ISSN No:-2456-2165

Rotor Current Control of DFIG Using Pi, Fuzzyand Fuzzy-Pi Controllers

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Abstract:- Doubly Fed Induction machines (DFIM) are very widely used to control the power flow in the power system. DFIM operating in generating mode is used to penetrate the active power into the power system. DFIG is driven by wind turbine that rotates at wind speed which is dynamic in nature. So a proper fast and accurate acting controller is required to operate the generator at the desired conditions. A new PI- Fuzzy logic controller is used to meet the desired specifications with least possible over/under shoots, settling time and steady state error. PI-fuzzy controller modulates pulse width given to rotor side converter of DFIG. The performance of the proposed controller is compared individually with both PI and Fuzzy logic controllers. The advantages of the proposed controller are described. The proposed PI-fuzzy based controlled and wind turbine driven DFIG can be used as a good decentralized and distributed generator which is useful as part of green and environmental friendly energy sector.

Keywords:- *Doubly fed Induction Generator (DFIG), PI-Fuzzy controller, Rotor Side Converter (RSC).*

I. INTRODUCTION

Electrical energy is the most consumed form of energy nowadays. Per capita consumption of electrical energy is increasing day by day across the globe. With increase in industrial revolution, the requirement for electrical energy is much more increased. Fossil fuels are burnt to produce huge steam energy which is used to to drive the turbines of thermal power plant based generators. Environment is getting polluted due to carbon emissions which is the main concern now and the quantity of coal is getting extinction over the years. These are the main reasons energy is required to produce at the cost of environmental safety. Renewable energy sources are largely used to produce electrical energy. Solar, wind[1], geothermal and tidal energy are main sources of renewable energy. In this paper, wind energy[2] based generator is used. Wind turbine[3] is driven by wind that is variable in nature. Wind turbine is modeled to produce equivalent mechanical power to drive the asynchronous generator [4]. Asynchronous generator rotates at speeds other than synchronous speed. Doubly Fed induction machine has four windings. This mode of operation is known as "generating mode." Various wind turbine models have been studied in this paper; The advantages of rotor connected back-to-back VSC control is mainly independent control methodologies for real and reactive powers, and relatively reduced VSC cost and losses. In the stator circuit, power is controlled through rotor direct and quadrature current components ($I_{dr,}I_{qr}$) using Proportional- Integral (PI) and Fuzzy Logic Control (FLC) controllers. The results implicate a better performance of the FLC. The settling time is reduced significantly, no overshoot occurs and oscillations are damped out at quick rate. However, the main contribution of the paper is to identify the impact of designing rotor current controller using a hybrid Fuzzy Proportional-Integral (Fuzzy PI) algorithm on the DFIG system response andpower injection. In the comparison between three types of control methodologies namely, PI, FLC and Fuzzy- PI, for a 1.5-MW horizontal axis fixed speed wind turbine is presented [8]. The steady state performance parameters considered in the paper are over/undershoot, settling time and steady state error. The results indicate that Fuzzy-PI scheme has reduced settling time, peak over/undershoot values and damped out oscillations at quicker rate. In [6], it is proposed a classical PI and Fuzzy-PI controller design to perform isolated control of real and reactive powers for DFIG. Hence the paper emphasizes the advantage of the hybrid Fuzzy-PI controller in obtaining the better steady state performance parameters, which affect the system performance to a great extent.

II. DOUBLY FED INDUCTIONGENERATOR:

Doubly fed induction machine is generally an electric electric generator or motor. The mode of operation depends on the electromagnetic torque and speed. The stator and rotor windings consume or inject the power between mechanical shaft and the entire electrical system. When a motoring torque is generated, which means the torque is positive, the doubly fed electric machine works as a doubly fed induction motor. When an electromagnetic torque is generated, the torque is negative then the machine works as a doubly fed induction generator.

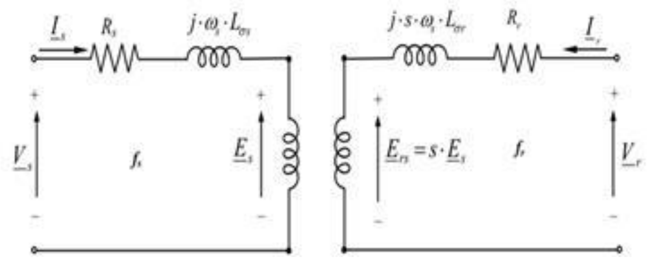


Fig: 1 : Single phase steady state equivalent electric circuit of the DFIM , rotor frequencies, current, and voltages referred to the stator.

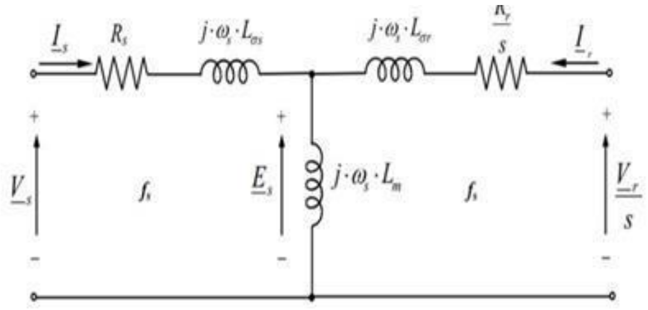


Fig 2: Single phase steady state equivalent electric circuit of the DFIM referred to the stator.

