ARTIFICIAL INTELLIGENCE TECHNIQUES-BASED LOW VOLTAGE RIDE THROUGH ENHANCEMENT OF DOUBLY FED INDUCTION WIND GENERATOR

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Abstract

Wind energy is increasingly used as renewable energy worldwide. According to grid codes, wind turbines (WT) should essentially be coupled to grid throughout as well as following fault and source reactive power toward the grid with an objective of maintaining grid voltage. Doubly fed induction generator (DFIG), a wind turbine type enabling speed adjustment, is getting established currently in wind industry. Many DFIGs employ crowbar-based system to shelter the converter at the rotor side during disturbed and/or distorted grid voltage circumstances. Although it helps in protecting the generator, it does not warrant an appropriate grid support. This shortcoming led to designing anew coordinated controller that excludes or even cancels the need of a crowbar. This paper proposes fault confrontation controller (FCC) design to augment the feature -of low voltage ride through (LVRT) in this turbine. Considering the system's nonlinear nature, an attractive FCC was constructed using computational intelligence (CI) techniques, namely fuzzy logic, back propagation network (BPN) and adaptive neuron fuzzy inference system (ANFIS).The simulation study demonstrates that the ANFIS system gives the best results for the proposed system.

Keywords: Doubly Fed Induction Generator, LVRT, ANFIS, Computational Intelligence

I. Introduction

Over the last years, installed capacity of wind power is increasing rapidly worldwide and wind power is applied in a wide range varying from few kilowatts to several megawatts[V],[VI]. The speed of the electrical generator used in wind turbines is fixed or might be variable. Among the different wind turbines characterized by

variable speed, specifically DFIG has gained remarkable attention due to its small-capacity converters, high energy efficiency, low cost and flexibility in power control [VIII],[XVI],[XI]. Doubly fed induction generator carries a DC link capacitor and an electronic converter with successive power supply attached with generator rotor whereas the stator device is affixed to grid without an intermediary. As the stator and grid are directly coupled, DFIG is generally sensitive to fluctuations in grid. Any kind of faults in the grid results in voltage dip in stator, which increases the stator current that in turn increases the rotor current due to magnetic coupling. Increase in rotor current during fault condition will not just destroy the power converter components but DC-link capacitor as well. A large wind power in flow though power system results in the revision of grid codes. Among the fundamental grid codes, Low Voltage Ride Through [XII] is noteworthy, according to which the systems for conversion of the wind energy must be grid-connected in the event of grid faults.

Several hardware- and software-based solutions were put forth[VII],[XIV] to augment LVRT potential of DFIG turbines. Crowbar circuit has been considered a successful hardware-based solution to protect the wind turbine [VII],[XIII],[XIV] but it cannot provide voltage support because it bypasses converter at rotor side (RSC) and DFIG acts as normal squirrel cage induction generator. A major disadvantage of this protection technique is that DFIG takes upper active power present in grid during fault, causing additional reduction of voltage in the grid. Considering this drawback, improved crowbar techniques which includes that united with a DC-link chopper[IV], limiting the rotor current with crowbar together with a series dynamic braking resistor, are proposed[II].All these techniques mainly focus on reducing the crowbar operation time. Voltage stability problem was resolved with Dynamic Voltage Regulators (DVR) [X] or Static Synchronous Compensator (STATCOM) installed at PCC [III]. To overcome the disadvantages of hardware-based fault ride through featuresa nd devices used for injecting reactive power, upgraded controllers such as hysteresis-based current regulator and model predictive control are applied [XV]. One drawback of the existing software-based solution is its computational complexity.

In the proposed system, an advanced intelligent controller is designed for the purpose of predicting the fault correction parameter, which subsequently augments the LVRT by i) protecting the converter at the rotor side against rotor over current and (ii) safeguarding the DC-link capacitor from the negative effects of overvoltage to ensure a stable operation without disconnecting the wind turbine from grid with minimal hardware requirements.

