

Mitigation The Impact of Voltage-Dip on The DFIG Using DVR Based on ANFIS Tool

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Abstract: The Doubly Fed Induction Generator (DFIG) performance affected by several states such as the stator voltage variation which has been concentrated by many researchers. When a voltage-dip happens, both stator and rotor currents increase to a high level. Additionally, the DC-link voltage is also increased to a high value. The researchers proposed multiple approaches to mitigate the serious effects that associated with the voltage-dip, but each method addresses one problem for a specific fault condition without taking into account addressing all parameters for various conditions, which shows the limitations of the methods used. Moreover, many schemes also neglect the shifting from generator to power consumer in some severe fault conditions. In this paper, Dynamic Voltage Restorer (DVR) integrated with adaptive-neuro-fuzzy-inference system (ANFIS) is implemented to enhance the DFIG operation during 50% symmetric-dip of the rated value, the torque ripples are reduced to 10% in this case compared with the crowbar (142.34%). The second tested case was 90% symmetric-dip, the torque ripples were 190.80%, 11.39% for Crowbar and DVR+ANFIS respectively. For the third case asymmetric-dip, the torque ripples were 140.42%, 10.25% respectively. Other parameters such as THD%, V_{dc} are also compared. The results are shown that crowbar circuit connection to the DFIG did not mitigate the over-currents. Additionally, the rotor-side converter (RSC) control is lost. The rotor-currents are reduced, and the DC-link voltage (V_{dc}) is increased from 1150 V to 1200 V. However, the proposed DVR based on (ANFIS) controllers provides the best performance by predicting the voltage-dip occurrence, the rotor-currents are reduced to the normal values comparing with Crowbar method, the (V_{dc}) is also reached to the nominal value (1150 V).

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1. Introduction

Recently, the environmental problems have led the world to discover new sources that are considered environmentally friendly energy sources. Wind-energy is one of the most desired and powerful solutions. Generating power based on wind is gradually growing everywhere. Wind system needs a generator to convert the mechanical power to an electrical one. The doubly-Fed induction generator (DFIG) is the first choice for power systems due to its small size, its converters with small power-ratings also provide. High ratings of power (MVA). It is also able to operate with both variable wind-speed as well as fixed frequency [1]. However, DFIG has a sensitivity to the sudden disturbances that happen in the grid. This is due to the connection of the stator directly to the grid; thus, a high current is created due to the voltage-dip. Due to the electromagnetic-coupling between the rotor and stator windings, over-currents are also created in the DFIG rotor. This in turn impacts passively on the rotor-side converter (RSC). Figure 1 explains the structure of the wind system using DFIG. Voltage-dip also causes over-voltage in the DC-Link [2].

The novel grid-codes recommended remaining the wind-turbines connected to the grid in the presence of voltage-dips by improving their performance under transient states [3]. Voltage-dip makes the wind turbines (WT) system interrupted frequently. For the large WT systems, the interruption leads to preventing the grid from multi-megawatts of power [4]. Previously, the level of WTs penetration was small compared with classical generation units [5], thus the WTs disconnections from the grid are allowed under voltage-dips to prevent the negative effects. Nowadays, the WTs penetration is obviously increased in the power system. Several researchers provide fault ride-through strategies. Some of these strategies improve the performance partially, and the others improve the performance completely. Several researchers tried to combine these strategies to provide powerful performance. A traditional crowbar protection is applied to protect the RSC against asymmetric and symmetric voltage, the V_{dc} of the DC-Link is improved at the asymmetric type, but there is no improvement to the rest of the parameters for other types of faults [6]. Under voltage-dip, this crowbar provides a path to allow the over-currents to pass through. In this case, the crowbar disconnects the RSC to protect it from the over-currents and this is considered the major disadvantage of this scheme [7]. When RSC is disconnected, the DFIG changes to a squirrel cage induction generator and receives reactive power. Additionally, Crowbar protection requires a suitable instant to be deactivated. This is necessary to decrease the consumption of reactive power and recover the DFIG control as mentioned in [8], the results explained that only rotor-current and dc voltage are improved under symmetric faults, the researcher did not treat the other types of faults. Additionally, the torque ripples are not taken into consideration. Ref [9] studied DFIG performance with the crowbar circuit under only a symmetric dip. The selected protection did not improve the rotor-current and other DFIG parameters. Ref [10] used STATCOM, that is installed on the grid-side converter, sharing with a super-capacitor which is installed on the DC-Link to enhance the DFIG performance. The outcomes illustrated that STATCOM reduced only the peak of V_{dc} but did not mitigate the ripples, the method is tested only for asymmetric dip. Ref [11] Compared between SVC, STATCOM, SDSC techniques to mitigate the fault effects, these methods are tested for only symmetric-dips. The results showed that SVC and STATCOM reduced the overvalues of the V_{dc} and rotor-currents, but they have not reduced the oscillations. The SDSC improved the DFIG's parameters and mitigated the ripples. Ref [12] Applied DVR circuit sharing with synchronous-reference frame control approach to compensate for the voltage-dip on the DFIG stator, the method is only applied for the asymmetric-dip. This method proved its ability to reduce the overcurrent and mitigate the T_{em} 's ripples. Ref [13] Investigated the DVR performance to compensate the symmetric-dip based on several control schemes; the studied schemes did not mitigate the ripples. Ref [14] Proposed DVR based on active-disturbance rejection control to enhance the LVRT needs; only the symmetric case is studied and also in this case, the torque's oscillations are not cancelled.

Problem of study:

From previous studies, it is found that each of them used a method to treat one type of fault without the rest of the types such as [8, 10, 13], and in each of these studies some parameters were improved. For example, ref [13] improved the current but did not mention the torque, and some of them reduced the capacitor voltage but did not eliminate the oscillations, and the rest of the studies are the same. Additionally, those methods also neglect the shifting from generator to power consumer in some severe fault conditions.