Table 1: Specifications of the DFIG in the case study

Parameter	Value	Feature
Synchronism	1500 rev/min	Synchronous speed at 50 Hz
Rated power	2 MW	Nominal stator three-phase active power
Rated stator voltage	690 Vrms	Line-to-line nominal stator voltage in rms
Rated stator current	1760 Arms	Each phase nominal stator current in rms
Rated torque	12.7 kNm	Nominal torque at generator or motormodes
Stator connection	Star	
p	2	Pair of poles
Rated rotor voltage	2070 Vrms	Line-to-line nominalrotor voltage in rms
Rotor connection	Star	
u	0.34	
Rs	2.6 mΩ	Stator resistance
$L_{\sigma s}$	87 µH	Stator leakageinductance
L_m	2.5mH	Magnetizing inductance
R_r'	26.1mΩ	Rotor resistance
$L_{\sigma r}$’	783µH	Rotor leakage inductance
R_r	2.9mΩ	Rotor resistance referred to the stator
$L_{\sigma r}$	87µH	Rotor leakage inductance referred to the stator

A) OVERALL WT BASED DFIG MODELDESIGN:

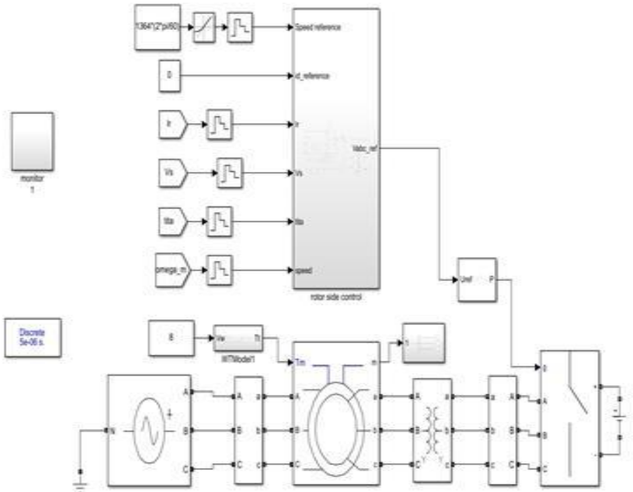


Fig 3: Overall Wind Turbine based DFIG model design

B) ROTOR SIDE CONTROL SYSTEM BASED SIMULATION BLOCK DIAGRAM OF A WT DFIG:

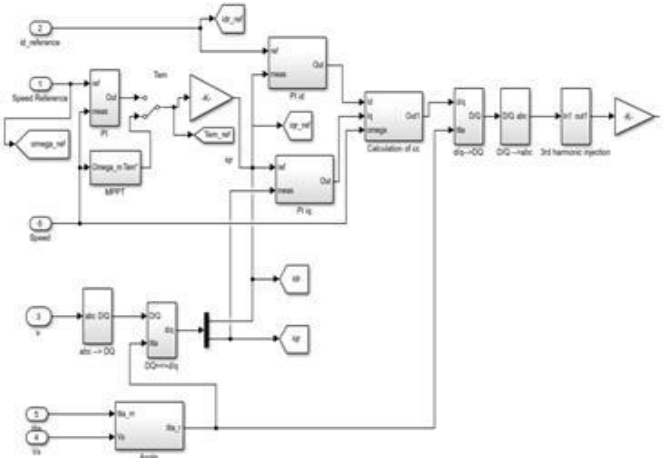


Fig 4: Rotor side Control system based simulation

Case 1) DFIG operation using PI controller:

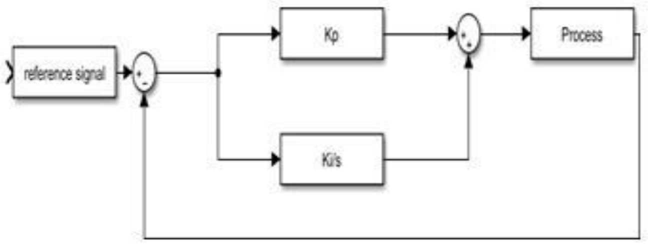


Fig 5: PI controller design of the DFIG wind turbine The values of the PI controller coefficients, and for both rotor current components, were tuned until the desired control gains were obtained. Here the process is Rotor side converter of DFIG.

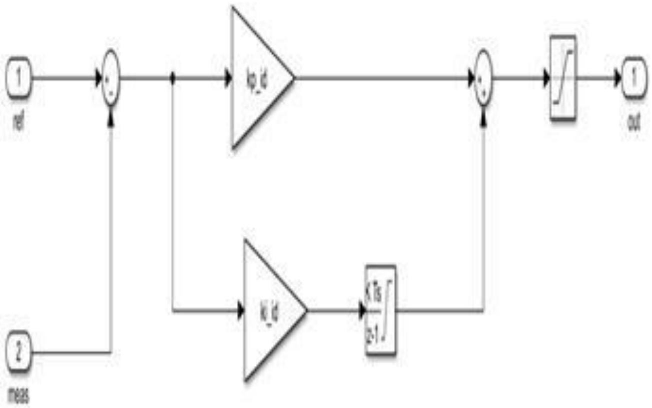


Fig 6: PI controller design of the DFIG wind turbine.

Case 2) DFIG operation using Fuzzy logic controller:

The main concept behind the fuzzy logic is studying analog inputs in terms of logical variables that can take continuous values between 0 and 1. Fuzzy logic control is considered[7], in many occasions, more effective than the conventional control, especially in large-scale systems. It is usually adopted in electronics systems in order to enhance the system performance by minimizing the fluctuations of the system outputs. Fuzzy logic is mainly based on the element (x) and the associated membership function (µ) which determines the percentage of this element belonging to the fuzzy set. A general fuzzy set (A) is represented by a membership function µ and the element which can have any value in the range (X) asrepresented in the equation below.

