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# A Novel Control Method Of Variable Speed Pumped Storage Power Plant

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***Abstract:*** *Despite the advantages of variable Speed pumped storage power plant (PSP) included, as following statements: increasment of optimum efficiency in production mode and consumption mode, high speed for grid's requirements response in critical moments (such as: disturbances, black out,...); it's necessary, to achieve these benefits easily by energy storage practices. Now Doubly Fed Asynchronous Machine (DFAM) technology by means of modern equipment (MLVSC, Cycloconvertor) and employment of them is considered to achieve mentioned purposes, synchronous machines instead in PSP units. In this paper, technical comparison between the several kinds of PSP's drives methods is presented; also a PSP's unit is modeled (as electric, hydraulic, mechanic& control system) and simulated by Direct Torque Control (DTC) technique and TwoLevelVSC equipment, as novelty.Application of TwoLevelVSC and DTC method togethercaused to increase very high dynamic response of PSP in uninterrupted operationthe whole of times.The results of paper in Generation mode, express to increase efficiency in one unit of 4×250MW PSP that justifiesvariable SpeedPSP application. The simulations performed by Matlab software.*
***Keywords:*** *Variable Speed Pumped Storage Power Plant (PSP), Direct Torque Control (DTC), Doubly Fed Asynchronous Machine (DAFM),Two-Level Voltage Source Converter (VSC).*

## I. Introduction

The novelty of variable speed machines (DFAM)[1] application has been introduced in the 1960s and 1970s immediately; after development of construction in the Pumped storage power plants in the world wide [1]. There are more than ten methods for driving and Starting DFAM. Some of these methods include: SFC[2]be side of one synchronous Machine, BrushlessDoubly-FedInduction Machine, DFAM with oneCycloconvertor and DFAM with Back-Back VSC (MLVSC)[3] among which MLVSC method, applied with two types as follow, Two-LVSC and Three-LVSC. By introduction of DTC method in the 1980s by I. Takahashi and T. Noguchi, Field Orientated Control (FOC) old method, instead with the twofold objective of simplifying the control algorithms and achieving similar or even better performances [2], [3] for driving DFAM.

In this paper, first introduced and evaluated the whole of applied control methods of DFAM in considering to technical points then employed simulations and model of DFAM's DTC with 2LVSC in a VSPSP's generator mode according to case study of 4× 250MW of SiahBisheh PSP by MATLAB Software, as novelty strategy, finally.

## II. Control methods of DFAM in PSP

Three important methods include: SFC side by side of synchronous machines, BDFIM andCycloconvertoror Inverters with DFAM, have been described as bellow:

### A. SFC equipment side by side of synchronous machines:

In this method, the benefits include: 1. the availability of Equipment related to SFC's building (grid side rectifier; harmonic eliminator inductor; machine (rotor) side alternator); 2. Prevent from inverse power flow inside generator, from grid; 3.Fast variations of load response; 4.Easy synchronized generator to grid where GOVERNOR application is inconclusive because of speed control. Soft starting and connection synchronous PSP to grid in pump mode and prevent from severe voltage dropping and inrush currents in condenser & motorized modes, are objectives of SFC equipment application. Fig. 1. Show the SFC equipment in a PSP.

1Doubly Fed Asynchronous Machines
2Static Frequency Converter
3Multilevel Voltage Source Converter