Therefore, since the electrical grid is vulnerable to multiple types of faults, an effective method must be employed to ensure optimal generator performance. This minimizes fault currents, protects the rotor windings and the RSC, and maintains the nominal values of both the capacitor voltage and electromagnetic torque. Furthermore, many studies have not addressed the problem of torque ripples, nor have they addressed the problem of the machine's shifting from power delivery to power consumption from the grid during faults. Based on the above, this study designed a DVR that integrates with ANFIS controllers, which are trained on a wide range of grid data. This enables it to adapt to all possible

fault types, while also offering flexibility and the ability to optimize generator parameters and adjust its ability to remain in power delivery mode during faults.

Aims of Study:

This study aims basically to mitigate the voltage-dip effects by designing a DVR integrated with ANFIS controllers to predict the voltage-dip occurrence and mitigate its effects, and remove the limitations of the other methods that mentioned in previous studies. The proposed scheme is compared with Crowbar for the following cases:

- 1-Symmetric voltage dip (50%) of the nominal value.
- 2- Symmetric voltage dip (90%) of the nominal value.
- 3-Asymmetric voltage dip

The proposed controller based on ANFIS must be able to adapt to various types of grid failures in short time, ensuring that the DFIG does not malfunction or degrade its performance, while also improving signal quality and reducing distortion and ripples.

DFIG is represented according to Park's transformation to convert three phase magnitudes to (dq) coordinates as following [14]:

DFIG's voltages according to the d-axis

$$V_{ds} = R_s i_{ds} + d\Psi_s/dt - \omega_s \Psi_{qs} \quad (1)$$

$$V_{qr} = R_r i_{qr} + \omega_r \sigma L_r i_{dr} + \sigma L_r \frac{d}{dt} i_{qr} + \omega_r \frac{d}{dt} \Psi_{qs} \quad (2)$$

DFIG's voltages according to q-axis

$$V_{dr} = R_r i_{dr} - \omega_r \sigma L_r i_{qr} + \sigma L_r \frac{d}{dt} i_{dr} + \frac{L_m}{L_s} \frac{d}{dt} \Psi_{ds} \quad (3)$$

$$V_{qs} = R_s i_{qs} + \frac{d\Psi_s}{dt} + \omega_s \Psi_{ds} \quad (4)$$

V_{ds} , I_{ds} , and Ψ_{ds} : are the stator (voltage, current and flux) respectively according to the direct axis.

V_{qs} , I_{qs} , and Ψ_{qs} : are the stator (voltage, current and flux) respectively according to the quadrature axis.

R_s : the stator-resistance.

V_{dr} , i_{dr} , and Ψ_{dr} : are the rotor (voltage, current and flux) respectively according to direct-axis [15].

V_{dr} , i_{dr} , and Ψ_{dr} : are the rotor (voltage, current and flux) respectively according to the quadrature axis [15].

ω_r : rotor speed

R_r : is the rotor-resistance.

L_r & L_s are the rotor and stator inductances respectively

σ : the DFIG's leakage-coefficient.

The electromagnetic-torque of DFIG is formulated as follows:

$$T_{em} = -\frac{3}{2} * P * L_r * (\Psi_{dr} i_{qr} - \Psi_{qr} i_{dr}) \quad (5)$$

Where P: Poles' DFIG number.

DFIG's Converters control schemes based on Space-Vector PWM:

Based on Fourier series, the three-phase voltage which is used to feed the 2-level RSC is written as follows:

$$U_A = \frac{2}{\pi} U_{dc} \sum_{n=1}^{\infty} \frac{1}{n} \sin(n\omega t) = U_m(n) \sum_{n=1}^{\infty} \sin(n\omega t) \quad (6)$$

$$U_{m(n)} = \frac{2}{n\pi} U_{dc}, n = 1 + 6k, k = 0, \pm 1, \pm 2, \dots$$

$$U_{dc} = V_{bus}$$

The value of $U_{m(n)}$ specifies the modulation-index m that is used in PWM methods. There are eight potential switches sequences corresponding to the voltage sectors that are shown in figure 2 [16]:

{V1, V2, V3, V4, V5, V6}: the active-vectors

{V0, V7}: the zero-vectors.

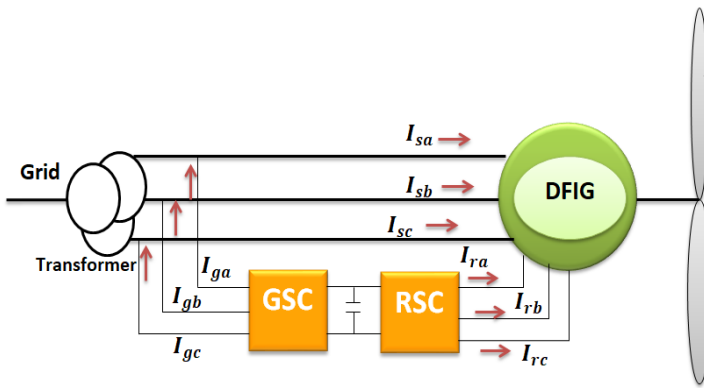


Figure 1. DFIG structure

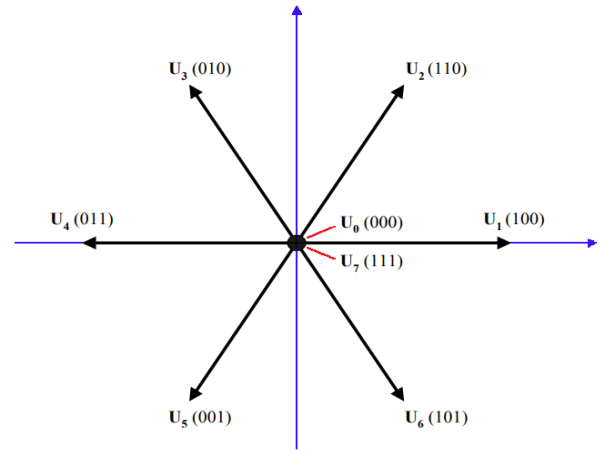


Figure. 2 Switching Sectors

2. Materials and Methods

Crowbar: This method consists of controllable resistors that are inserted between the RSC and DFIG's rotor to limit the high rotor currents during the transient case. Crowbar is activated when a voltage dip occurs and disconnects the RSC by inserting resistors to the three-phase rotor windings in series. After recovering the voltage, it reconnects RSC again to the rotor-winding [6]. In this study, the resistor value of crowbar resistor is (0.2) ohm. Figure 3 shows the Crowbar representation in MATLAB.

