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Modeling and Simulation of Pump Storage Based on Indirect Field Oriented Control

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Abstract

This paper derived the mathematical model of indirect field oriented control (IFOC) applied in pump storage to obtain the variable speed. The two identical seven level H- bridge multilevel converters connected in cascade have been used to generate 6KV on the rotor side. The input of power cell of H-bridge cascaded multilevel converter fed from a phase-shift transformer to reduce the total harmonic distortion of rotor currents. The slip angle of doubly fed asynchronous induction machine is calculated by using the stator flux of indirect field oriented control (IFOC). The slip angle calculated is used to control of variable speed of the pump storage based on machine parameters.

Keywords*: variable speed pump storage, H- Bridge cascaded multilevel converter, FOC, DFASPSU, multilevel converter*

1. Introduction

In recent years, the variable-speed pump storage technique has been a good way to hoard large amounts of electrical energy. In addition, it used to progress towards the controllability, grid balancing, increase energy efficiency and stability of power networks.

Pump storage is divided into three types: (1) separate turbine and pump, (2) fixed speed pump turbine,(3) variable-speed pump turbine. Since the nineties of the last century to now the variable-speed pump turbine also called reversible pump turbine machine is used in some countries such as Japan and Germany [1, 2]. This configuration consists of two water reservoirs and reversible pump-turbine. The machine must operate as a generator in turbine mode and as a motor by changing the direction of rotation when the system is operated in pumping mode.

To achieve variable speed of pump storage doubly fed adjustable speed pumped storage unit (DFASPSU), the rotor winding of doubly fed machine connected to power electronics converter and the stator connected to the grid.

Up to now the power electronics converter used in pump is divided into four types: (AC-AC) cycloconverter, two levels back to back (AC-DC-AC) converter, three levels back to back (AC-DC-AC) converter and H-bridge cascaded multilevel converter [3]. Some of these power electronics converters are application in pump storage stations in some countries. The H-bridge cascaded multilevel converter is a new technology under study used in pump storage station; it has some features to use in high power application [4, 5]. The control strategy used in [4] is open loop control (phase shifted modulation).

Field oriented control (FOC) also called vector control is control techniques used in the high-power medium voltage drive. It has a number of features, including: (1) can be design it in real time by using digital processors, (2) offer excellent dynamic realization, and (3) reduce motor size [6].

Although [7] has analyzed and studied the mathematical dynamic model of DFASPSU, by using rotor flux field orient control technique depended on (AC-AC) cycloconverter. The results compared with the Ohkawachi power station in Japan. Field oriented control is used to propose a rotor speed for induction machine based on a model reference adaptive system (MRAS) [8].

In this paper, the mathematical model of variable-speed pump storage is derived using stator flux indirect field oriented control (IFOC) depends on the H-bridge cascaded multilevel

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converter. This model used to obtain the variable speed of pump storage, the slip angle for indirect field oriented control is obtained from the measured rotor speed and calculated stator flux angle based on machine parameters.PSIM software program is used to build the model and satisfied the simulation.

2. Research Method

2.1. Analysis of Vector Control

In [6] and [9] FOC and its application in an induction machine have been discussed. It consists of controlling the ac voltage and current represented by a vector. This control based on the transformation from stationary frame of the induction machine to the synchronous frame similar to that of a DC machine control.

This paper focuses on IFOC application in variable-speed pump storage based H-bridge cascaded multilevel converter to obtain the variable speed of the pump storage. FOC theory depends on the conversion of a stationary frame to synchronous frame of physical quantities such as current, voltage, magnetic flux and transfer of ac quantities to dc quantities in a synchronous frame corresponding to the ac frequency.

Dynamic model of the induction machine is divided into two types: space vector and dq axis model. Both models are evenly valid for the analysis of transient and steady-state performance of the induction machine.