The paper is divided in to several sections. A DFIG wind turbine model and a schematic presentation of the proposed controller are presented in the next section. Design of fault confrontation controller with fuzzy logic is presented in section3.Section 4 details the identification of fault correction parameter with neural network. In section 5,an ANFIS-based design of fault confrontation controller is given. The results obtained from three techniques are described in the concluding remarks.

II. DFIG wind Turbine Modeling for LVRT Study

Modeling of DFIG

DFIG consists of dual voltage source converters. These components are coupled to the grid and rotor. DFIG control constitutes the RSC and GSC (grid-side converter) controllers. Stator active power, in addition to reactive power, is restrained with an RSC controller, whereas the DC-link voltage through GSC controller. DC link capacitor that consecutively connects the dual converters reduces voltage ripple. Both converters regulate rotor voltages using PWM strategy, which in turn helps control rotor currents.

The d-q reference frame exhibiting synchronous rotation was selected for mimicking the dynamic nature of DFIG. The detailed mathematical modeling was illustrated in the studies [IX, I]. Only the equations necessary for LVRT study are mentioned here. The wind turbine's output power can be written in the following form:

$$P_{out} = \frac{1}{2} \rho \pi R^2 V_\infty^3 C_p$$

(1)

In the equation, the variables ρ and v denote air density and wind speed, respectively. R represents rotor radius, while Cp the power coefficient.

The following equations represent a d-q or synchronous reference frame related tostator voltage as well as rotor circuits:

$$v_{sd} = R_s i_{sd} - \omega_s \lambda_{sq} + \frac{d\lambda_{sd}}{dt}$$

(2)

$$v_{sq} = R_s i_{sq} + \omega_s \lambda_{sd} + \frac{d\lambda_{sq}}{dt}$$

(3)

$$v_{rd} = R_r i_{rd} - (\omega_s - \omega_r)\lambda_{rq} + \frac{d\lambda_{rd}}{dt}$$

(4)

$$v_{rq} = R_r i_{rq} + (\omega_s - \omega_r)\lambda_{rd} + \frac{d\lambda_{rq}}{dt}$$

(5)

In the above, the parameter λ indicates flux linkage. ω_r and ω_s stand for rotor angular speed and synchronous speed, respectively. R denotes resistance. R and s given in subscript represent the quantities of rotor and stator, respectively.

Description of proposed controller

An illustration of the intended FCC is depicted in Fig. 1.
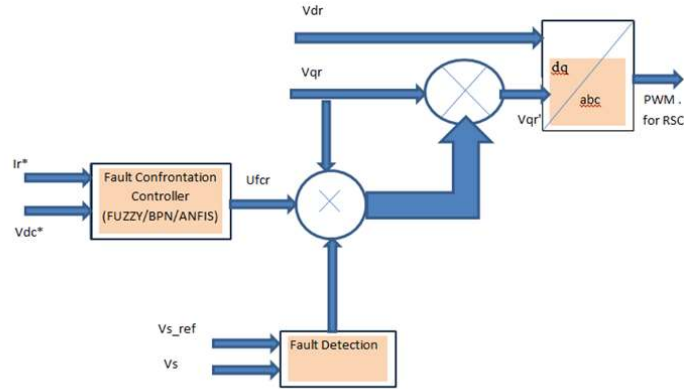
Fig. 1: Schematic diagram of fault confrontation controller