DVR: This strategy is characterized by complexity and high cost. It has the same structure as STATCOM-device [17]. Figure 4 explains the connection of the DVR to the grid. DVR represents a signal amplifier that amplifies the voltage signal to enhance the low voltage ride-through of DFIG and keep the DFIG voltage at the desired level. By this way, DFIG will remain connected to the power system at both steady and fault states. During the voltage compensation by DVR, the DFIG provides active power to the grid by DVR [18].

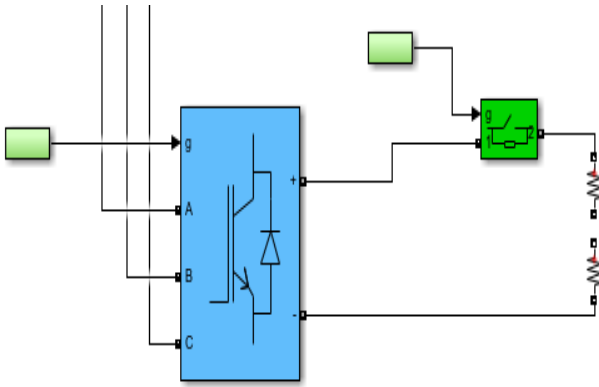


Figure. 3 Crowbar diagram

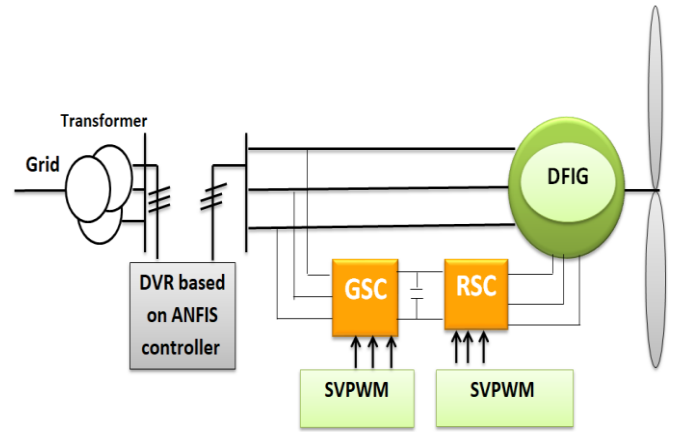


Figure 4. DVR connected to the grid

The DVR injects the desired voltage (V_{inj}) that is generated by the converter through a coupling-transformer. The injected voltage is controlled to mitigate the effects of faults and enhance the LVRT capability of DFIG. Thereby, any disturbance in the grid is compensated by a suitable voltage. The DVR has two modes to operate as follows: standby mode where the injection voltage equals zero and the semiconductors do not switch in this mode and the boost mode where the injection voltage is larger than zero and the DVR injects voltage to mitigate the voltage-dip effects. A closed-loop control is used to control the injection of DVR, according to the dq reference-frame. The classical control scheme for the DVR depends on PI controllers in general due to their simplicity [16]. The gains of traditional PI controllers are constant and do not have the capability to control the DVR injection process effectively to meet the variations of voltage dip [16].

ANFIS controllers: The traditional Fuzzy-logic controllers rely on the relation between the parameters and the membership-functions. Additionally, the rules of the controllers depend on the expert opinion. By this way, the parameters changing is implemented by an error and trial method with no optimization approach [19]. Therefore, multiple approaches have been proposed to overcome these problems such as Particle Swarm [18], neural-networks, Genetic Algorithms [20]. ANFIS is an algorithm that employs the fuzzy system to convert the input into a demanded output. This is implemented by interconnected ANN elements and data connections [6]. A SUGENO type is selected for the ANFIS controller, which combines the properties of the traditional fuzzy principles and the neural network. This strategy decreases the required time for determining the rules and ranges. It also optimizes the outcomes. ANFIS consists of 5 layers that are interconnected as follows:

1. Fuzzification: this layer is responsible to obtain the inputs' membership function.
2. Rule: this layer multiplies the inputs and gives the outputs to the following layer.
3. Normalization.
4. Defuzzification.
5. Output.

To design this controller, some steps should be implemented in MATLAB. The required data for training (inputs and outputs) is obtained from the grid voltage and exported to the workspace in MATLAB. After that, data should be exported to the ANFIS toolbox to start the training process. GUSSMF memberships and the hybrid methods are used. When the ANFIS designing is completed, it is applied on the DVR controller, figures (5- a, b), show the structure of the used ANFIS. Table 1 represents the parameters that are used to design the ANFIS controllers.