The stator and rotor voltage of symmetrical three phase induction machine in space vector model [6] are given by

$$\vec{v}_s = R_s \vec{i}_s + \frac{d}{dt}\vec{\lambda}_s + j\omega_s \vec{\lambda}_s \quad (1)$$

$$\vec{v}_r = R_r \vec{i}_r + \frac{d}{dt}\vec{\lambda}_s + j\left(\omega_s - \omega_r\right)\vec{\lambda}_r \quad (2)$$

where $\vec{v}_s$ is the stator voltage vector, $\vec{i}_s$ is the stator current vector, $\vec{v}_r$ the rotor voltage vector, $\vec{i}_r$ the rotor current, R_s the stator resistance, R_r the rotor resistance, $\vec{\lambda}_s$ is the stator flux linkage vector, $\vec{\lambda}_r$ is the rotor flux linkage vector, ω_s is the synchronous frequency of stationary reference frame and ω_r the rotor frequency of stationary reference frame.

Flux linkage equations

$$\vec{\lambda}_s = L_s \vec{i}_s + L_m \vec{i}_r \quad (3)$$

$$\vec{\lambda}_r = L_r \vec{i}_r + L_m \vec{i}_s \quad (4)$$

where $L_s = L_{ls} + L_m$ is the stator self inductance, $L_r = L_{lr} + L_m$ is the rotor self inductance ; L_m is the magnetizing inductance; and L_{ls} and L_{lr} are the stator and rotor leakage inductances respectively.

The dq model of induction machine can be obtained using three-phase circuit theory and then transformed into the two phase frame. The space vectors of induction machine model into d and q axis components given by:

$$\vec{v}_s = v_{ds} + jv_{qs}; \qquad \vec{i}_s = i_{ds} + ji_{qs}; \qquad \vec{\lambda}_s = \lambda_{ds} + j\lambda_{qs} \quad (5)$$

$$\vec{v}_r = v_{dr} + jv_{qr}; \qquad \vec{i}_r = i_{dr} + ji_{qr}; \qquad \vec{\lambda}_r = \lambda_{dr} + j\lambda_{qr} \quad (6)$$

The dq equations can be obtained by substituting (5) and (6) in (1) to (4), the dq axis voltage equations calculated by:

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\lambda_{ds} - \omega_s \lambda_{qs}; \quad v_{qs} = R_s i_{qs} + \frac{d}{dt}\lambda_{qs} + \omega_s \lambda_{ds} \tag{7}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\lambda_{dr} - \left(\omega_s - \omega_r\right)\lambda_{qr;} \quad v_{qr} = R_r i_{qr} + \frac{d}{dt}\lambda_{qr} + \left(\omega_s - \omega_r\right)\lambda_{dr} \tag{8}$$

2.2. Model of Variable Speed Pump Storage

The field oriented control can be generally classified into two types; direct field oriented control and indirect oriented control [6, 10]. The types of field orientation divided into three types; stator flux, rotor flux, and air-gap flux [11].

In this paper, the stator of the wound rotor induction machine is directly connected to the grid, and its voltage and frequency can be considered constant under the normal operating conditions. It is, therefore, consonant with use stator voltage oriented control (SVOC) for build the model. The stator voltage oriented control is achieved by aligning the d-axis of the synchronous reference frame with the stator voltage vector vs. the resultant d- and q-axis stator voltages are

$$v_{qs} = 0; \qquad v_{ds} = v_s \tag{9}$$

Based on the measured rotor current variable and the machine model, the stator flux method calculates (1) the stip angle θ_{sl} for field orientation, (2) the flux producing current i_{dr} ,(3) the electromagnetic torque T_e or the torque producing current i_{qr} and (4) the stator speed ω_s .

For indirect field-oriented control schemes the angle between the stator voltage vector and the rotor is the slip angle, calculated by

$$\theta_{sl} = \theta_s - \theta_r \tag{10}$$

or

$$\theta_{sl} = \int \left(\omega_s - \omega_r\right) dt \tag{11}$$

The stator current

$$\vec{i}_s = \frac{\lambda_s - L_m \vec{i}_r}{L_s} \tag{12}$$

into (1) yields

$$\vec{v}_s = \frac{R_s}{L_s}\left(\vec{\lambda}_s - L_m \vec{i}_r\right) + j\omega_s \vec{\lambda}_s + \frac{d}{dt}\vec{\lambda}_s \tag{13}$$

from which

$$\left(1 + \tau_s\left(\frac{d}{dt} + j\omega_s\right)\right)\vec{\lambda}_r = \vec{v}_s \tau_s + L_m \vec{i}_r \tag{14}$$

