inputs to the Park transform that provides the current in the (d,q) rotating reference frame. The components i_{ds} and i_{qs} are compared to the references i_{ds}^* (the flux reference) and i_{qs}^* (the torque reference). hence the rotor flux is fixed in synchronous permanent magnet motors, there is no need for flux generation [13]. The outputs of the current controllers are V_{ds}^*andV_{ds}^*; they are applied to the inverse Park transform. The outputs of this projection are V_{ds}^{s*} $*$ andV_{ds}^{s*}, which are the components of the stator vector voltage in the stationary orthogonal frame of reference. These are the inputs to the Space Vector PWM. The voltage source inverter makes use of the space vector pulse width modulation technique due to the known advantages of better utilization of the DC bus voltage, reduced harmonic currents and considerable freedom in the placement of the space vector in a sector through the choice of switching frequency. The outputs of this block are the signals that drive the inverter. The space vector pulse width modulation scheme will be clearly explained in the next sections. It is important to know that both park and inverse park transforms require the rotor angle θ_e. Figure 10 describes the overall nonlinear FOC scheme.

3.4. Space Vector Pulse Width Modulation

The space vector pulse width modulation (SVPWM) technique is a better technique for pulse width modulation voltage source inverters because it gives an output with less harmonic distortion. In this technique, phase voltages are represented as a space vector model and the inverter switches between two adjacent active vectors and a zero vector during a switching period [14]. There are eight possible states associated with a reference vector and in order to achieve a rotating field, the inverter must be switched to six of the eight states. The other two states are zero vectors. In Figure 11, the angle between any two vectors is 60°. In the notation describing the states of the three-phase inverter (shown in Figure 11), this depends on the on and off state of the transistor. For example, the state when transistors T1, T4, T5 are on and T2, T3, T6 are off can be shown with the notation (+-+) [15]. The line-to-neutral voltages can be converted into a space vector from equation (22).

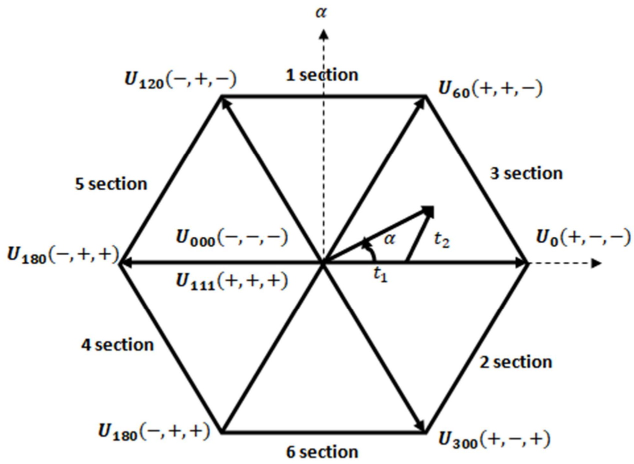

Figure 11. *Representation of an inverter state in reference frame. [15].*

$$U_s = V_{an}(t)e^{j0} + V_{bn}(t)e^{j\frac{3}{2}} + V_{cn}(t)e^{-j\frac{2}{3}} \qquad (22)$$

Where the components are of angles $\left(0, \frac{-2\pi}{3}, \frac{2\pi}{3}\right)$

The overall nonlinear FOC control of an induction motor is shown as designed in Matlab/simulink is shown in figure 12.