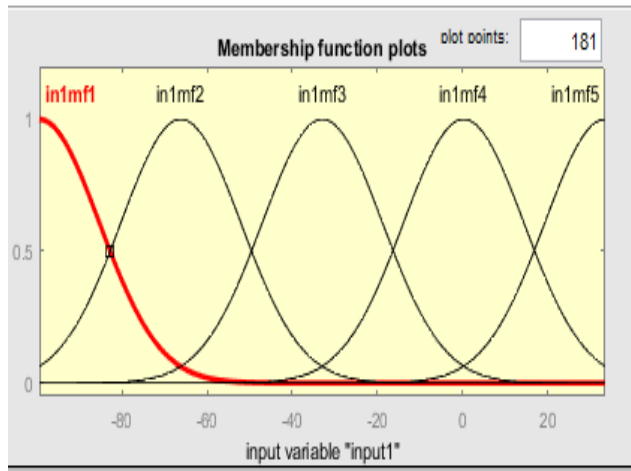
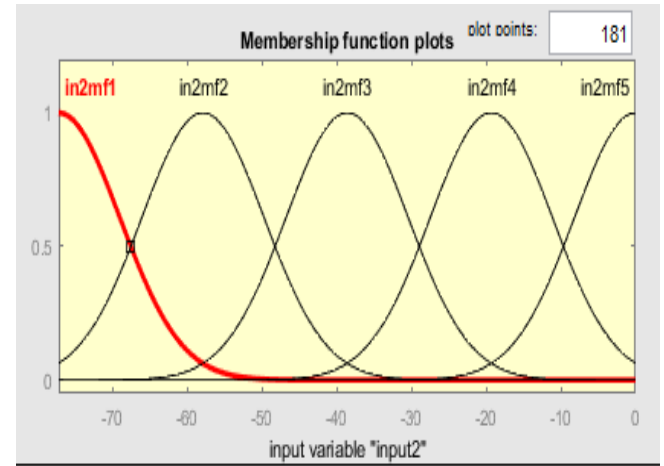


Figure 5. the Memberships of (a) the input1



(b) the input 2

Figure 6 presented the block diagram of the control loops based on ANFIS which is applied to drive the DVR. ANFIS provides more accuracy to the DVR by predicting the voltage-dip. When the DVR becomes able to predict the voltage-dip, a proper level of voltage is provided to the grid by the DVR which enhances the DFIG performance.

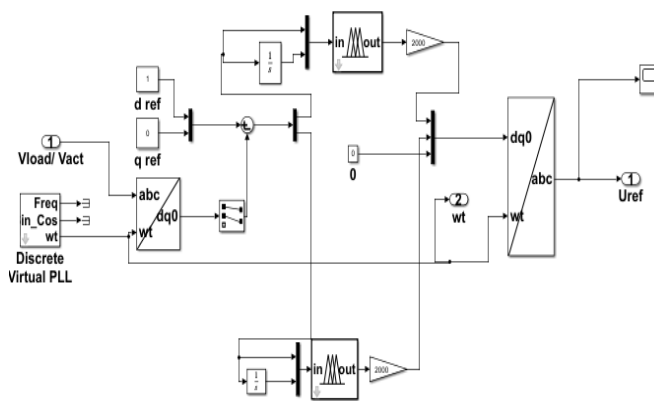


Figure 6. Structure of the control scheme in DVR

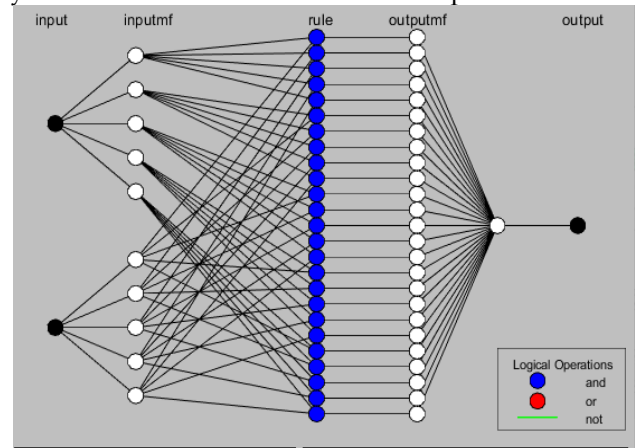


Figure 8. Structure of ANFIS for two inputs and one output

The controllers are trained to maintain the stator voltage at its nominal value, thus improving the performance of the machine and ensuring that it is not affected by faults caused by the grid, regardless of its type. The ANFIS training is implemented by collecting the data (inputs & outputs) from the simulations that represent the DFIG behavior during several types of voltage dips with traditional PI controllers. The inputs are collected from the instantaneous values of the load voltage after converting it from a three-phase quantity to a two-phase quantity according to the transformations (dq), and the outputs are represented by reference signals that are used to implement the control loops for the DVR. Table 2 shows the basic parameters of the DFIG to implement this study.

Table 1. Parameters of the designed ANFIS

Parameter	Value
Inputs	2
Outputs	1

Table 2. Parameters of DFIG

Parameters	Values
P_n (MW)	3
T_{em} (PU)	0.8

Rules	25	$V_{stator} (V)$	690
Epochs	3	$n_{nominal} (r.p.m)$	1500
MF of the input 1	5	Pole	2
MF of the input 2	5	$R_r (Pu)$	0.024
MF of the output	14	$R_s (Pu)$	0.026
Inference system type	SUGENO	$L_r (Pu)$	$0.85 * 10^{-3}$
Method	Hybrid	$L_s (Pu)$	$0.85 * 10^{-3}$

The surface curve of input 1(error voltage) and input 2(changes in the error), and the output for the first controller in this study are shown in figure 7. These curves represent the basic used data to train the controller. Figure (7) represents the relation between the inputs of the second controller depending on ANFIS, and illustrates that the controller linked the input data to the output depending on two factors, the Fuzzy rules as well as the Memberships. The surfaces present the nonlinear features that have peaks and bottoms, this proved the ability of the ANFIS controller to adapt to complicated inputs and capture the changes in the dataset. These curves implies that the inputs' variations impact the output. The various gathering of the inputs is causing varying levels of smoothness or unexpected transformations in output. The curves also show that there is no discontinuity, this means that there are no overfitting problems, and that the training data and fuzzy rules are appropriate.