$A \quad = \{(,())| \in \}.$

Fuzzy logic controller for the rotor currentcomponents

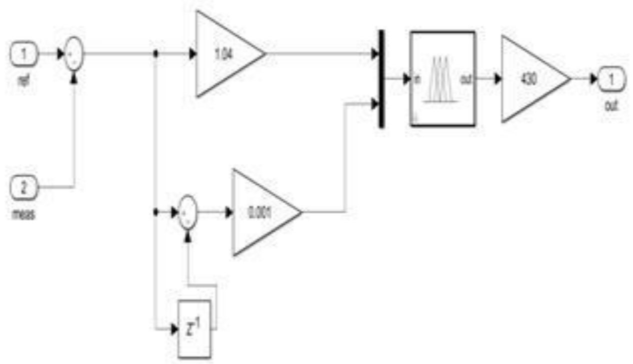
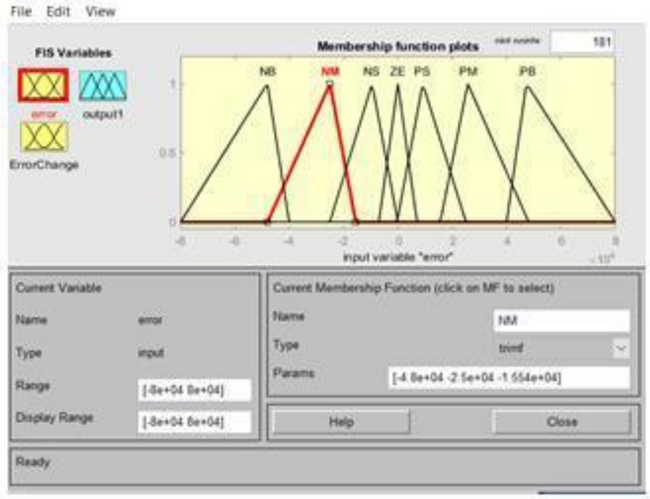


Fig 7: Fuzzy logic controller for the rotor current components

Input membership functions for fuzzy controller.



Current Variable

Name error

Type input

Range [-8e+04 8e+04]

Display Range [-8e+04 8e+04]

Current Membership Function (click on MF to select)

Name NM

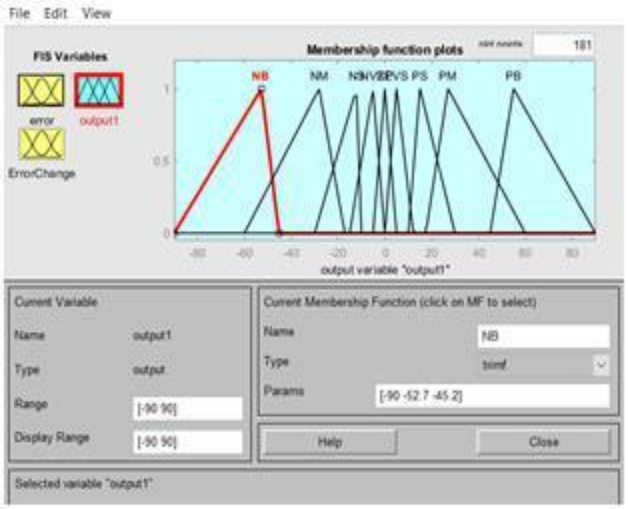
Type trimf

Params [-4.8e+04 -2.5e+04 -1.554e+04]

Ready

Fig 8: Input membership functions for fuzzycontroller.

Output membership functions for fuzzy controller.



Current Variable

Name output1

Type output

Range [-90 90]

Display Range [-90 90]

Current Membership Function (click on MF to select)

Name NB

Type trimf

Params [-90 -52.7 -45.2]

Selected variable "output1"

Fig 9: Output membership functions for fuzzy controller

Case 3) DFIG operation using Fuzzy-PIlogic controller:

Fuzzy PI controller[6] is a hybrid controller that employs PI gains to create a nonlinear response. In this work, suitable PI gains were selected using trail error tuning method to obtain best system response that maximizes power extraction at different wind speeds. The obtained PI gains are:Kp = 0.5771 and Ki = 491.5995. Two fuzzy logic controller inputs are chosen: i) The rotor current error and ii) The one-step delayed rotor current error.

Fuzzy-PI controller design for rotor currentcomponents:

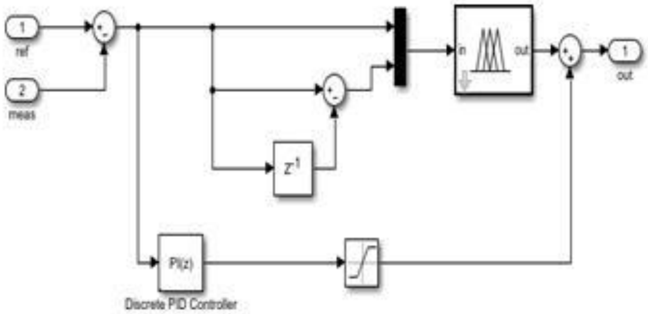
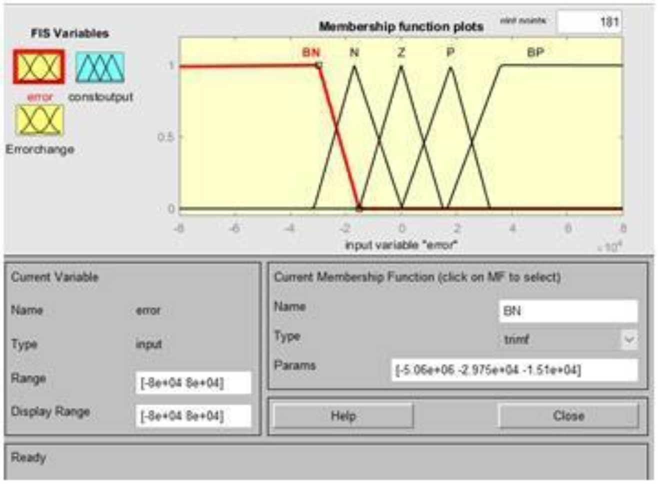