The roposed controller attenuates the system disturbance caused by the fault with appropriate coordination of both the converters. Computational Intelligent controller (FUZZY/BPN/ANFIS) is used for achieving efficient control in a very short period. System should not be affected by measurement noise or the absence of information. Conventional RSC controller is modified by adding the FCC block as shown in the figure. The block functions only when Vs (stator voltage) differs by>10% from the reference value. However, GSC control remains unaltered. Successful LVRT can be achieved by properly controlling the rotor overcurrent along with DC-link overvoltage during fault and restoration. Extra energy that was produced under the transient state should be transferred via converters to grid, to restore the rotor current together with DC-link voltage for achieving normal values. In cases during which rotor current is damped quickly, there will be a sudden increase in DC link voltage. Instead, if it is reduced slowly, there are chances for the rotor current to reach unfavorable values. Therefore, rotor current's correction signals must account for the respective DC voltage values.As depicted in the figure, Vrq output of conventional RSC controller is adjustedby Ufcr derived by intelligent controller(Fuzzy/BPN/ANFIS). Inputs of the controller Vdc* and ir* are given as follows:

$$V_{dc}^* = \frac{V_{dc} - V_{dcss}}{V_{dc\_mav} - V_{dcss}} \tag{6}$$

$$i_r^* = \frac{i_r - i_{rss}}{i_{r\_mav} - i_{rss}} \tag{7}$$

wheress indicator denotes the value in steady state, while mav indicator the maximum acceptable value spacified by manufacturer. In proposed system Vestas 2MW wind turbine ratings are used. i_r stands for the rms current of the rotor. In order to ensure

equal participation to the modulation of Fault Confrontation controller output,the deviations from values of steady state for the two quantities are divided by the deviations that are maximum acceptable. Only positive deviations are considered and negative deviations are taken as zero. The concept of proposed controller can be applied in different ratings of the machines. Rules applicable for the controller are the same. However, the only difference would be the highest values fixed by manufacturer.

III. Design of Fault Confrontation Controller with Fuzzy Logic

Fuzzy logic is nothing but the Boolean logic's extension. It is characterized by an appreciable flexibility allowing reasoning, and thus to consider uncertainties and inaccuracies. It can handle non-linearity and does not need an accurate mathematical model. A Fuzzy inference system appropriate for the controller proposed is shown in Fig. 2.Fuzzy rules of Fault confrontation controller are given in table 1.


System lvrt: 2 inputs, 1 outputs, 9 rules
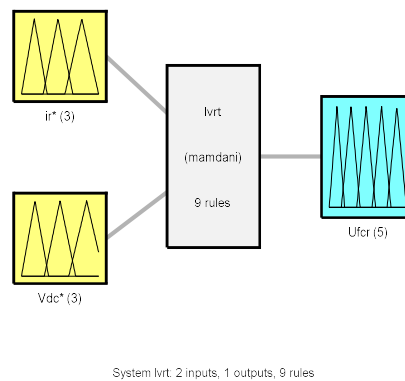
Fig. 2:LVRT fuzzy inference system