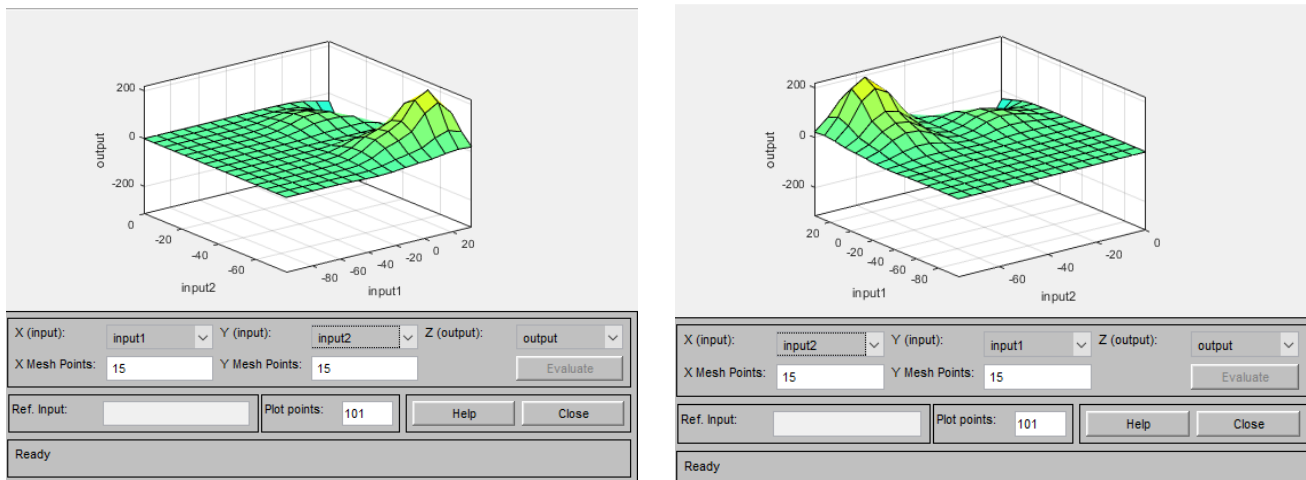


Figure 7. 3-D representation of the inputs and outputs of the ANFIS controller

The controller is managed by 25 fuzzy rules that are represented by figure (9), the design is implemented by a hybrid ANN structure that combines the fuzzy logic basics and a neural network. Through the training process, the relation between the inputs and output is modified, and their impact on the output. The figure explains how the output changes due to the input changes. This indicates the controllers' ability to adapt their performance to represent the nonlinear relation. The detailed fuzzy rules for the controller are mentioned in the appendix.

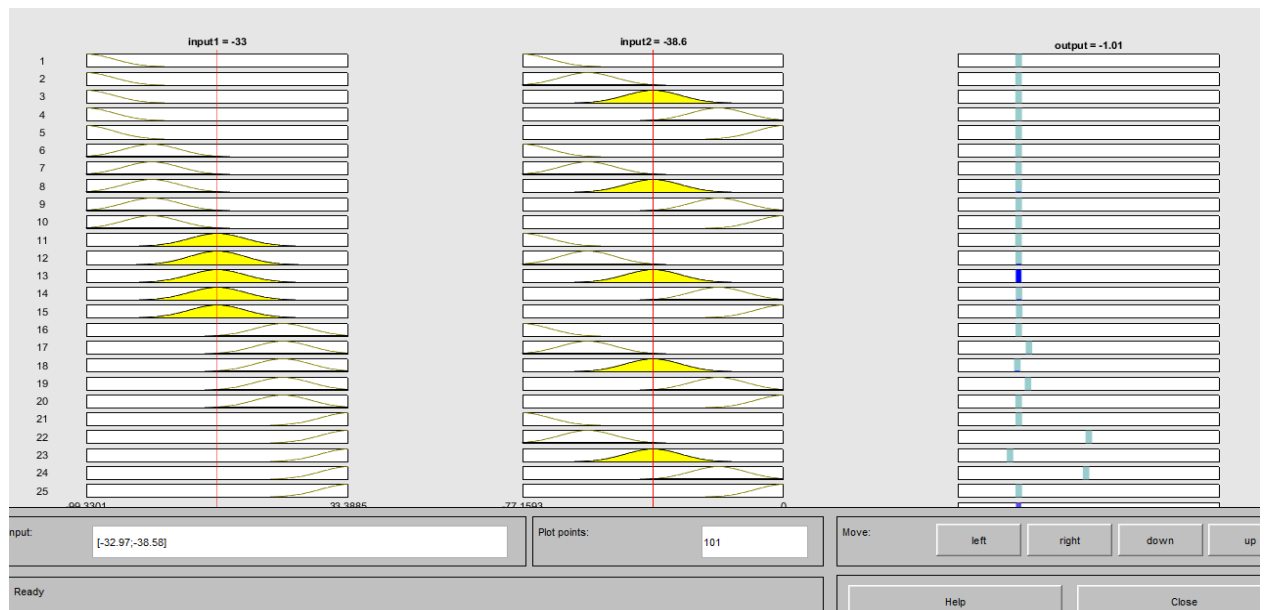


Figure 9. The rules of inputs and output of the ANFIS after training

For DFIG control, the SVPWM is applied to the rotor-side converter (RSC). The DFIG performance is investigated with DVR based on ANFIS-controllers during three phase voltage-dip. In fact, speed changes are not taken into account because the focus of the controller design is on transient cases related to faults. In these cases, wind speed changes do not affect the design of the control scheme. If they are taken into account, the results do not change and what will happen is only a repetition of the results. Based on the above, the value of speed (11.5 m/s) is determined as it is the optimal speed that achieves the maximum power obtained from the turbine

Case 1: Symmetric-dip (50 %)

The system is simulated with two various approaches to test their performance during disturbances. The grid-side converter is also controlled by the SVPWM approach. The disturbance is represented by a three-phase voltage-dip. It occurs at 0.44 sec and it is cleared at 0.55 sec. In the following part, the performance of DFIG is investigated. The value of voltage dip is 50% of the rated voltage.