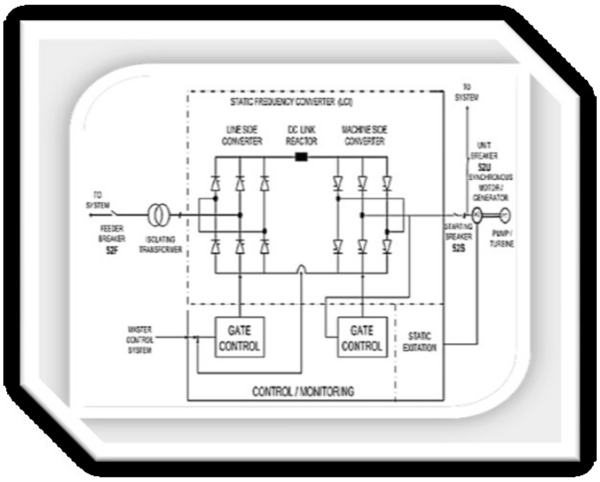



Fig.1. SFC equipment in a PSP schematic

When the unit can be operated at the rated speed; SFC can be dismissed by suitable electrical switching is improved stability, good electrical switching can be dismissed. Finally, it should be stated, although the stabilization of system improved by SFC equipment but system stability does not have much value by one than synchronous machines on the electrical network. Synchronous machines as stabilizers have effective& economic performance [4], [5]. InFig.2. Although this method has a wider range of performance than the method of poles changeable, but designing of the frequency converter as turbine's nominal power is one of the drawbacks of this method; because large volume and hence the high cost of installing these units. Today's application of DFAM technology rather than synchronous generators is one of the most efficient methods due to Considerable reduction in frequency converter's capacity, for solving the efficiency dropping problem in the changing of the pumped performance in to the turbine mode and reduction and elimination of mentioned restrictions.

**B. BDFIM**

In this suggested topology, in fact it is induction machine that stator section has two different kind of winding (different poles) that On the one hand connected to power system directly and on the other hand to one by frequency converter interface. Its rotor section is common. Then it has two different kind ofsynchronous speed.Building diagram of BDFIM, are shown in Fig.2.

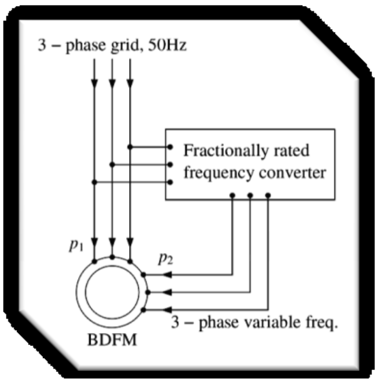



Fig.2. BDFIM building diagram

Therefore, maintenance costs will reduce significantly and increase reliability. So far, this method has been employed in Wind power plant [6]. With advances in technology are expected to employ this one in the structure of Pumped storage plants.

**C. DFAM with Ac- Ac Convertors:**

Cycloconvertor is direct decreasing frequency Convertor. The one equipment, employs SCR Thyristor as switching element and included two 3phases unparalleled current poles, embedded each phase as positive and negative ones.

By this instrument, DFAM's rotor windings connected to grid. Hence, provided optimum speed control on fourth modes (motor and generator modes in Sub synchronism or hyper synchronism) by means of regulating in SCR's firing angles.in this method, stator windings connected to power system, directly. In Fig.3 DFAM with Cycloconvertor building diagram in contact on grid, are illustrated. Therefore, speed, active and reactive power controlled by means of three phase Cycloconvertor's control set. In addition 3phases current of machine's rotor winding provided by Slip energy recovery.

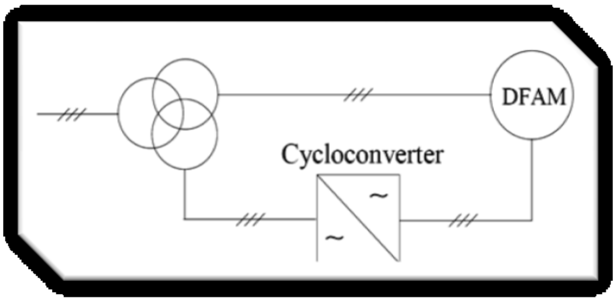



Fig.3 DFAM with Cycloconvertor building diagram

Despite of most Cycloconvertor's advantages included, as follow: 1. to be make high reliability; 2. Low maintenance cost; 3. Stability in transient, dynamic and steady state modes and … this equipment has many kind of restrictions, due to its connection to system, directly. They are suggested bellow:

a. When disturbances happen in power system, Cycloconvertor performance limited similar to other equipment (SFC, VSC).
b. Harmonic existence in out of convertor.
c. Effect on power system.
d. Effect of induction load on performance of ac controllers' angle phase (Cycloconvertor).