Table 1: Fault confrontation controller rules

| Ir* Vdc*	S	M	B
S	OK	PS	PB
M	NS	OK	PS
B	NB	NS	OK

For inputs, the following subsets are applicable: Small(S),Medium(M)and BIG (B),while 5 are applicable for output: Ufcr: OK, Positive Small (PS),Positive Big (PB),Negative Small (NS) and Negative Big(NB).Fuzzy sets are simulated with different membership functions including Gbell, Triangular, Gaussian, Trapezoidal, sigmoid and Pi. The output and input membership functions are shown in Figure 3-5.
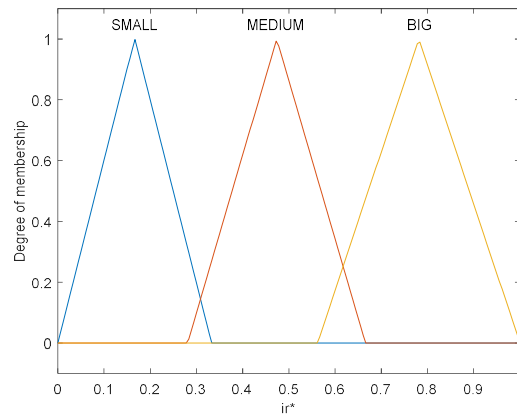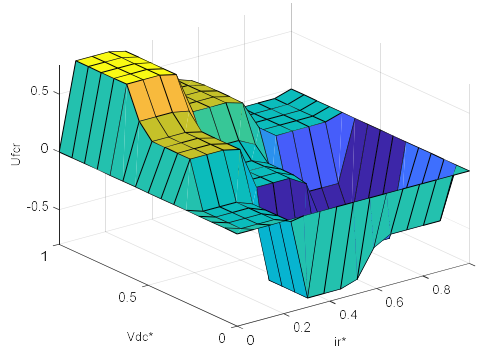
Fig. 3: Input ir* membership functions
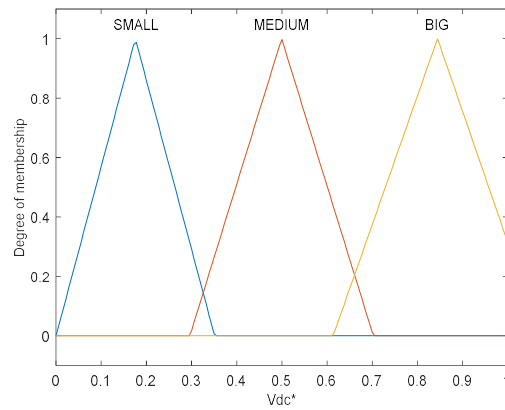
Fig. 4: Input V_{dc}^* membership functions
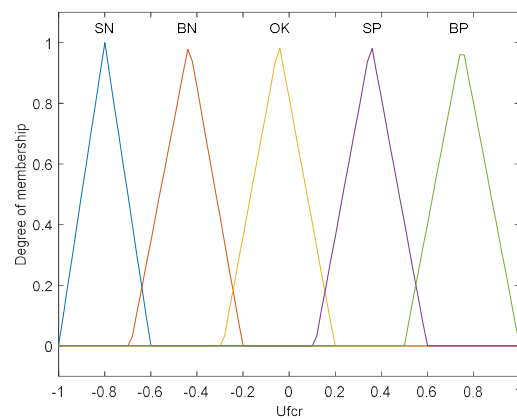
Fig. 5: Output Ufcr membership functions

A 3D curve representing the mapping from 2inputs Ir* and Vdc* to Fault Confrontation Controller output Ufcr is shown in Fig. 6.


Fig. 6: Surface view of LVRT Fuzzy inference system

The following parameters are used to determine the efficiency of fuzzy logic control: Standard Deviation, RMSE (root mean square error), and Minimum and maximum error.

Table 2: Performance Measure comparison with Different membership function in Fuzzy logic

Performance parameter	Triangular	Gbell	Trapezoidal	Gaussian	sigmoid	Pi
Root Mean Square error	0.1542	0.1656	0.1887	0.1641	0.4954	0.2165
Standard Deviation	0.6657	0.6291	0.6447	0.6375	0.1572	0.5332
Minimum Error	4.42e-05	6.76e-06	1.38e-06	2.88e-07	7.59e-05	6.86e-06
Maximum Error	1	0.6514	1	0.6272	1.0548	1

From Table 2 it is clear that Triangular Membership function gives the best optimized result for the proposed system with the root mean square error value of 0.1542. Fig.7 gives the graphical representation of table 2. Since the minimum error value is very less, it is not included in bar chart.
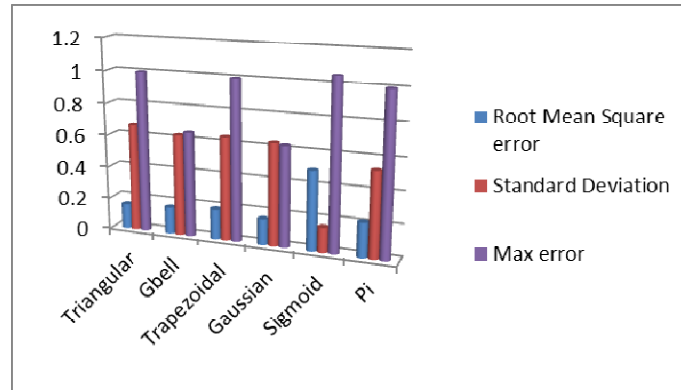
Fig. 7: Performance measures of Fuzzy logic control with different membership functions

IV.   Fault Confrontation Controller Design with BPN

Back propagation network allows preparing the artificial neural networks. The BPN learning algorithm is popularly used forthe purpose of training an MNN (multi-layered neural network),so it can identifya function which can best map inputs to their appropriate output.