3. Results

The DFIG performance is investigated under a symmetric voltage-dip with the two schemes. The stator voltage decreases at 0.44 sec, then it is recovered to its normal value at 0.55 sec. In the first case, the crowbar is shorting the RSC when the voltage-dip is detected. Then it is deactivated when the voltage is recovered in 0.55 sec. In the second case, it is applied to the DVR that is controlled by ANFIS-controllers; this strategy proves that it is the best solution to eliminate the voltage-dip effects.

The DFIG performance under disturbance is investigated for two schemes. The RSC is controlled with SVPWM integrating with (Crowbar, DVR integrated with ANFIS-controllers). These strategies are tested for three fault cases as follows:

The figure 11 explained how the rotor-voltage is increased from (0.7 to 1 Pu) during the period from 0.44 sec to 0.55 sec due to the fault, which has negative effects on the RSC performance.

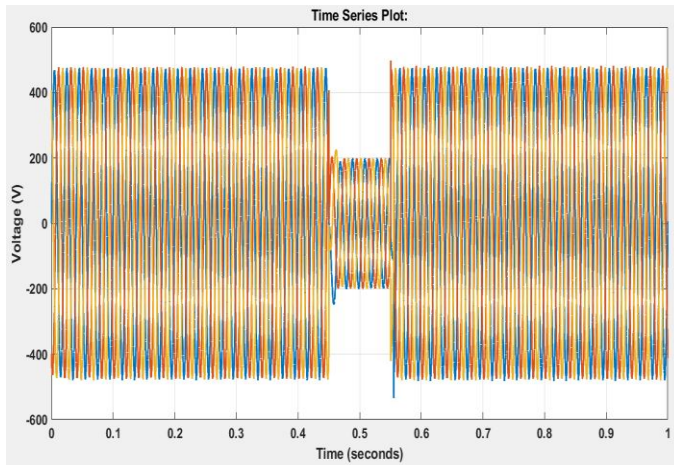


Figure 10. The stator-voltage with 50% symmetric-dip occurring between 0.44 to 0.55 sec

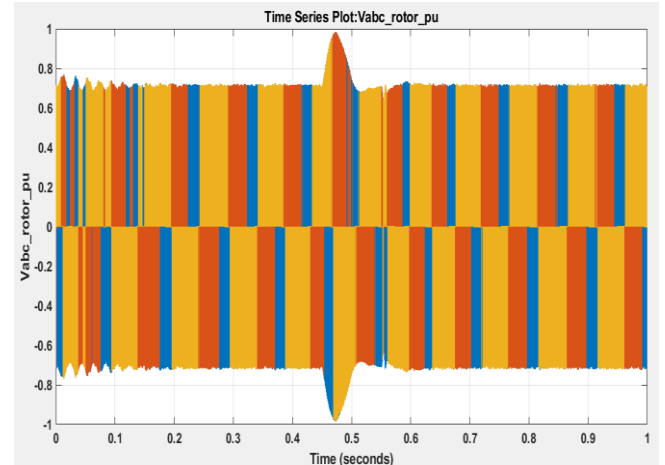


Figure 11. The rotor-voltage signal under voltage-dip

Figure 12 shows the dc-link voltages for the three conditions. Figure (12 a) shows how the resulting (V_{dc}) reaches to a high value (1634 V) compared with the nominal one.

For the first strategy (crowbar), the DC-link voltage (V_{dc}) experiences high values during the voltage-dip as shown in figure (12 b). To overcome the crowbar limitations, the DVR with ANFIS-controllers is used. The oscillations and high values are mitigated. In the figure (12. c) the V_{dc} becomes more better compared with the Crowbar.

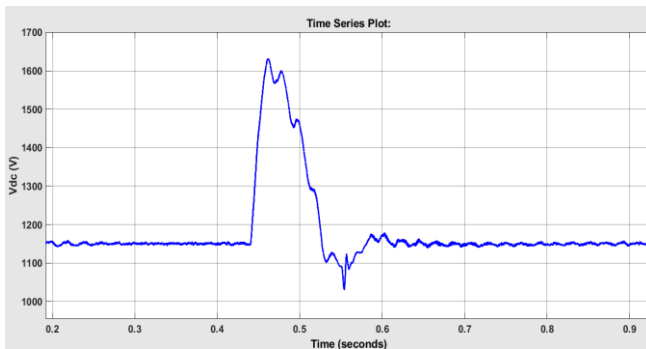
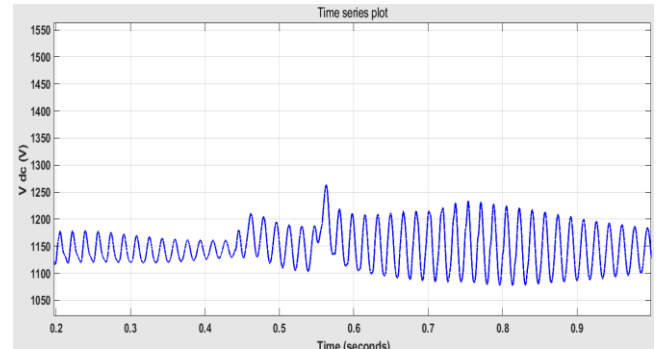


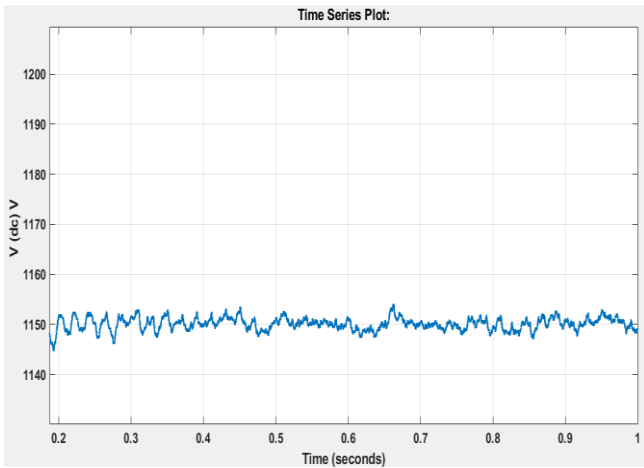
Figure 12. DC-Link Voltages under voltage dip a) without any method



(b) Crowbar

The rotor-currents (I_r) for the two methods are compared as shown in figure 13. The (crowbar) protects the RSC from the over-currents. When the voltage-dip occurs, Crowbar is activated [9]. The figure (13 b) demonstrates that the I_r is oscillated during the voltage-dip with imbalance state. This influences negatively on the DFIG performance. For the proposed method, it is clearly shown that the resulting I_r is sinusoidal and without any distortion as shown in figure (11 c).