Where τ_s is the stator time constant, calculated by

$$\tau_s = \frac{L_s}{R_s} \tag{15}$$

Resolving (14) into the dq-axis components according to (9) and $\left(j\lambda_{qs} = 0 \,\&\, \lambda_{ds} = \lambda_s \right)$ obtained

$$\lambda_s \left(1 + \frac{d}{dt}\tau_s \right) = v_s \tau_s + L_m \, i_{dr} \tag{16}$$

$$\omega_s \lambda_s \tau_s = L_m \, i_{qr} \tag{17}$$

from which

$$\omega_s = \frac{L_m}{\tau_s \lambda_s} i_{qr} \tag{18}$$

Figure 1 shows the block diagram of indirect field oriented control with stator flux of variable speed pump storage.

From (16) during operation λ_s^* is kept constant $\left(\frac{d}{dt}\lambda_s^* = 0 \right)$ therefore, i_{dr}^* can be written as:

$$i_{dr}^* = \frac{\lambda_s^* - v_{ds}\tau_s}{L_m} \tag{19}$$

According to [10] the electromagnetic torque can be express as a function of rotor current and stator flux linkages :

$$T_e = K_T \left(-i_{qr}\lambda_{ds} + i_{dr}\lambda_{qs} \right) \tag{20}$$

where $K_T = \frac{3PL_m}{2L_s}$.

Writing (20) into dq-axis components and taking into account the stator flux orientation $\left(j\lambda_{qs} = 0,\ \lambda_{ds} = \lambda_s \right)$

$$i_{qr}^* = \frac{-1}{K_T \lambda_s^*} T_e^* \tag{21}$$

According to [7] the power of generator and motor calculated by

$$P_{Generator} = P_T - P_J \tag{22}$$

$$P_{Motor} = P_P + P_J \tag{23}$$

where $P_{Generator}$ is the power output of generator, P_{Motor} is the power input of motor, P_T is the power output of turbine, P_P is the power input of pump, and P_J is the electrical power of rotor.