Architecture of proposed system network consists of 2 input neuron, one output neuron and 3 hidden layers with 10:5:2 neurons. Learning process is started with the random initialization of the model with two inputs Vdc* and Ir*. Equations for calculating these values are expressed in Eqs. (6) and (7).After initialization, the inputs are sentin to network layer, while the model's actual output is estimated by forward propagation. Loss function is defined to contrast the difference between actual output and desired output and to understand how well Neural Network could generate outputs that are almost identical to the preferred values. In the proposed system, three layers are used in neural network separating the output and inputs to achieve more differences in neural network's functionality. From the derivative of loss function the error is propagated back from the end to the start. Delta rule is used for the weight updation. Learning rate 0.2 and the momentum parameter 0.3 are used to ensure that he weight gets updated in a smooth and slow manner. Among 9594 samples, 4797 rows have been taken for training the neural network and remaining for testing. Figure 8 and Figure 9 show the relationship between actual and desired value for trained data set and for the test data set.

Learning process has taken 65 iterations. Following an iteration, the weight is updated by gradient descent force towards a much lesser global loss function. The system's performance is measured with maximum and minimum error and root mean square error, and the values have been tabulated as shown in table 3. Root mean square error of trained and test data set remains at the same value of 0.0315. Maximum and minimum error is minimum for the trained data set, while for the test data set the error is maximum. But when compared to Fuzzy logic system the back propagation network gives minimum error.
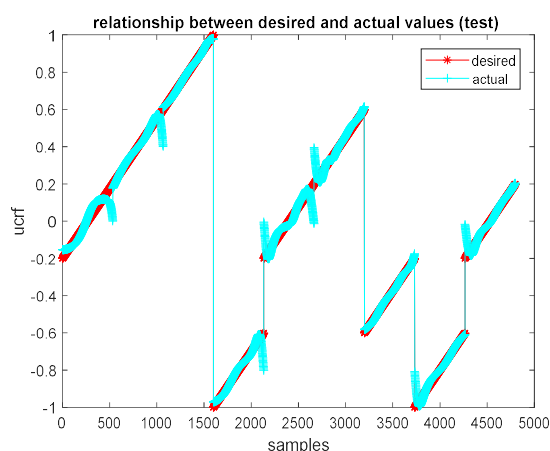
Table 3: Performance measures with Back propagation network

Dataset/parameters	Maximum error	Minimum error	rmse	Learning Parameter	Momentum parameter
trained	0.2015	6.0318e-06	0.0316	0.2	0.3
test	0.2042	9.3267e-07	0.0316		
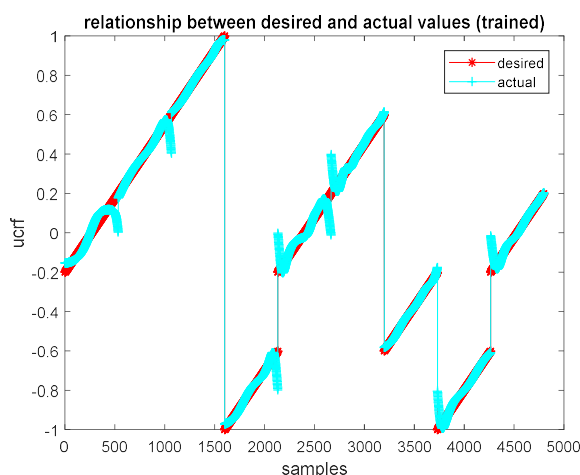
Fig. 8: Relationship between the desired and the actual values (Trained Data set)