Fig 10: Fuzzy-PI controller design for rotor current components

Input membership functions for fuzzy-PI controller:



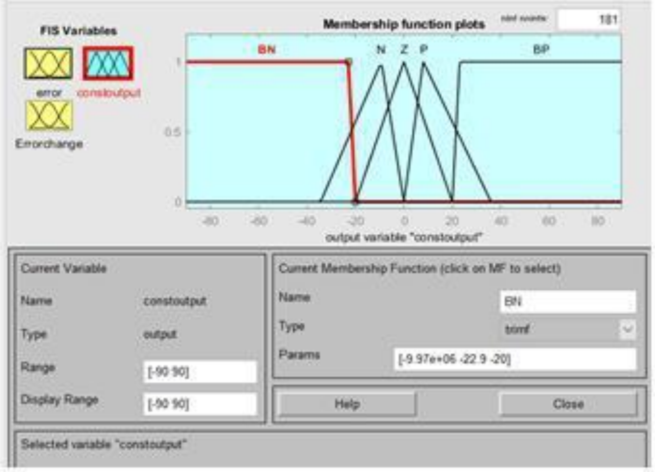
Current Variable
Name error
Type input
Range [-8e+04 8e+04]
Display Range [-8e+04 8e+04]

Current Membership Function (click on MF to select)
Name BN
Type trimf
Params [-5.06e+06 -2.975e+04 -1.51e+04]

Ready

Fig 11: Input membership functions for fuzzy-PI controller

Output membership functions for fuzzy-PI controller.



Current Variable
Name constoutput
Type output
Range [-90 90]
Display Range [-90 90]

Current Membership Function (click on MF to select)
Name BN
Type trimf
Params [-9.97e+06 -22.9 -20]

Selected variable "constoutput"

Fig 12: Output membership functions for fuzzy-PI controller.

III. SIMULATION RESULTS

A) PI controller:

Tuned values
Kp=0.5771.
Ki= 491.5995.

Three phase stator voltage system with PI controller :

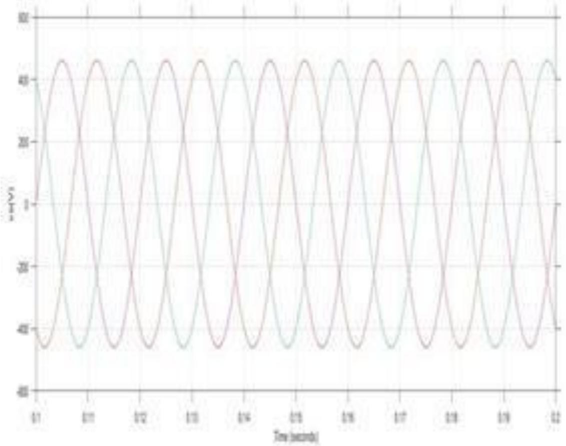


Fig 13: Three phase stator voltage waveforms

Three phase Rotor current waveform with PI controller :

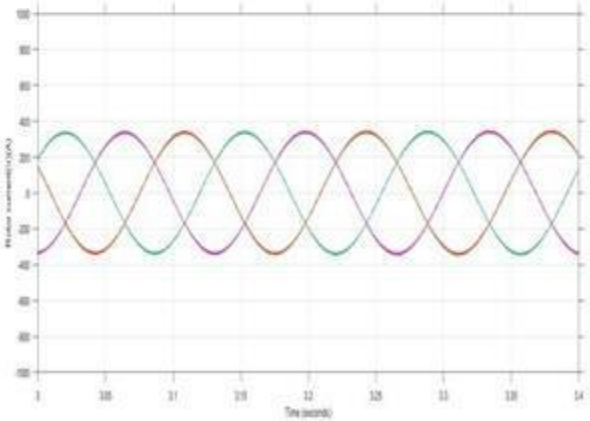


Fig 14: Three phase rotor current waveforms

Reference Values:

1) Reference speed is 1364 rpm or 142.7 rad/sec.
2) Reference Torque is -5582 N-m
3) Reference direct axis current component of rotor current is zero.
4) Reference quadrature current component is1112 A.

Direct axis component of rotor current wave with PI controller (I_{dr}):

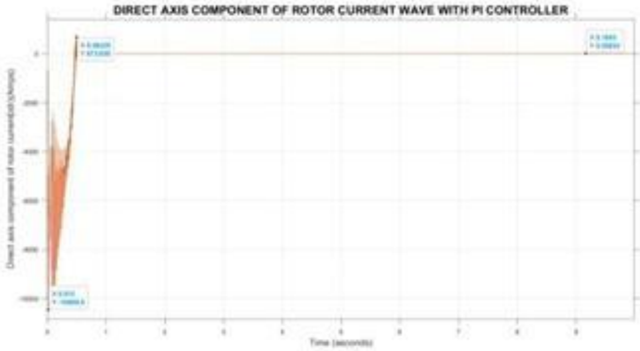


Fig 15: Direct component of rotor current waveform.