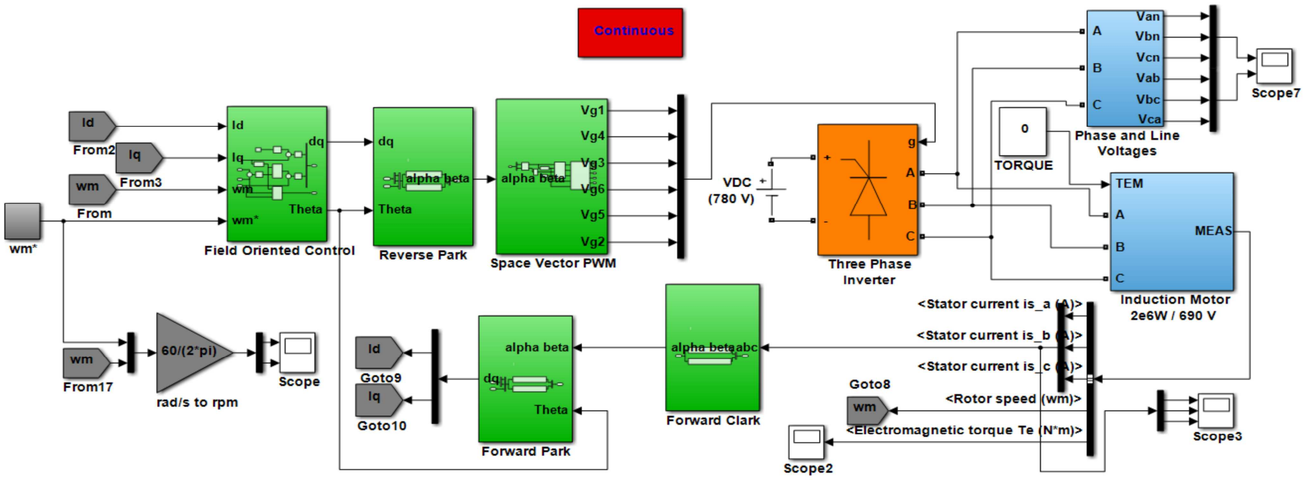

Figure 12. *Overall simulink implementation of the nonlinear FOC for an induction motor.*

4. Results and Discussions

4.1. Dynamic Performance of Linear and Non Linear FOC Under Intermittent Loading

In order to avoid large increase in the torque produced, the following motor parameters in table 1 will be used to analyze the dynamic performance of the induction motor drive under the control of linear and nonlinear FOC.

Table 1. *Motor parameters for dynamic analysis of induction motor drive.*

Parameters Parameters	Values
Stator resistance	1ohm
Rotor resistance	5.23ohms
Kp	0.3
Ki	≤ 0.1

At a constant Kp and Ki value, the performance of the linear and nonlinear field oriented control of torque, rotor speed and current can be analyzed using a dynamic evaluation by variation of load as the simulation runs to understand the performance of the system, non linearity in FOC leads to faster response of systems under control.

In field oriented control of the DC motor system, the d-q reference frame are locked to the rotor flux vector and are employed to achieve decoupling between the DC motor flux and the torque unlike other control schemes, non linear FOC control provides more precision for load torque control and uses sensors for the speed control of the rotor and magnetic flux to provide data for the FOC algorithms [14].

Figure 13 compares the linear and non linear FOC of the electromagnetic torque, three things can be observed.

Non linear FOC reduces the overshoot in control, unlike the linear controller.

There is reduction in torque distortions even when torque load is increased when using the non linear controller (reduced steady state error).

The non linear control shows a better and faster response the intermittent loading as compared to the linear control.