Fig. 9: Relationship between the desired and the actual values (Test Data set)

V.   Design of Fault Confrontation Controller with ANFIS

ANFIS represents a popular soft computing process in control area which works on the basis of Takagi–Sugeno fuzzy inference system. This technique is characterized by the benefits of neural network in addition to fuzzy logic system. FIS (Fuzzy Inference System) is a main element of ANFIS, and thus FIS acasts the model fo rmapping the characteristics of an input to its membership functions. These functions are then mapped to rules which in turn are mapped to the output

characteristics. Finally, these characteristics are mapped to their membership functions, which in turn are mapped to an output with single value or an output-associated decision. Several studies have used ANFIS for designingor regulating onlinear systems.

The proposed ANFIS architecture has 2inputs consisting of 5 layers. The inputs of ANFIS, Vdc* and ir* are given in Eqs. (6) and (7). An ANFIS output represents control signal Ufcr for fault correction to enhance the LVRT capability. Three cases with Triangular, Gbell, and PI membership functions are used, while the performance is again measured with Standard Deviation, RMSE, and minimum and maximum error. Comparative result between the performance measures is given in table 4.
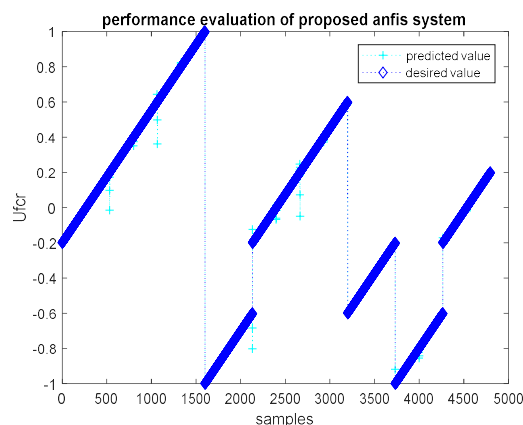
ANFIS with Triangular Membership Function

Fuzzy inference system is created with 2inputs and 1output. Three triangular membership functions are used for both input variables. ANFIS output is measured with root mean square value of 0.0407 and standard deviation is 0.0335. Maximum and minimum error is 0.2119 and 3.0609e-06. For same triangular membership function, number of variables are increased to 5,7 and 9 and the results are tabulated in Table 4. Triangular membership function with 7 variables gives the optimal root mean square error value of 0.0078.

Table 4: **ANFIS output with triangular membership function.**

S.No	No.Of variables	Triangular Membership function			
		RMSE	ST	Max	Min
1	3	0.0407	0.0335	0.2119	3.0609e-06
2	5	0.0211	0.0200	0.2170	7.0416e-08
3	7	0.0078	0.0077	0.2484	3.3574e-08
4	9	0.0115	0.0112	0.2874	2.6523e-08

The performance of the discussed ANFIS system is evaluated in Fig. 10.

Fig. 10: Performance evaluation of the proposed ANFIS system(Triangular Membership function)

Instead ofa Triangular membership function,Gbell and pi membership functions with 7 variables are trained and the ANFIS output is presented in table 5.

Table 5: ANFIS output of proposed system

| S.No	No.of variables	Triangular		Membership		GBELL Membership function				PI Membership Function			
		function											
1	7	RMSE	ST	Max	Min	RMSE	ST	MAX	MIN	RMSE	ST	MAX	MIN
		0.0078	0.0077	0.2484	3.3574e-08	0.0125	.0119	0.2077	7.0408e-07	0.0157	0.0149	0.2102	2.9099e-07

VI.   Simulation Results

Fault Correction parameter with the proposed fault confrontation controller is predicted using three soft computing techniques namely fuzzy logic, back propagation and ANFIS. Performance parameters of the three techniques are tabulated in table 6, and the results are presented as a graph in Fig. 11.