Quadrature axis component of rotor current wave with PI controller (I_{qr}):

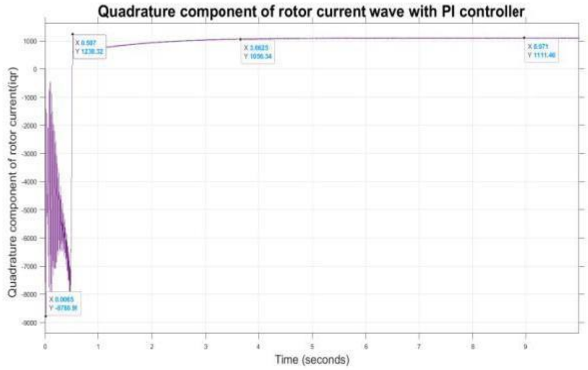


Fig 16: Quadrature component of rotor current waveform

Rotor speed with PI controller(W_r:

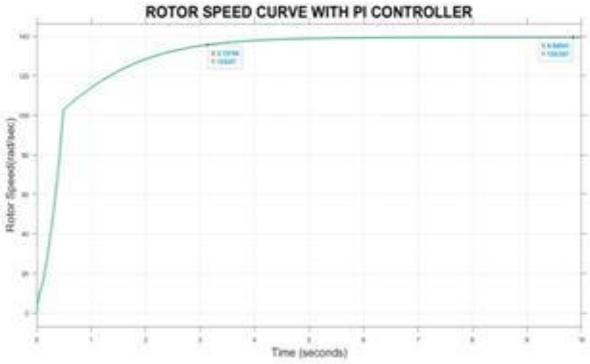


Fig 17: rotor speed waveform

Electromagnetic torque with Pi controller(T_e)

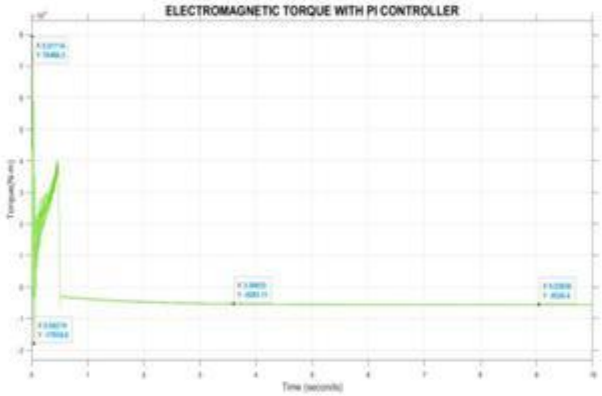


Fig 18: Electromagnetic torque waveform

Performance parameters peak overshoot, settling time (5% tolerance) and Steady StateError for the variables is given Shown below . PI controller is used to obtain the desired characteristics.

Table 2: Steady state analysis for DFIG wind turbine with PI controller.

Performance parameter	I_{dr}	I_{qr}	Rotor speed	Torque
Peak over shoot	673.655 A	1238.32 A	---	794466.3 N-m
Peak under shoot	-10468.4 A	-8780.9 A	---	-17936.3 N-m
Settling time (5%)	---	3.662 Sec	3.131 Sec	3.59653 Sec
Steady State Error	-8.558 A	-0.54 A	-3.193 rad/sec	51.6 N- m

Fuzzy logic controller:

Three phase stator voltage system with Fuzzy logic controller

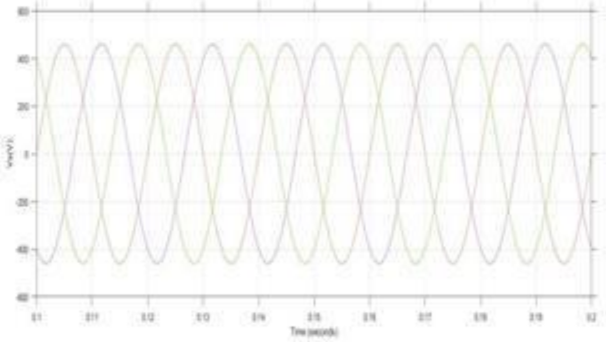


Fig 19: Three phase stator voltage waveforms

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Three phase rotor current waveform with Fuzzy logic controller

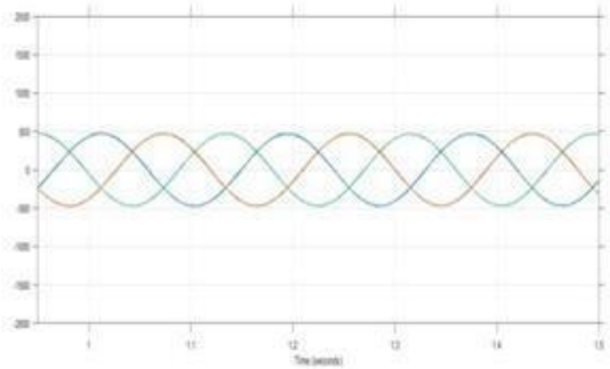

Fig 20: Three phase rotor current waveforms

Reference Values:

1) Reference speed is 1364 rpm or 142.7 rad/sec.
2) Reference Torque is -5582 N-m
3) Reference direct axis current component of rotor Current is zero.
4) Reference quadrature current component is 1112 A.