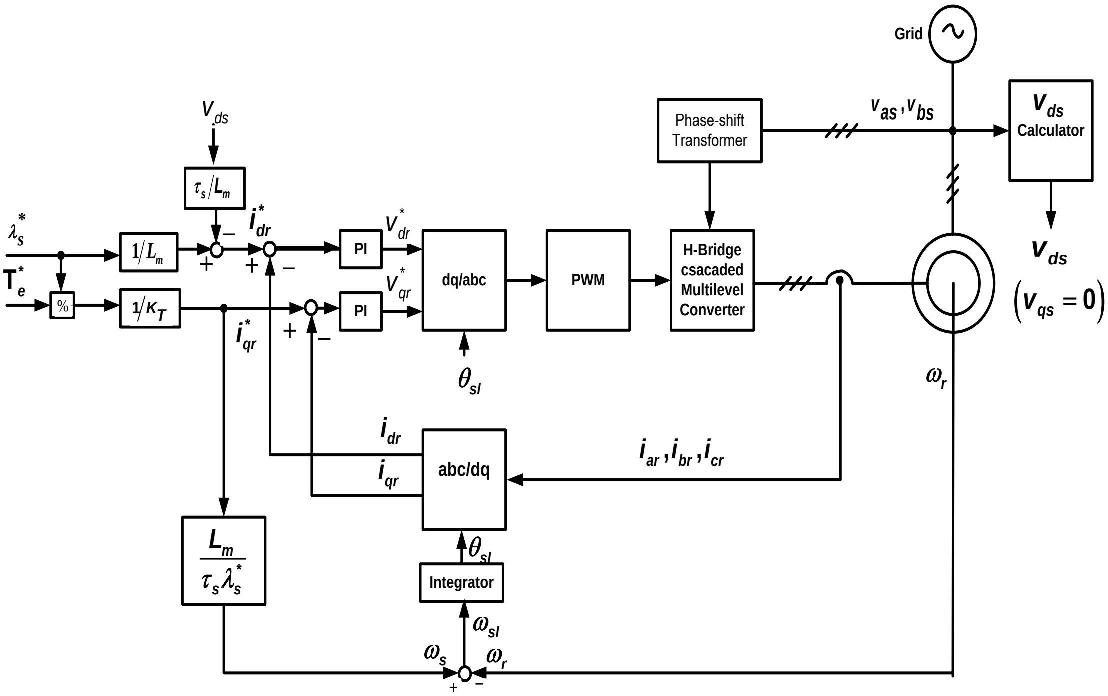


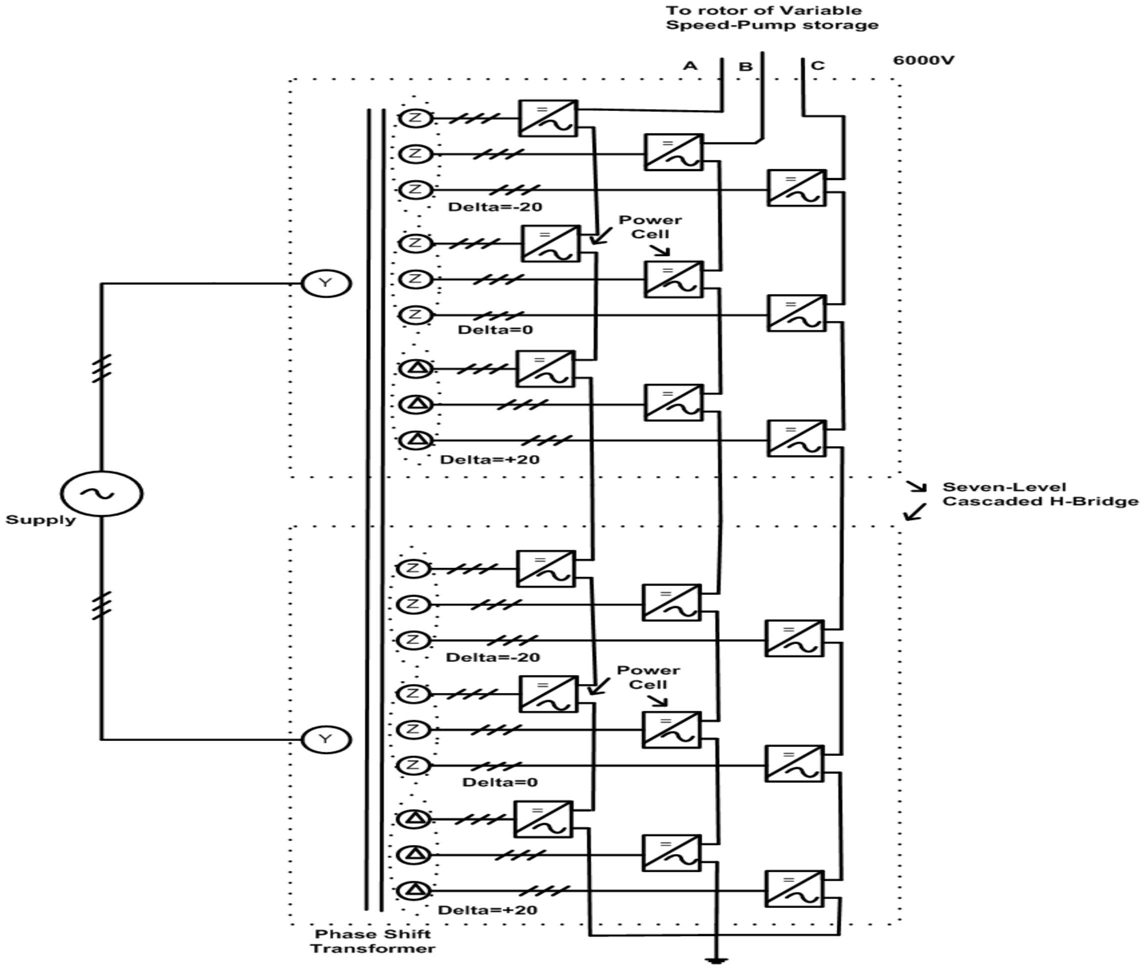
Figure 1. Indirect field oriented control with stator flux orientation