The figure (13) presents that the rotor currents have a high peak at 0.44 sec.



(c) DVR+ANFIS

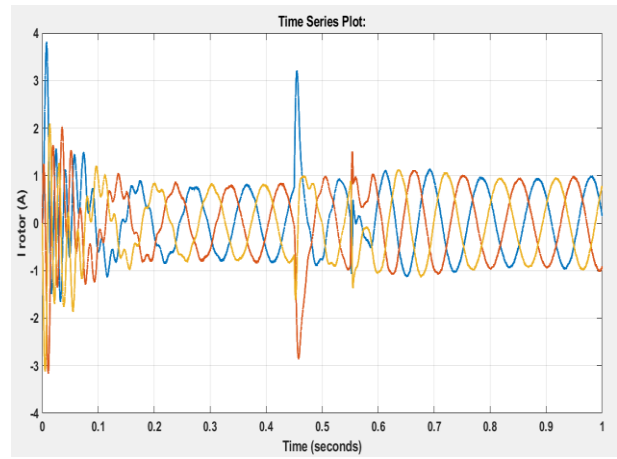
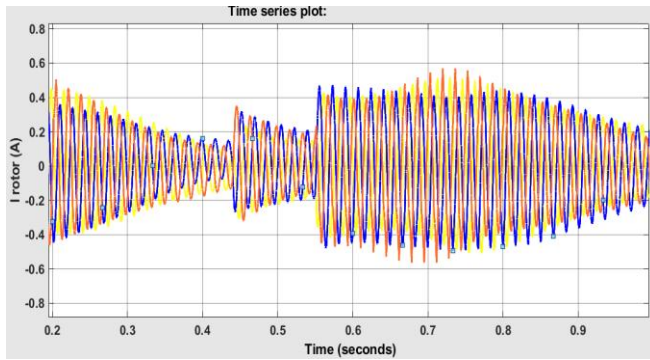
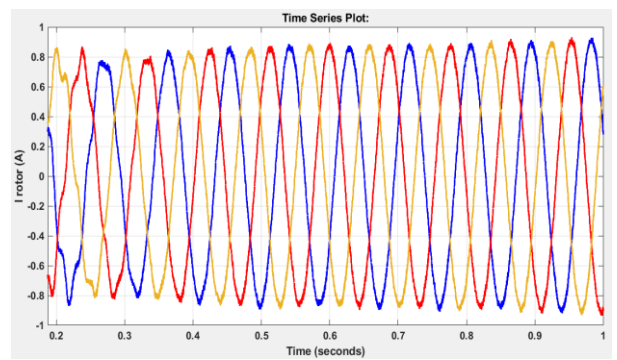


Figure 13. The rotor-currents under voltage dip a) without any method



(b) Crowbar



(c) DVR+ANFIS

The T_{em} is obviously oscillating at 0.44 sec when the fault is started, the negative peak is occurred due to the over rotor-current. At the end of the fault, the T_{em} increased to a positive value (0.8 N.m), this means abnormal operation of the machine.

when the crowbar is activated. This occurs due to the RSC control losing from 0.44 to 0.55 sec, as shown in figure (14 b). When the voltage is recovered, T_{em} is not returned to its nominal value before the voltage-dip, it still oscillates with considerable ripples. Figure (14 c) shows that T_{em} is improved in this case. It is clearly shown how the proposed technique mitigates the high peaks from the T_{em} . This strategy also mitigates the ripples from T_{em} during the dip; this result agrees with ref [19].

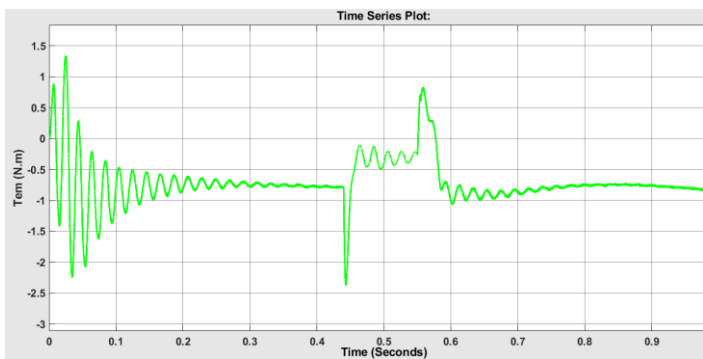
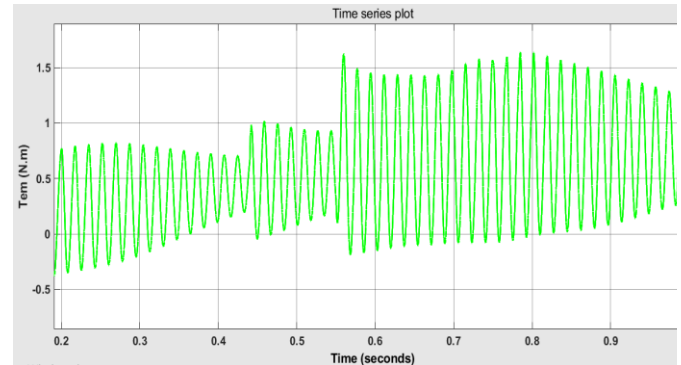
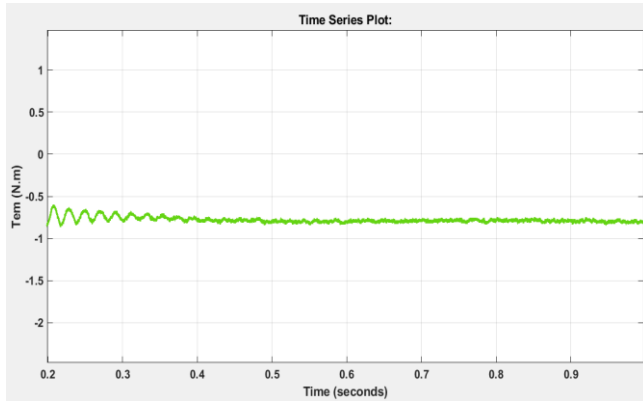