Direct axis component of rotor current wave with fuzzy logic controller (I_{dr}):

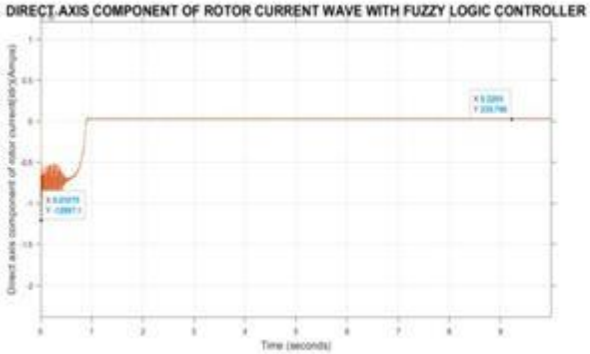

Fig 21: Direct component of rotor current waveform

Quadrature axis component of rotor current wave with fuzzy logic controller(I_{qr}):

The performance parameters are peak over shoot, peak under shoot, settling time (5% tolerance) and Steady State Error for the variables are tabulated below 3.1 when Fuzzy controller is used to obtain the desired characteristics.

Table 3: Steady state analysis for DFIG wind turbine with fuzzy controller

Performance parameter	I_{dr}	I_{qr}	Rotor speed	Torque
Peak over shoot	---	---	---	29684.6 N-m
Peak under shoot	-12097.1 A	-7347.08 A	---	- 8917.5 N-m
Settling time (5%)	---	0.968 Sec	0.897 Sec	1.614 Sec
Steady State Error	238.73 A	-17.18 A	-3.715 rad/sec	262.12 N-m

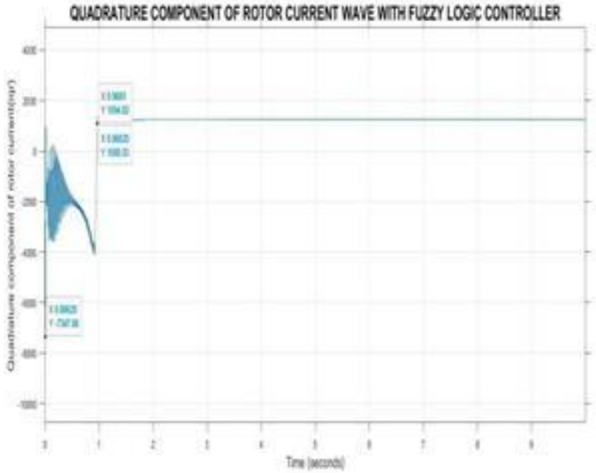

Fig 22: Quadrature component of rotor current waveform.

Rotor Speed curve with Fuzzy logiccontroller (W_r):

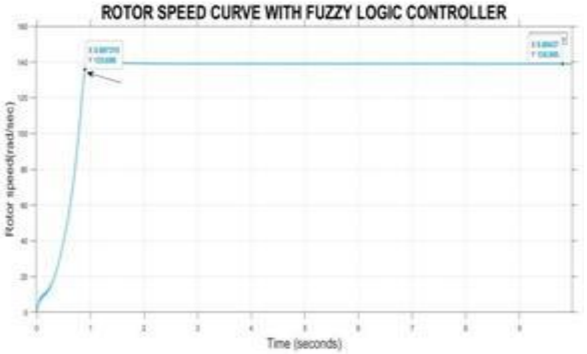

Fig 23: Rotor speed waveform

Electromagnetic torque wave with fuzzy logic controller (T_e):

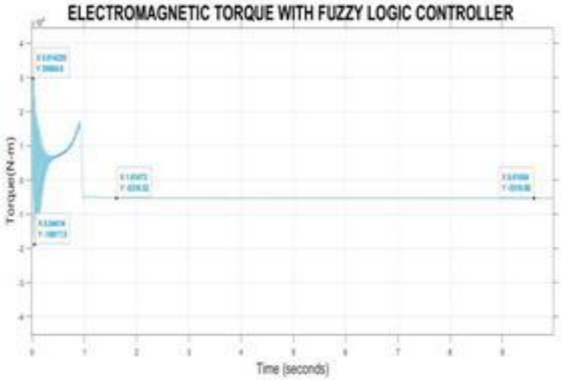

Fig 24: Electromagnetic torque waveform

C) Fuzzy-PI logic controller:

Three phase stator voltage system with fuzzy- PI controller

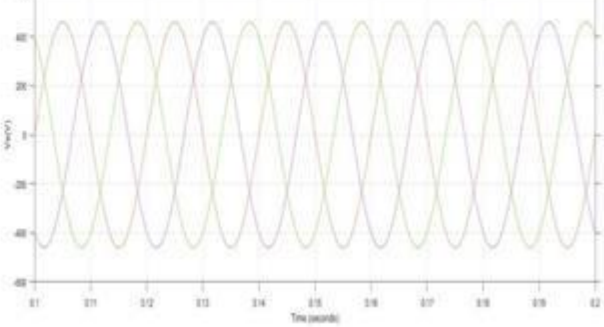

Fig 25: Three phase stator voltage waveforms

Three phase rotor current waveform with fuzzy-Pi controller

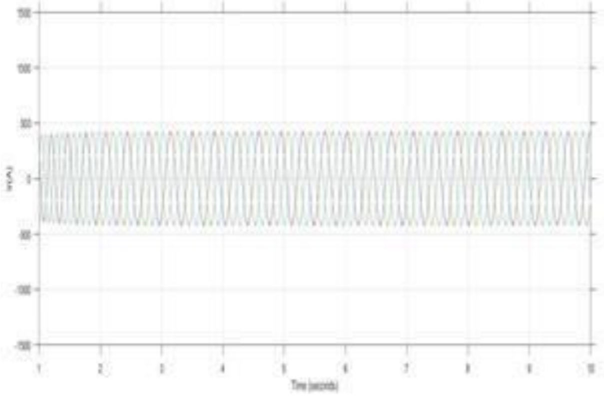

Fig 26: Three phase rotor current waveforms

Direct axis component of rotor current wave with fuzzy-PI controller (I_{dr}):