2.3. H-Bridge Cascaded Multilevel Converter

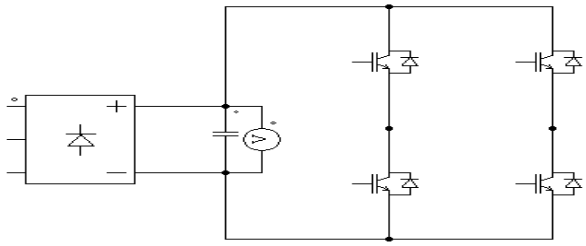
The configuration of H-bridge cascaded multilevel converter used to control the rotor side is shown in Figure 2, where two identical units of the seven level CHB converters are connected in cascade. Each power cell produced a 590 V. This topology consists of CHB converters and phase shift transformer. The main purposes of the shift phase transformer are: isolated power supplies for the power cells, improve the THD of the line current and separation between the utility and the converter for common mode voltage mitigation. According to [4], the phase -shift transformer connection, modulation techniques and advantages of H-bridge cascaded multilevel converter has been discussed. The in-phase disposition pulse width modulaation (IPD PWM) as shown has been designed to generate switching signals for full bridge inverter side. Although [12] has analyzed and used the carrier phase shift SPWM technology to generate the pluses of H-bridge cascaded multilevel inverter side. The angle between any phases of phase shift transformer is 20^o for any two identical seven levels of the H-bridge cascaded converter. The secondary winding of the shift phase transformer is connected to rectifier side of power cell. It is connected with construction $\left(Y/Z-2, Y/Z-2, Y/\Delta, Y/Z-1, Y/Z-1\right)$ .The pulses of this model are 30 diode rectifiers.

3. Results and Discussion

The PSIM software is used to build and simulate the overall system. The parameters of induction machine as shown in Table I. Based on the derivation obtained from section (2.2), the indirect stator-flux field orientation of the simulation of an overall system depends on the machine parameter's values R_s, L_s and L_m



(a) Circuit diagram



(b) Power Cell

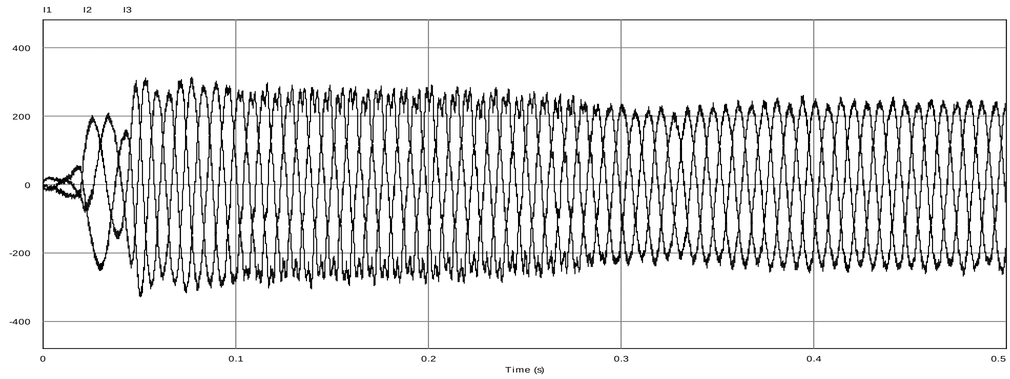
Figure 2. Configuration of 6KV with two identical 7-level H-bridge converters in cascade

Table 1. Induction Machine Parameters

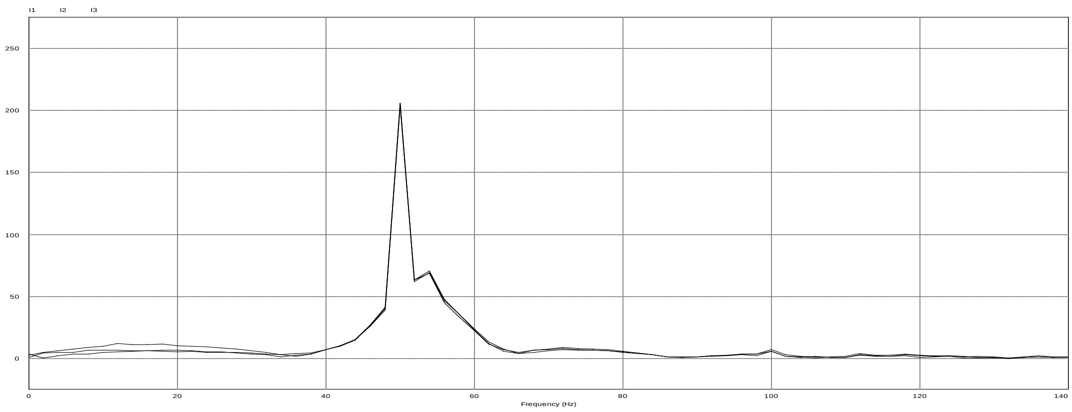
Parameter	Value
Number of poles (P)	6
Stator resistance (R_s)	1Ω
Stator leakage inductance (L_s)	1mH
Rotor resistance (R_r)	1Ω
Rotor leakage inductance (L_r)	1mH
Magnetizing inductance (L_m)	40mH
Moment of Inertia	50m kgm^2