**D. DFAM with Back to Back Convertors (VSC):**

The way of VSC's Connection is likes to Cycloconvertor. There are rectifier and inverter in this method. Very fast and without interruption performance caused to reduce their considerable volume than the same of equipment. There are different kinds of switch, such as: 1. SCR; 2. IGBT[4];3.IGCT[5]; 4. GTO[6]; 5. IECT[7]. At high frequency application it is used mostly in MLVSC.Details of MLVSC's structure in 3Level for a Variable Speed PSP with capacity of2 × 320 MW are illustrated, in Fig.4 [7].

The benefits of MLVSC application than Cycloconvertor are as bellow:

a. Lower quantity of transformer and power electronic elements in inverter set than Cycloconvertor one.
b. To help voltage stability in grid; when disturbances (such as: SCC[8]) happen due to higher Inverter's switching frequencies.
c. To apply as STATCOM[9] and it produces reactive power in grid side.

Comparative evaluation on modern mentioned Driving methods with technical & economical considerations are

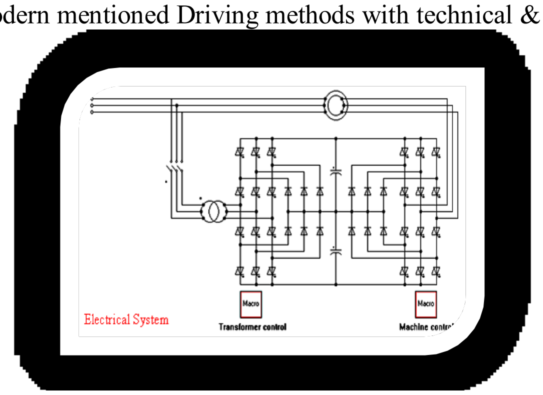



Fig.4. 3LVSC's structure in a Variable Speed PSP with capacity of 2 × 320 MW

[4] Insulated Gate bipolar Transistor
[5] ThyristorInjection Gate- commuted
[6] Gate Turn Off Thyristor
[7] Injection Enhanced Gate Transistor
[8] Short connection circuit
[9] Static Compensator

Illustrated in Table I. The suggested SFC equipment in this table has vast application in PSP now. This is very best equipment with economic consideration than the other adjustable speed methods but be notice, the other adjustable speed methods prefer from one due to both economic&technical consideration. Among of driving methods, PWM-MLVSC topology is proposed because of very fast driving speed and uninterrupted operation when happen a fault. Final method of this technique provides good dynamic response and quality of steady state in terms of stator current distortion.This method hasn't been applied in PSP, yet [8].

Table I
Technical and Economic Evaluation of Modern ControlStrategies in PSP

| **Driving Methods** | **Efficiencies** | **Equipment Type** | **Primary Costs** | **Reliability** | **O&M Costs** | **Driving speed** | **More Advantages** |
|---|---|---|---|---|---|---|---|
| **Synchronous Machine Drive** | 70% | SFC | Average Enough | Average | Low | Fast | Braking Ability |
| **DFAMDrive** | 80% | Cycloconvertor | High | High | very Slight | Fast Enough | Uninterrupted Operation in Voltage Dropping |
| | | MLVSC | Very High | High | Slight Enough | very Fast | Switching at High Frequency |
| | | PWM-MLVSC | VeryHigh | High | Slight | very Fast | Uninterrupted Operation in SCC |

## III. DTC strategy in DFAM:

The DTC is based on a direct control of two magnitudes of the machine, i.e. the electromagnetic torque and the rotor flux of the machine. This method is an alternative control solution for AC drives, ingeneral, that present control principles and performance features, different fromvector control techniques, as shown in old papers such as: FOC, FLC[10]…. This control technique hasthe following general benefits: 1.Reliability; 2.Good perturbation rejection; 3.fast dynamic response and so on [9]. Fig.5 shows Variable Speed PSP that controlled by DTC. Torque and the rotor flux amplitude of DFAM employed as main parameters in this method. Hence, the torque has a differentmanner affected by the rotor voltage vectors thus the operation conditions of the machine and the position of the rotor and stator flux space vectors described in the rotor reference frame make them [10].