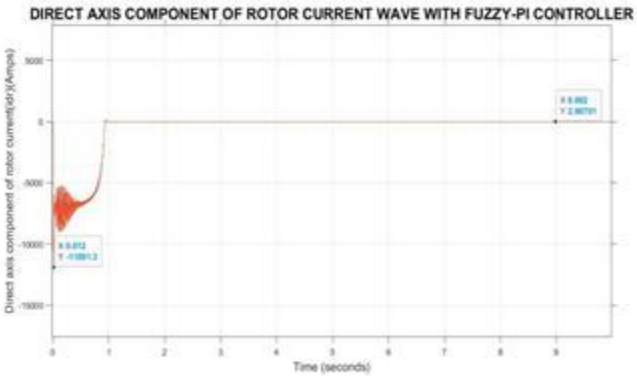

Fig 27: Direct component of rotor current waveform

Quadrature axis component of rotor current wave with fuzzy-PI controller(I_{qr}):

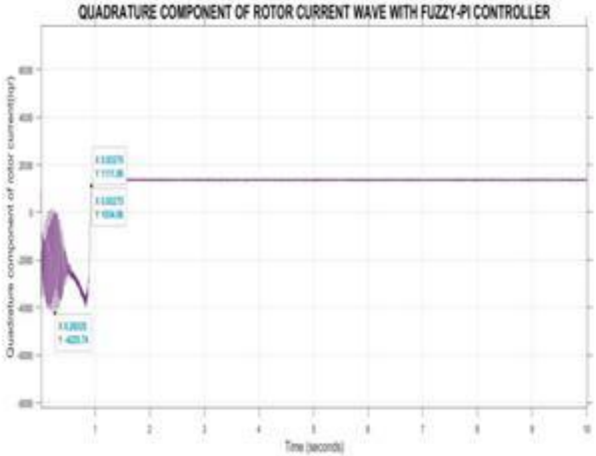

Fig 28: Quadrature component of rotor current waveform

Rotor Speed curve with fuzzy-PIcontroller (W_r):

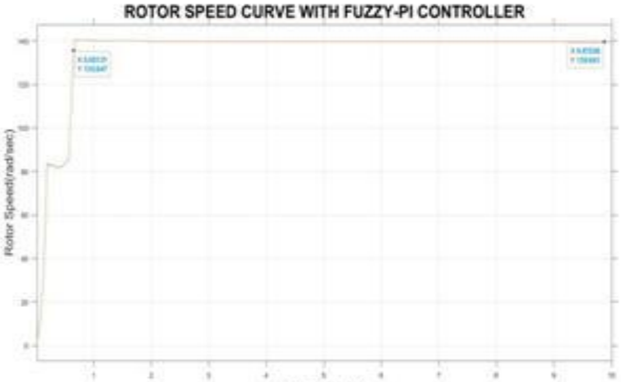

Fig 29: Rotor speed waveform

Electromagnetic torque wave with fuzzy- PI controller(T_e)

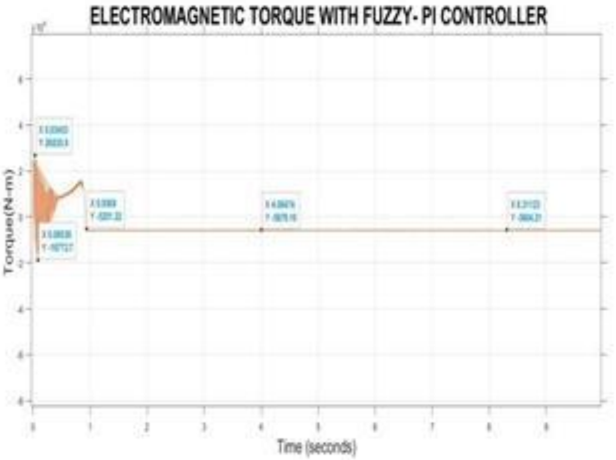

Fig 30: Electromagnetic torque waveform

Reference Values:

1) Reference speed is 1364 rpm or 142.7 rad/sec.
2) Reference Torque is -5582 N-m
3) Reference direct axis current component of rotor current is zero.
4) Reference quadrature current component is 1112 A.

The performance parameters like peak over shoot, peak under shoot, settling time (5% tolerance) and Steady State Error for the variables is tabulated below 4.1 when Fuzzy-PI controller is used to obtain the desired characteristics.

Table 4: Steady state analysis for DFIG wind turbine with fuzzy-PI controller

Performance parameter	I_{dr}	I_{qr}	**Rotor speed**	**Torque**
Peak over shoot	---	---	---	26835.6 N-m
Peak under shoot	-11891.3 A	- 4225 A	---	-18772.7 N-m
Settling time (5%)	---	0.932 Sec	0.651 Sec	0.9368 Sec
Steady State Error	2.907 A	-0.14 A	-3.04 rad/sec	-22.21 N-m

IV. RESULT ANALYSIS

The controllable variables I_{dr} ,I_{qr} and their waveforms are shown for three case studies in the simulation results of chapters 2, 3 and 4. The speed and electromagnetic torque waves are observed for the three case studies in the simulation results of chapters 2, 3 and 4.