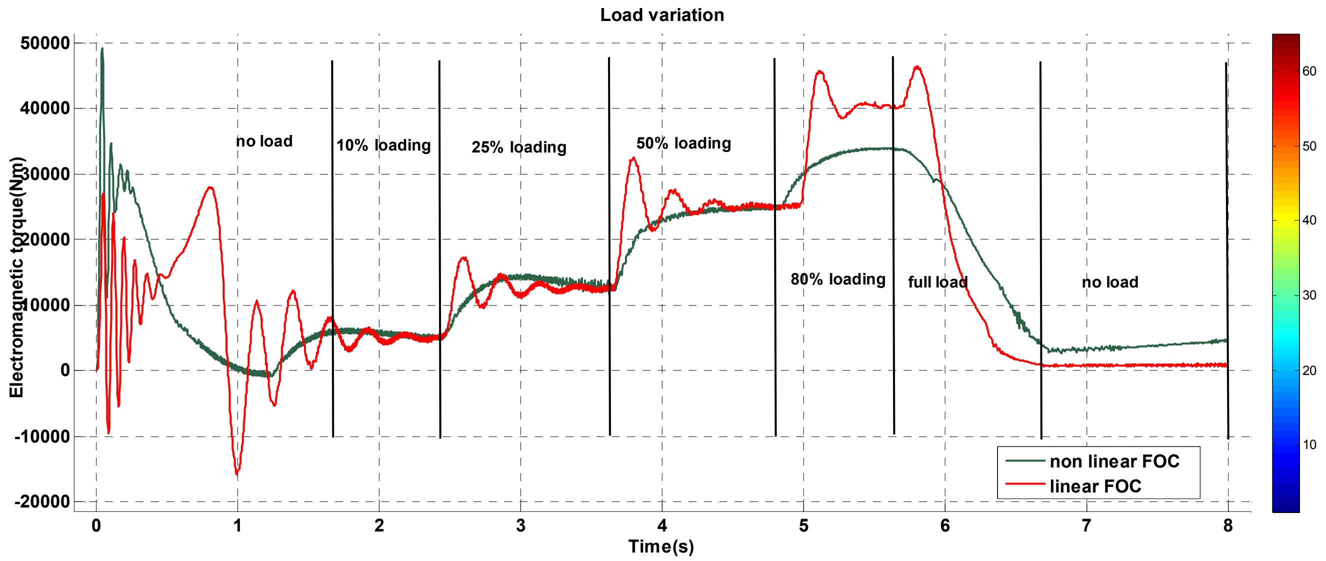

Figure 13. *Dynamic performance of torque at intermittent loading.*

The distortion in response of the linear is as a results of linear controller struggling to cope with stringent dynamic requirements of non linear systems, from the speed control in figure 14, it can be seen that non linear FOC shows better performance and robustness in control of the rotor speed, also the response of the system to the non linear control is quicker and better.

4.2. Stator and Rotor Current Performances Under Intermittent Loading

Figures 15 and 16 shows the stator and rotor current dynamic performance at intermittent loading, it can be seen that as the torque load is increased, both stator and rotor currents keep increasing until the load is dropped back to no load, the linear controller show large distortion in its performances at the start of the simulation i.e no load, but this high current distortion are reduced during start of simulation by using the non linear controller, in real time analysis this large start up currents could cause high surges that can blow up appliances during usage.

Figures 17 and 18 shows the dynamic performance of the current components of the rotor and stator of the induction motor, the plots show that there is increase in current values as torque load increases for both nonlinear and linear control, but there is much distortion in control using linear FOC, and this distortions are highest at the start of the simulation [16].