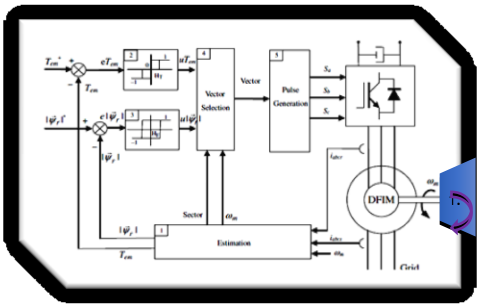



Fig.5. Hydraulic Turbine controlled by DTC

### A. Model Equations of the DFAM:

In this section the model equations of the DFAM are presented. Since the DTC is based on a direct control of the torque and flux rotor, it is necessary to deduce the relation between all the involved magnitudes to know how they affect to the controlled variables. Hence, the voltage and flux equations in the stator and the rotor reference frame are:

$$\vec{v}_s^s = R_s\vec{\imath}_s^s + \frac{d}{dt}\vec{\varphi}_s (1)$$
$$\vec{v}_r^r = R_r\vec{\imath}_r^r + \frac{d}{dt}\vec{\varphi}_r (2)$$

$$\vec{\varphi}_s^s = L_s\vec{\imath}_s^s + L_h\vec{\imath}_r^s (3)$$
$$\vec{\varphi}_r^r = L_r\vec{\imath}_r^r + L_h\vec{\imath}_s^r (4)$$

Thus, the torque can be calculated directly from the stator flux and rotor current as follows:

[10]Fuzzy Logic Control

$T_{em} = \frac{3}{2} * p.p.\frac{L_h}{\sigma * L_s * L_r} |\overrightarrow{\varphi_s}||\overrightarrow{\varphi_r}| \sin\delta$ (5)

Where $\vec{\imath}_r^s$, $\vec{\imath}_s^r$, $\vec{\imath}_r^r$, $\vec{v}_r^r$, $\vec{v}_s^s$,$\vec{\imath}_s^s$,$L_r$,$L_s$in order are rotor current vector in stator side, stator current vector in rotor side, Rotor current vector, Rotor voltage vector, Stator voltage vector, Stator current vector, Rotor self-inductance andStator self-inductance; in continuous,$L_h$, $\sigma$, $P.P.$, $R_s$, $R_r$, $T_{em}$, $\vec{\varphi}_r$, $\vec{\varphi}_s$ are Mutual-inductance, Leakage coefficient, Pair of poles, Stator resistance, Rotor resistance, Total electromagnetic torque, Rotor flux linkage vector, Stator flux linkage vector, Respectively. Also, δ is the angle between the stator and the rotor flux space vectors. The voltage dropped in the stator resistance has been neglected. Hence, the last equation show that the torque can be controlled by modifying the relative angle between the rotor and stator flux space vectors and their amplitudes. In the following section, the effect of the stator and rotor voltages on the fluxes will be analyzed by Fig.6 in D&Q axis [10].

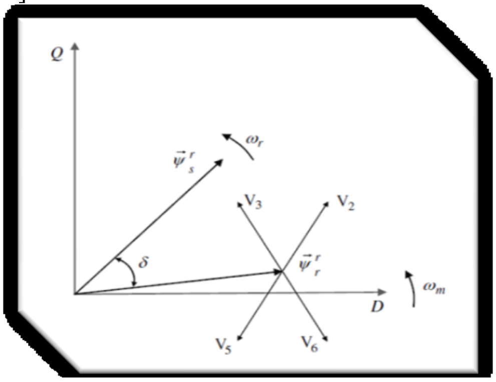



Fig.6. Effect of voltage vectors on regulation of torque and flux amplitude

**B. Effect of Voltage Vectors on DTC:**

In the study of the space vector diagram, it seeks to create a circular trajectory of the rotor flux space vector, as depicted in Fig. 6. By injecting the available rotor voltage vectors, the amplitude of the rotor flux space vector and its movement are controlled, in order to locate it to a specific distance from the stator flux space vector. Thus, with this simple control strategy, it is possible to modify the electromagnetic torque of the machine according to (5) [8]. Considering to Fig.7, space distances are 60°, called sector, in 2L_VSC