Table 6: Performance measure with 3 different Soft Computing Techniques

| S.No	Technique	Triangular Membership function (7 levels)			
		RMSE	SD	Max	Min
1	Fuzzy	0.1542	0.6657	1	4.427e-05
2	BBN	0.0316	0.5299	0.2025	9.3267e-07
3	ANFIS	0.0078	0.0077	0.2484	3.3574e-08

From Fig.11, It is inferred that Back Propagation network outperforms Fuzzy logic control system. Compared to BPN, ANFIS gives the best-optimized result with minimum error.
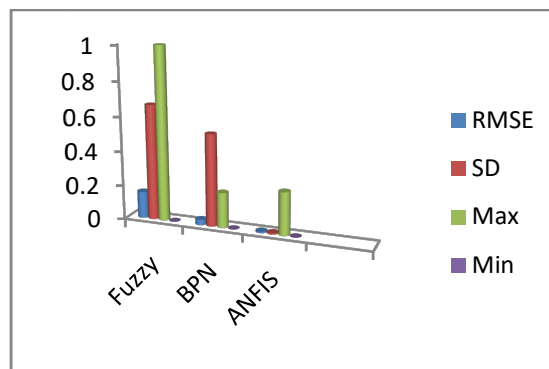
Fig. 11: Performance comparison between Fuzzy/BPN/ANFIS

LVRT Protection with CROWBAR

Crowbar protection technique is implemented for protecting the converter against overcurrent during transient condition. The DFIG Matlab/Simulink with crowbar is presented in Fig. 12.
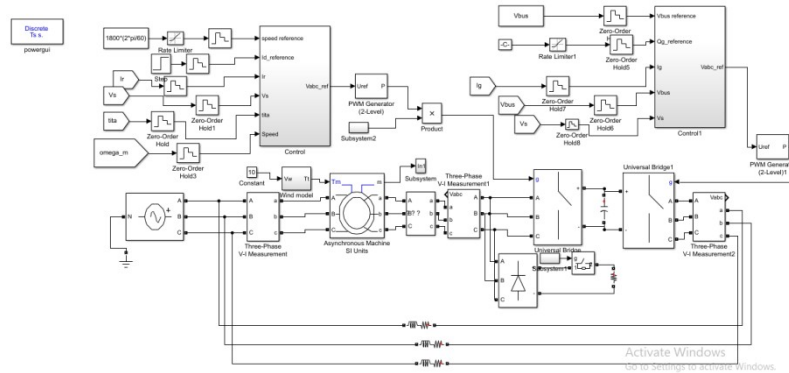
Fig. 12:MATLAB/SIMULINK model of DFIG with Crowbar circuit

During the times rotor current surpasses its threshold, crowbar circuit becomes activated; this also applies to dc-link voltage. There will be a huge increase in rotor current at the event of fault. If it flows through the RSC, then the converter will fail. Hence, crowbar is activated and excess energy will be dissipated in the crowbar resistor (Fig. 13).
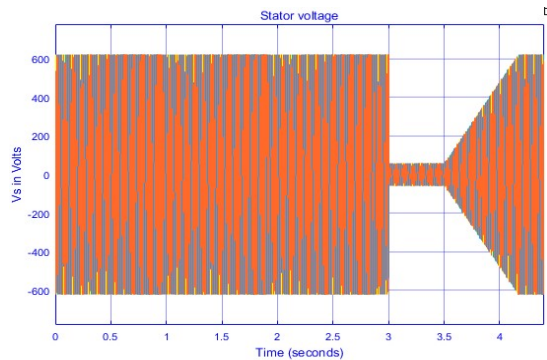

Fig. 13: Crowbar current during voltage dip

In the considered study, symmetrical fault is created at t = 3s. Hence rotor inrush current of about4000A is made to flow through the crowbar resistor in addition torotor side converter bypass. During crowbar activation, the rotor circuit is disconnected from the grid, which leads to the absorption of reactive power present ingrid. As a result, there occurs additional alleviation of grid voltage, which is not encouraged by the present grid code. Hence soft computing technique based modified vector control is implemented to RSC to avoid the stoppage of wind turbine during low voltage or grid fault conditions.