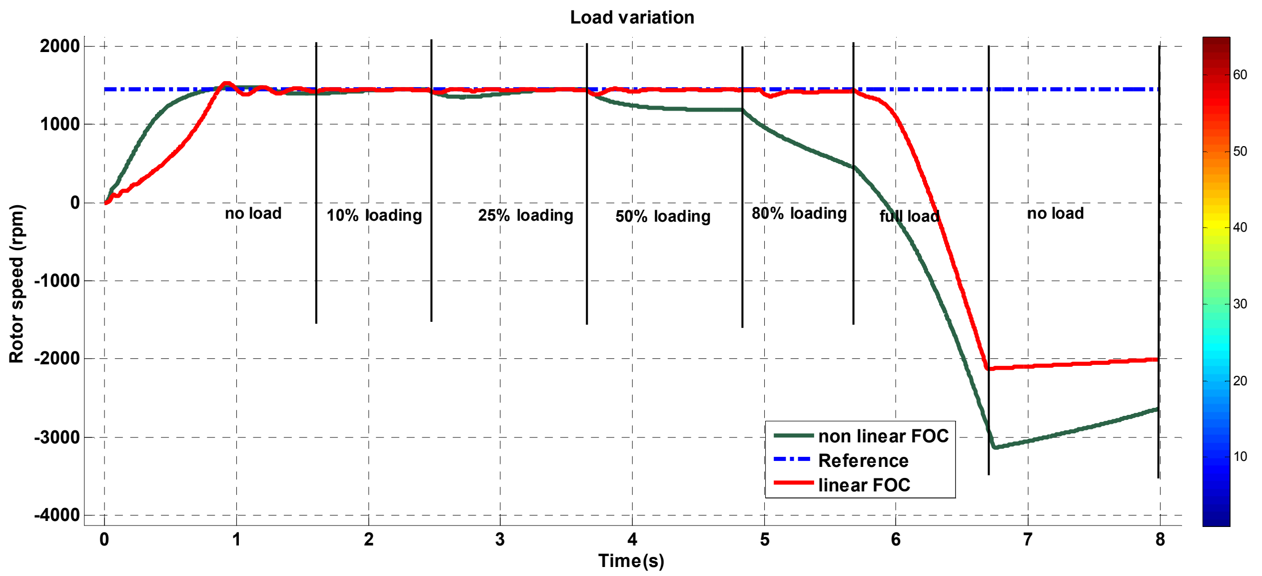

Figure 14. Dynamic performance of rotor speed at intermittent loading.

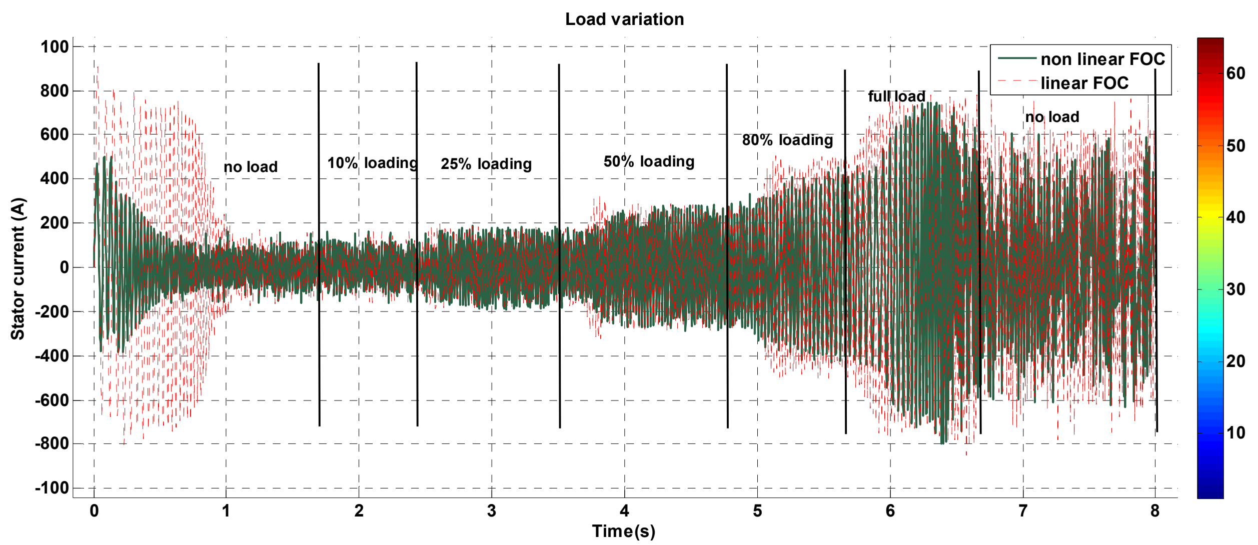

Figure 15. Dynamic performance of stator current at intermittent loading.