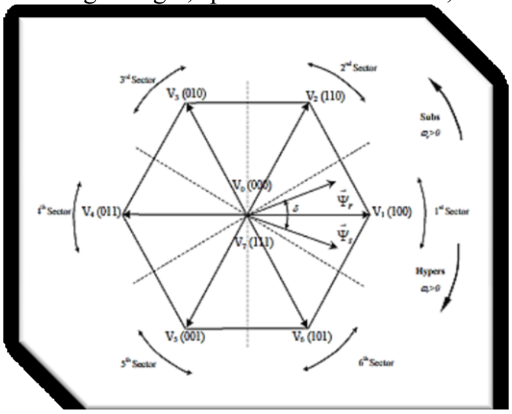



Fig.7. Flux space vectors in the rotor reference frame, in generator mode

When the speed of the machine is higher than the synchronous speed, as the space vectors rotate clockwise, the effect of the zero vectors on the electromagnetic torque for example, is the opposite at lower speeds than the synchronous speed. The corresponding space vector representation of the fluxes in the rotor reference frame is illustrated in Fig. 7 [9].

The block diagram of the proposed control strategy is shown in Fig. 5. As mentioned before, the directly controlled variables are the torque and rotor flux. Fig. 5 shows that the control strategy is divided into five different tasks represented in seven different blocks. The tasks carried out in blocks 1–5 are the DTC principles formulated in [11] and are estimable according to equations (1)-(5) [12].

From the torque and rotor flux references, the control strategy calculates the pulses (Sa, Sb, and Sc) for the insulated gate bipolar transistors (IGBTs) of the two-level voltage converter; More Details in this field and also, about total of DTFC strategy expressed in [11], [8], [9].

There is Table of 2LVSC'S switching considering torque& flux errors and rotor flux sectors described about DTC technology inTable II.

Table II
Table of 2LVSC'S switching in DTC Technology

| HT | | 1 | | 0 | | -1 | |
|---|---|---|---|---|---|---|---|
| H$\varphi$ | | 1 | -1 | 1 | -1 | 1 | -1 |
| Rotor Flux Sectors | 1 | $V_6$ | $V_5$ | $V_7$ | $V_0$ | $V_2$ | $V_3$ |
| | 2 | $V_1$ | $V_6$ | $V_0$ | $V_7$ | $V_3$ | $V_4$ |
| | 3 | $V_2$ | $V_1$ | $V_7$ | $V_0$ | $V_4$ | $V_5$ |
| | 4 | $V_3$ | $V_2$ | $V_0$ | $V_7$ | $V_5$ | $V_6$ |
| | 5 | $V_4$ | $V_3$ | $V_7$ | $V_0$ | $V_6$ | $V_1$ |
| | 6 | $V_5$ | $V_4$ | $V_0$ | $V_7$ | $V_1$ | $V_2$ |

## IV. Hydraulic Model of Variable Speed PSP

Hydraulic parts of these Plants are illustrated in Fig.11 [13], [14] as follow:

**A. Penstock Model**:

The Penstock is modeled by the following basic equations considering non-elastic water column. These equation Related to water's speed in Penstock, gravity influenced acceleration of water and power generation inside the turbine:

$$(H_0 - H - H_f)\rho g A = \rho A l (10)$$
$$H_f = f \times \frac{L}{D} \times \frac{U^2}{2g} = f_p \times Q^2 (11)$$
$$f_p = \frac{L}{D} \times \frac{f}{2g} \times \frac{1}{A^2} (12)$$

Water's initial time, required time during for water in $H_{base}$ (head) that one arrive at $U_{base}$ (speed) from static mode in the Penstock. This is as bellow:

$$T_w = \frac{LQ_{base}}{H_{base}\, gA} \times \frac{LU_{base}}{H_{base}\, g} (13)$$

**B. Surge Tank Model:**

Elasticity of channel wall causes traveling waves as pressure and flow in water; it is generally recognized Water Hammer or Ram Impact. In fact, Water hammer is the sudden change in rate of water flow when pressure regulation inside water accomplishes in higher and lower margin than normal margin of pressure. It is two necessary numbers of problems to be caused Ram Impact in power plant's channel, as follow: 1.To open and close Plant's input valves; 2. Regulation of Guide van's openness. Surge Tank making is to overcome the damaging effects of water hammer in Hydroelectric Plants.