ANFIS based modified vector control for LVRT enhancement of DFIG

Fault confrontation controller is designed with three soft computing techniques namely Fuzzy control, Back propagation network and ANFIS. Among these techniques, ANFIS has given the best result with a minimum root mean square error value of 0.0078. Hence, ANFIS technique has been adopted for predicting fault correction parameter as well as modifying the vector control of RSC. Stator voltage measurement with ANFIS controller during fault condition is shown in Fig. 14.Voltage dip of 85% is created at 3 s and cleared at 3.5 s. Voltage rebuilds to the post fault state at t=4.1s.


Fig. 14: Stator voltage with ANFIS modified vector control

Rotor current during voltage dip is presented in Fig. 15.Fault is created at 3s. Hence, the rotor current increases to the value of 2000A which is below the threshold limit which converter can withstand. But with conventional control it has reached the value of 4000A.Stator current variation during transient condition is also reduced to the lower value around 7000A at t= 3s. At t=3.1s, stator current reaches the low value and attains the prefault value around t=3.5s.
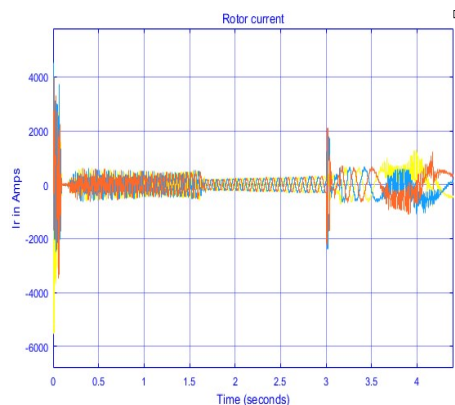
Fig. 15: Rotor current with ANFIS-modified vector control

With the modified vector control technique, crowbar circuit is disabled. Hence, no current flows through the crowbar circuit (Fig. 16).
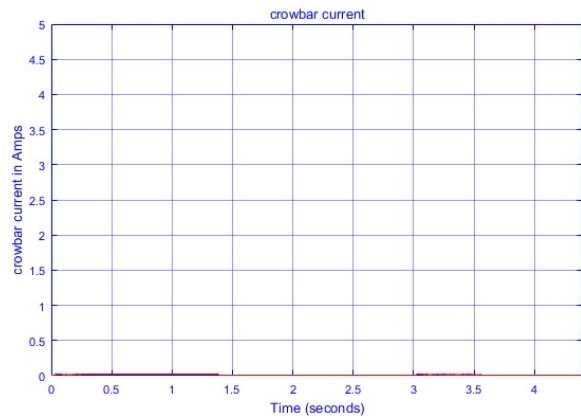
Fig. 16: Crowbar current with ANFIS modified vector control

VII. Conclusion and Future work

Computational Intelligence-based Fault confrontation controller is used to predict the Fault correction parameter to augment the LVRT of DFIG turbine attached to grid requiring minimal hardware and less computational complexity. The operational efficiency of three soft computing techniques is analyzed in the present paper. Simulation results show that the ANFIS with Triangular membership function gives the best result in 7 levels. ANFIS method is therefore the most promising solution for LVRT enhancement. ANFIS Fault confrontation controller is incorporated in power system network and stator voltage responses and rotor current responses at the transient state are given.During fault condition, increased rotor current of about 4000A will flow through the crowbar resistor that disconnects the RSC and gives protection. But in ANFIS-modified vector control, crowbar circuit is eliminated, and therefore, no current flows through it, while RSC is still connected with grid and ensures power system stability. In future, Storage system (Battery/Flywheel/Super Capacitor) can be implemented across the DC link for energy storage.

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