The rotor currents and its fundamental frequency obtained by IFOC is shown in Figure 3. It shows that the current achieves a maximum value at fundamental frequency.

The phase voltage generated by seven-level cascaded H-Bridge converter in phase A is shown in Figure 4. During the transient state, only three and five levels are generated; the voltage arrives at the complete level at a steady state. The line to line voltage generated by the two identical cascaded H-bridge converters connected in cascade.

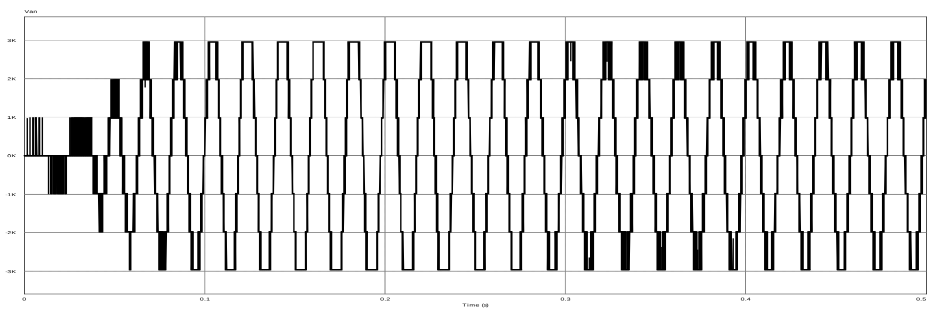


(a)

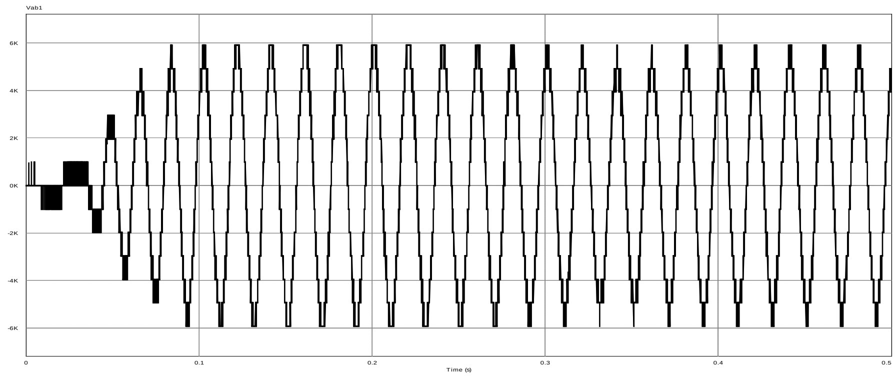


(b)

Figure 3. Waveforms of (a) rotor currents (b) rotor currents fundamental frequency



(a)

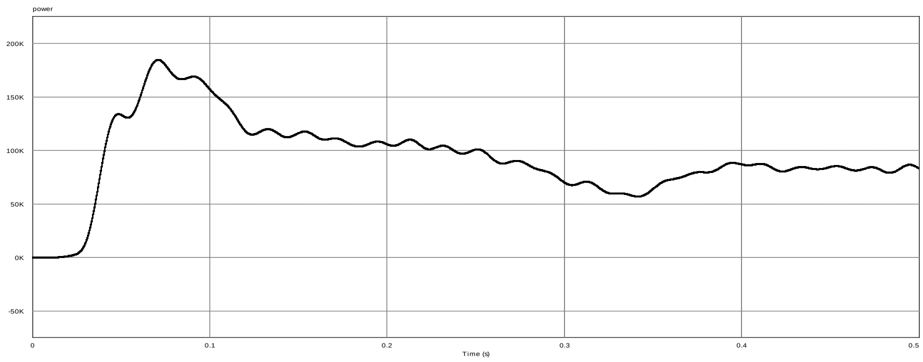


(b)