In a rigid system, the period of surge tank's oscillation is calculated as follows ($H_f$ neglected):

$$T_{st} = 2\pi \sqrt{\frac{lA_s}{gA}} (14)$$

$$C_s = \frac{A_s H_{base}}{Q_{base}} (15)$$

**C. Turbine Model:**

Output power of turbine is expressed as bellow:

$$P_m = \eta Q \rho g H \ (16)$$

It is important to produce effective current in output power, non-load current ($Q_{nl}$) subtracted by main current (Q) in actual condition considering losses existence. Considering turbine damping due to turbine vans' openness (G) and rotor speed changes is importance, too.

$$P_m = A_t H (Q - Q_{nl}) - D_n G \Delta\omega \ (17)$$

Current rate of turbine is expressed as bellow:

$$Q = G\sqrt{H} \qquad (18)$$

Plant's hydraulic parts Model is shown in Fig.12 [15] for non-elastic& elastic water column.

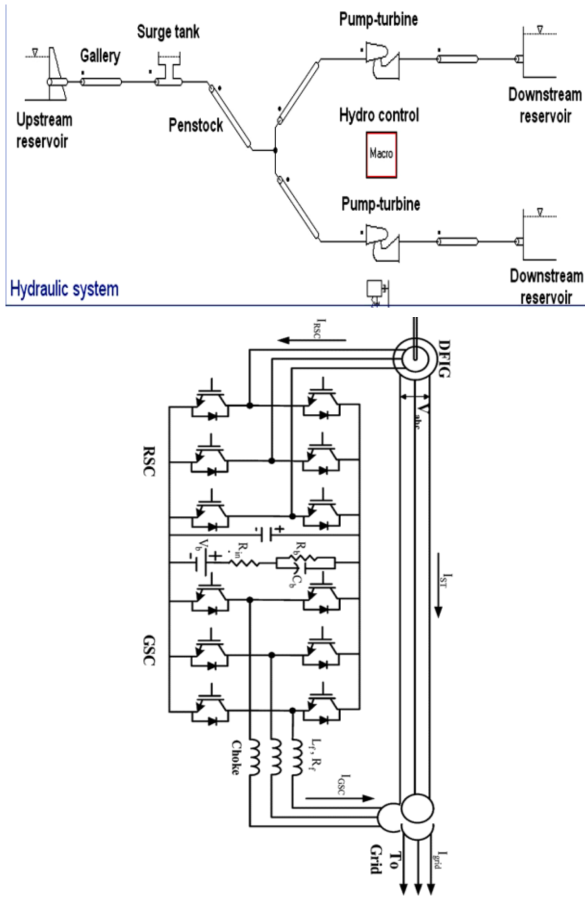



Fig.11 Variable Speed PSP's Hydraulic parts

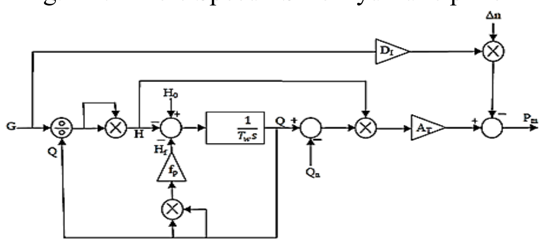


Fig.12 Plant's hydraulic parts Model

## V. Case Study

The Siahbisheh PSP situated between Karaj Chaloos, and the neighboring Siahbisheh village, in north of Iran [15]. These plants have 4 synchronous units with capacity of 250MW. In this paper, one of plant's units analyzed and simulated as DFAM considering proposed strategy by replaced synchronous one. Important parameters about it illustrated in Tables as bellow:

Table III
Turbine and HydraulicCharacteristics of Siahbisheh PSP

| Turbine Characteristics | | | | |
|---|---|---|---|---|
| Speed (rpm) | Non_Load Debbi ($m^3/s$) | Nominal Height (m) | Nominal Power (MW) | Nominal Debbi ($m^3/s$) |
| 500 | 8 | 476.17 | 260.35 | 59.49 |