In the below tables, for the given input wind speed of 8m/s and the specified reference parameters ,the response of controllable variables i_{dr}, i_{qr} and rotor speed(W_r) and electromagnetic torque (T_e) is plotted. From the graphs, performance parameters like peak overshoot, undershoot and the settling time with 5% tolerance limit and steady state error are found out. These parameters are compared for a variable with three studied cases (PI, Fuzzy and Fuzzy-PI).The results are shown in the below table and analyzed further.

a) For Direct axis component of rotorcurrent (I_{dr}):

Table 5: Performance Parameters for waveform with three controllers.

Controller	**Peak overshoot**	**Peak undershoot**	**Settling time (5%)**	**Steady State Error**
PI CONTROLLER	673.5 A	-10468.4 A	----	-8.558 A
FUZZY CONTROLLER	----	- 12097.1 A	----	238.73A
FUZZY-PI CONTROLLER	----	-11891.3 A	----	2.907 A

Analysis:

1) With PI controller, has less steady state error (-8.558 A) than Fuzzy controller (238.73 A).
2) With Fuzzy controller has no peak overshoot where as PI controller has 673.5 A.
3) Fuzzy-PI controller is giving better results than PI and Fuzzy controllers.
4) The steady state error is least (2.907 A) with Fuzzy-Pi controller.

b)For Quadrature axis component of rotor current (I_{qr}):

Table 6: Performance Parameters for I_{qr} waveform with three controllers

Controller	Peak overshoot	Peak under shoot	Settling time (5%)	Steady State Error
PI CONTROLLER	1238.32 A	-8780.9A	3.664 Sec	-0.54 A
FUZZY CONTROLLER	----	-7347 A	0.968 Sec	-17.18 A
FUZZY-PI CONTROLLER	----	-4225 A	0.932 Sec	-0.14 A

Analysis:

1) With PI controller, has less steady state error (-0.54 A) than Fuzzy controller (-17.18A).
2) With Fuzzy controller has no peak overshoot where as PI controller has 1238.32 A.
3) Peak undershoot is least for Fuzzy-PI controller than fuzzy and PI.
4) Settling time is least (0.932 sec) for Fuzzy-PI controller than Fuzzy (0.968 sec) than PI (3.664 sec).
5) The steady state error is least(-0.14 A) with Fuzzy-Pi controller.

It is observed that Fuzzy-PI controller is giving better results than PI and Fuzzy controllers.

c) For Rotor Speed(W_r):

d) Table 7: Performance Parameters for W_r waveform with three controllers:

CONTROLLER	Peak overshoot	Peak under shoot	Settling time (5%)	Steady State Error
PI	----	----	3.131 Sec	-3.193 rad/sec
FUZZY	----	----	0.897 Sec	-3.715 rad/sec
FUZZY-PI	-----	----	0.651 Sec	-3.039 rad/sc

Analysis:

1) There are no peak overshoot and undershoots for the speed waveform.
2) Settling time is least for Fuzzy-PI than Fuzzythan PI.
3) The steady state error is also least Fuzzy-PI than Fuzzy than PI.

d) For Electromagnetic torque(T_e):

Table 8: Performance Parameters for

CONTROLLER	Peak Overshoot	Peak under shoot	Settling time (5%)	Steady State Error
PI CONTROLLER	79466.3 N-m	- 17936.3 N-m	3.59653 Sec	51.6 N-m
FUZZY CONTROLLER	29684.6 N-m	-8917.5 N-m	1.614 Sec	262.12 N-m
FUZZY-PI CONTROLLER	26835.6 N-m	- 18772.7 N-m	0.9368 Sec	-22.21 N-m

Analysis:

1) The peak overshoot is least for Fuzzy-PI controller.
2) Settling time is least for Fuzzy-PI than Fuzzythan PI.
3) The steady state error is also least Fuzzy-PI than Fuzzy than PI.

V. CONCLUSION

In this paper, a Two MW DFIG wind turbine controller designs of types PI, fuzzy logic, and fuzzy-PI are used to observe the performance of the DFIG wind turbines. In this paper, Wind turbine driven DFIG models are developed and studied using Simulink. A new speed controller is designed to enforce the mechanical torque m to follow the maximum possible power pattern according to wind dynamics. PI controller is designed to control rotor current direct and quadrature axis components. The gain parameters of the PI controller , and are fine tuned until the required performance parameters are obtained. The observation is that the PI design cannot meet the desired system performance as the settling time of the and q components is waveform with three controllers . obtained high as well as the over/undershoot for all parameters. So, a new and complex effective controller called as fuzzy logic controller is designed and used. Fuzzy controller is exhibiting effective improvement in terms of the system parameters peak over/undershoot and settling time, when compared to the DFIG with PI controller. The system parameter steady state error is more for the Fuzzy logic controller. A new and hybrid fuzzy-PI logic controller is proposed and designed to further improve the system performance. The DFIG wind turbine response with fuzzy-PI controller exhibits better performance for the parameters steady state error and settling time. Thus a combined and hybrid PI-fuzzy logic controller is giving better results, which is improving the performance and operation of the doubly fed induction generator.

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