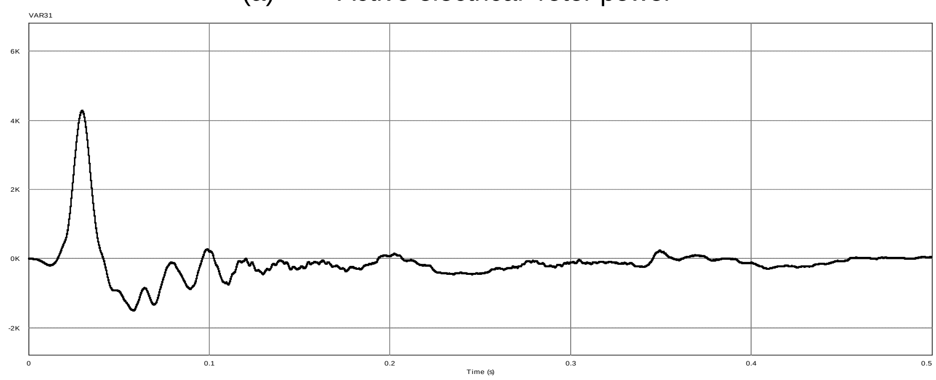
Figure 4. Waveforms of (a) phase voltage (b) line to line voltage with THD 10.7%

Figure 5 illustrates the waveforms of electrical active rotor power and reactive stator power respectevily. It is shown that the value obtained of reactive power is a good value approximately equal zero.

Using indirect stator flux field oriented control obtained variable speed of the machine. It has shown in Figure 6. The control of variable speed in this paper better than [3, 4], because only achieved it by changing the value of initial rotor speed, but in [3, 4] by changing the frequency of all input's sources of rectifier side.



(a) Active electrical rotor power



(b) Reactive stator power

Figure 5. Active electrical rotor power and stator reactive power

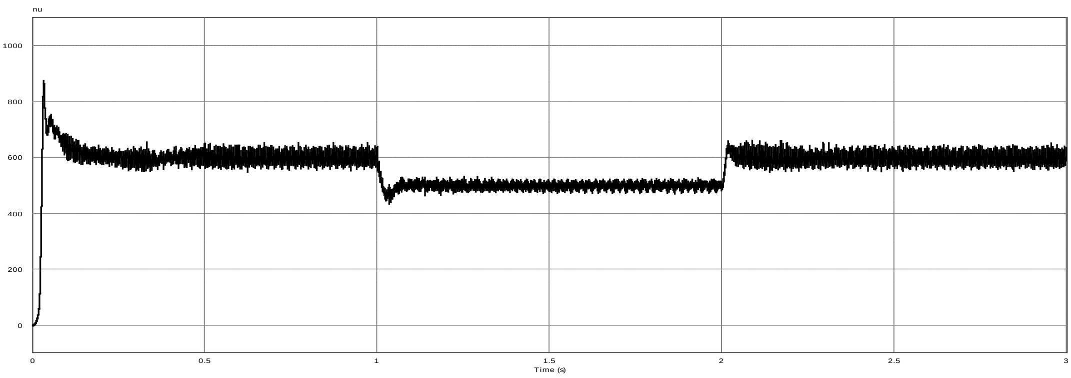


Figure 6. Speed changing from 400 rpm to 600 rpm

4. Conclusion

A mathematical model of a doubly fed adjustable-speed pumped storage unit (DFASPSU) based indirect field oriented control (IFOC) has been developed. A stator voltage oriented control (SVOC) scheme for the unit was derived and simulated. The use of this kind of technology (indirect field oriented control stator flux type) it easy obtained the variable speed of pump storage and best value of reactive power. The power electronics converter used to generate a high voltage on the rotor side is two identical seven levels H-Bridge cascaded multilevel converter connected in cascade. The system has been analyzed by using the PSIM software program.

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