Hydraulic Characteristics

| Part | Type | Length (m) | Diameter (m) | Nominal Current $(m^3/s)$ | Speed $(m/s)$ | Friction Factor |
|---|---|---|---|---|---|---|
| Right Water ways | Metal | 882 | 5 | 130 | 6.62 | 0.008 |
| | Concrete | 1926 | 5.6 | 130 | 5.09 | 0.012 |
| LeftWa terways | Metal | 902 | 5 | 130 | 6.62 | 0.008 |
| | Concrete | 1969 | 5.6 | 130 | 5.09 | 0.012 |

Table IVConvertor&TransformerCharacteristics

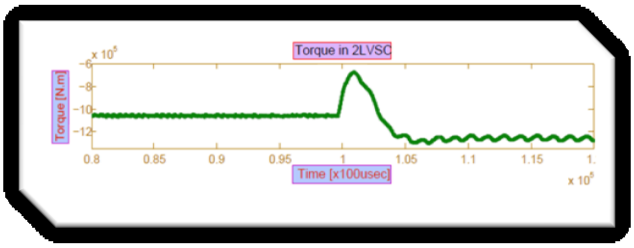
| Frequency (HZ) | Transformer Connection | Output Voltage (KV) | Input Voltage (KV) | Capacity (MVA) |
|---|---|---|---|---|
| 50 | Yy0 | 3 | 18 | 26.17 |

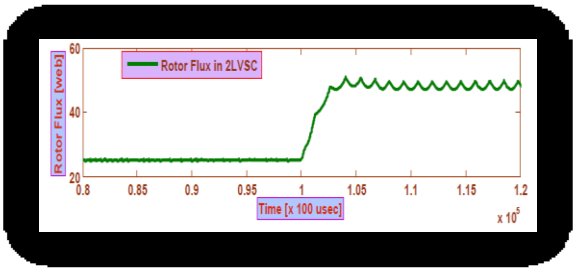
Table VApplicable DFAM Characteristics inSiahbisheh PSP

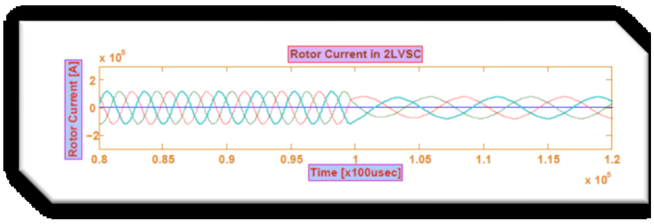
| Mutual Reactance (Pu) | Rotor Reactance (Pu) | Rotor Resistor (Pu) | Stator Reactance (Pu) | Rotor Resistor (Pu) | Pair Poles | Rotor Voltage (KV) | Stator Voltage (KV) | Active Power (MW) | Apparent power (MVA) |
|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 0.101 | 0.01453 | 0.1 | 0.01393 | 6 | 3 | 18 | 250 | 306 |

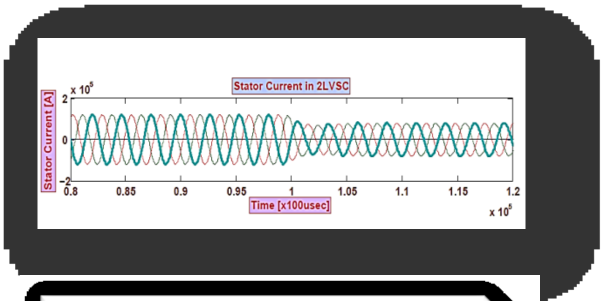
**A. Simulation Results:**

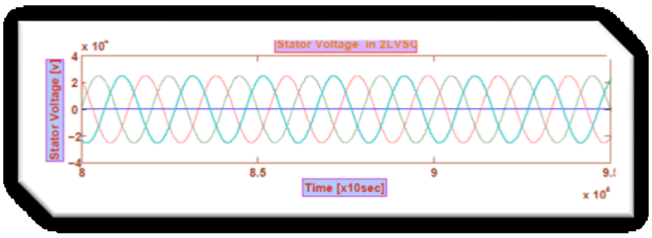
The simulation results are presented for the studied strategy in generating mode (by DTC Technology with 2LVSC) by means of MATLAB software for SiahBisheh PSP considering tables of case research. The Figures show that changes in Electromagnetic Torque, Rotor Flux, Stator voltage& current, Rotor current and Rotor Flux position. The new reference torque is reached very fast in less than 0.1s rather than proposed strategy in [14] because the torque is controlled by the electrical system, as shown in Fig. 13 while rotor flux is constant; In Fig.15 amplitude of rotor current is lower than stator current in 075 s. amplitude of voltage stator has stayed constant the whole of times, illustrated in Fig 17.