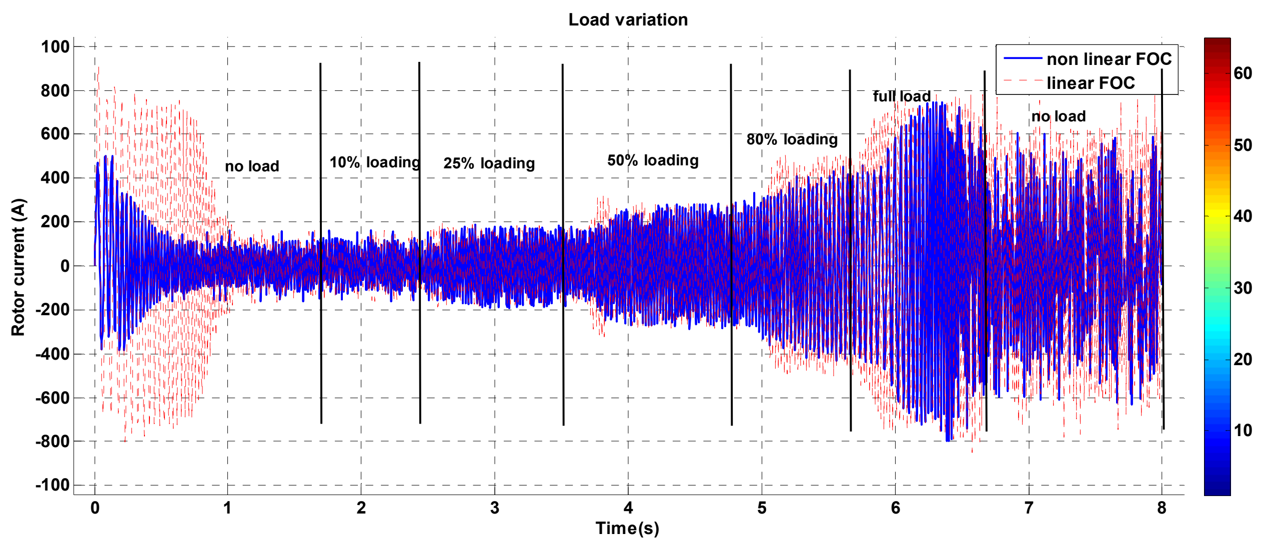

Figure 16. Dynamic performance of rotor current at intermittent loading.