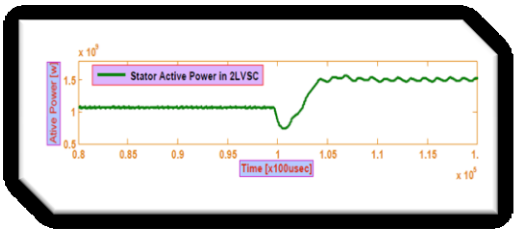




Fig.17Stator Voltage in DTC

Fig.18Stator Active Power in DTC

In figures 18&19, stator active power increased 30%, approximately and stator reactive power decreased the same quantity, too; therefore, the fly wheeling effects of DFAM's rotor presented.

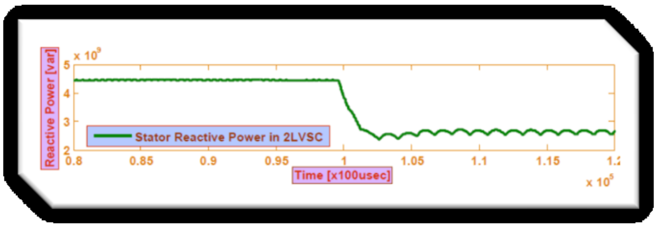



Fig.19 Stator Reactive Power in DTC

Regulation of rotor flux position and rotor speed are depicted in order figures 20 and 21.

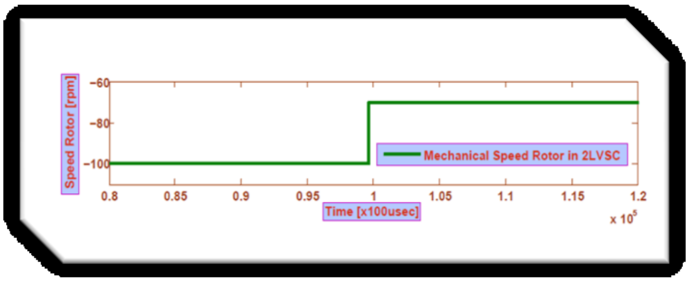



Fig.20Rotor Speed in DTC

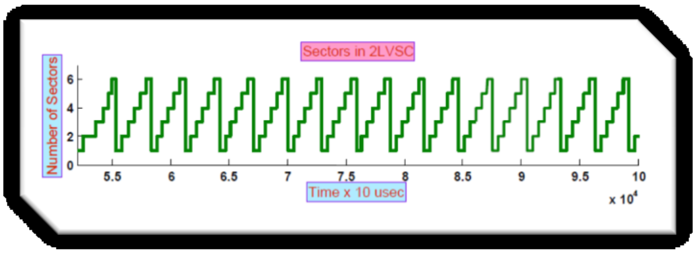



Fig.21 Rotor Flux Position in DTC

## VI. Conclusion

In this paper, technical evaluation& comparison between the whole of PSP's drives methods performed. Investigation results show although, primary costs of Variable Speed PSP is more expensive than PSP but also, the VSPSP has more efficiency than PSP that it's 10% approximately. Among of drive& control topologies for PSP, DTC with 2LVSC is proposed. By this topology, despite of correction and elimination the some of the other equipment's restrictions, provided to increase dynamic response, uninterrupted operation when happen a fault and separate and optimum control between active &reactive power achieved. No need to reactive power compensator in grid side is one of the other Variable SpeedPSP's benefits, too.

The behavior of a Variable SpeedPSP's unit of 4×250 MW, including hydraulic, electro-mechanical and control systems has been simulated in generating mode. It is show that the strategy based on generator power control provides all of mentioned advantages, such as: extremely high dynamic performances in fullcompatibility with safety requirements. Indeed, a 30% activepower change can be achieved in 0.1s by proposed strategy, due to the flywheel effect. Also, efficiency in generation mode has incraesed.

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