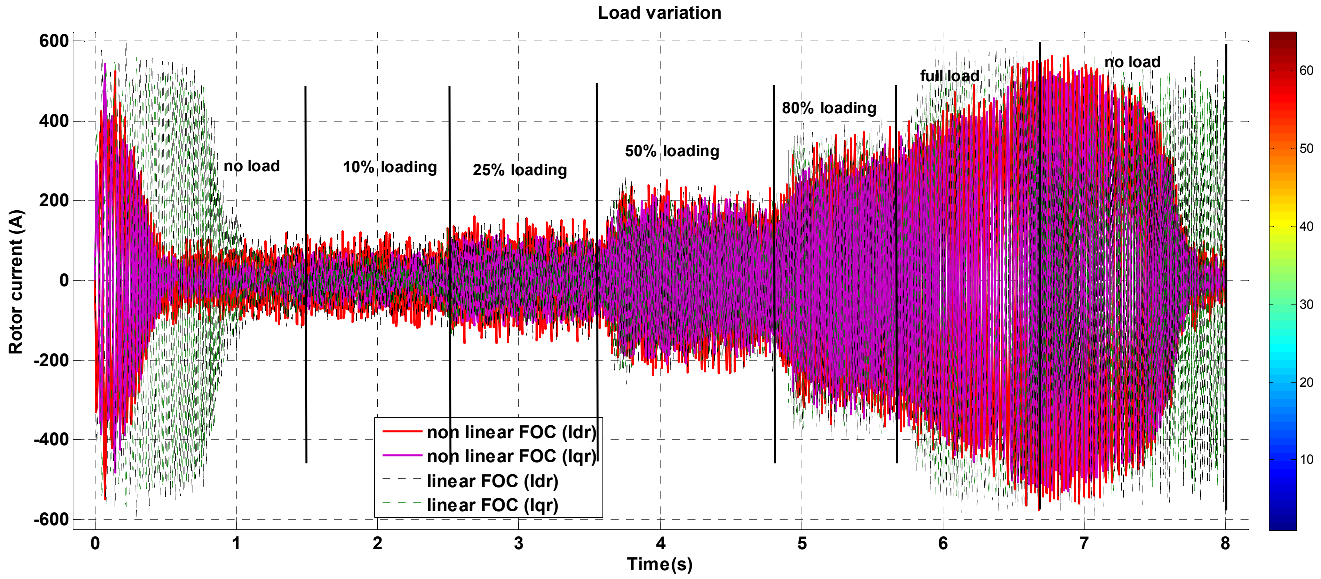

Figure 17. *Control of rotor current components under intermittent loading.*

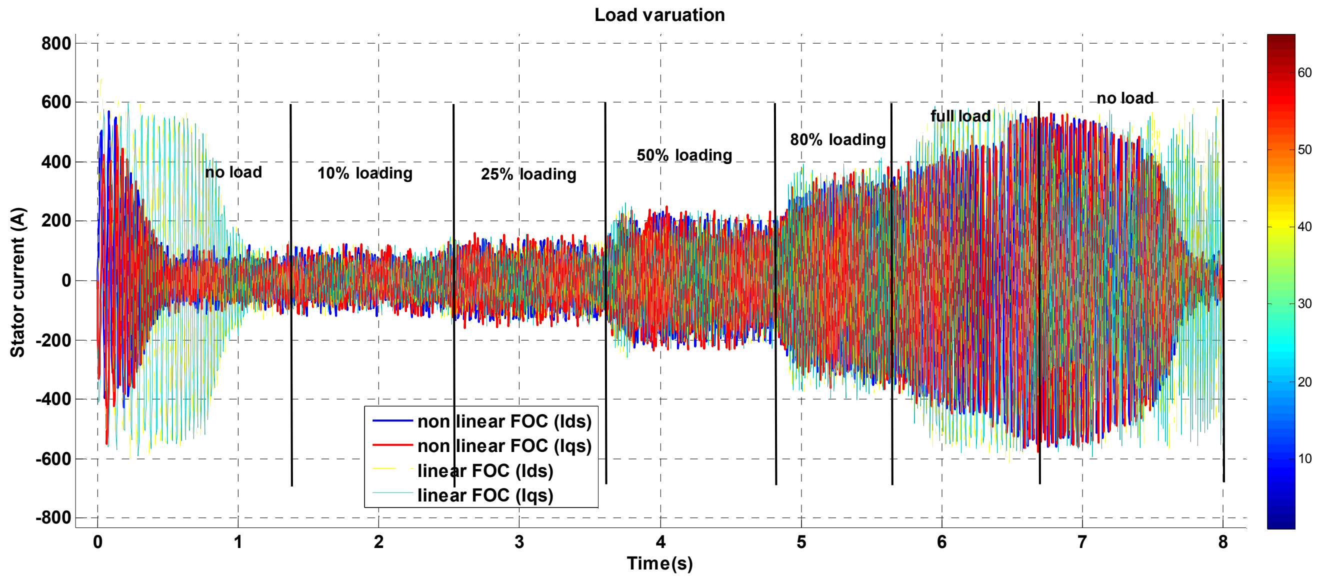

Figure 18. *Control of rotor current components at intermittent loading.*

5. Conclusion

The effect of intermittent loading on the dynamic performance of linear and non linear FOC on induction motor has been implemented. The FOC control scheme has been implemented using the PWM technique to reduce harmonic current responsible for distortion in the system. Comparison has been done for both the linear and non linear control action on intermittent loading and it can be seen that on dynamic intermittent loading the nonlinear FOC reduces distortion and gives a better performance to the control of induction motor, the results presented includes the effect of intermittent loading on load torque, speed and current component, any ripple in DC motor speed and electromechanical torque are due to abrupt changes in reference speed.

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