Figure 14. Electromagnetic-Torque for DFIG with a) without any method



(b) Crowbar

Furthermore, the rotor-voltage is also enhanced, this in turn improves the V_{dc} and enhances the performance during the voltage-dip occurrence, as shown in figure 15.



(a) DVR with ANFIS-controllers

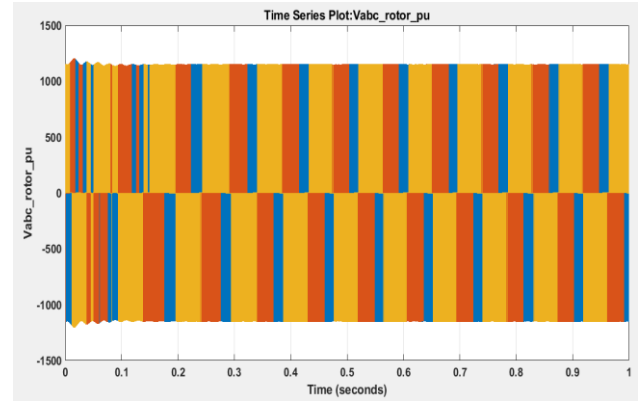


Figure 15. Rotor voltage for DFIG using DVR+ANFIS

Table 3 summarizes the results of the DFIG's parameters in the three conditions in the case of symmetric voltage-dip (50%) as follows.

Case2: 90% Symmetric dip:

In this case, a symmetric voltage dip (90%) as a severe condition is applied, in this case the stator voltage is decreased from 0.44 sec to 0.55 sec, then it is recovered to its nominal value, as seen in figure 16.

In this case, the increasing of stator voltage directly influences on the rotor voltage of the machine. Figure 17 shows how rotor voltage increases at the time from 0.44 sec to 0.55 sec. This increasing from (0.7 to 1.02) has negative effects on the RSC converter, the DC-link between RSC and GSC.

To address the above effects, methods are commonly used to protect the machine and improve its performance during voltage disturbances. Figure 18 shows the resulting DC-link voltage (V_{dc}). The first condition (figure 18 a) illustrates how the voltage dip causes an increase in the (V_{dc}) from 1150 V to 2235 V without applying any protection tool. This increase has the ability to damage the capacitor in the dc-link. By applying Crowbar, the V_{dc} value is reduced to 1950 V, but the value is still very high and much greater than the nominal value (1150). This is explained by the limitations of this method and its inability to handle the excess voltage resulting from the fault. The designed ANFIS with the DVR mitigates clearly the over-voltage in the DC-link compared with the other method and maintains the nominal voltage during the fault, figure (18 c).

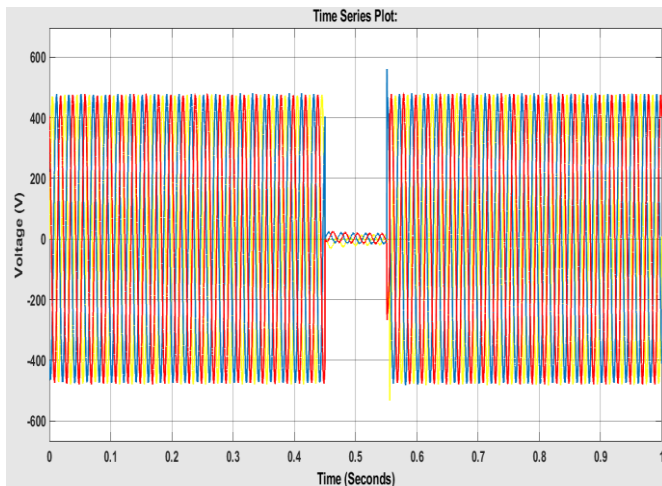


Figure 16. The stator-voltage with 90% voltage-dip occurring between 0.44 to 0.55 sec

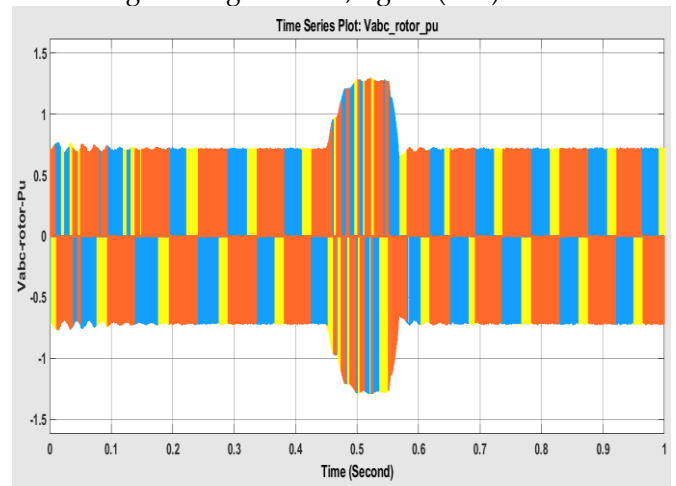


Figure 17. The rotor-voltage signal under voltage-dip

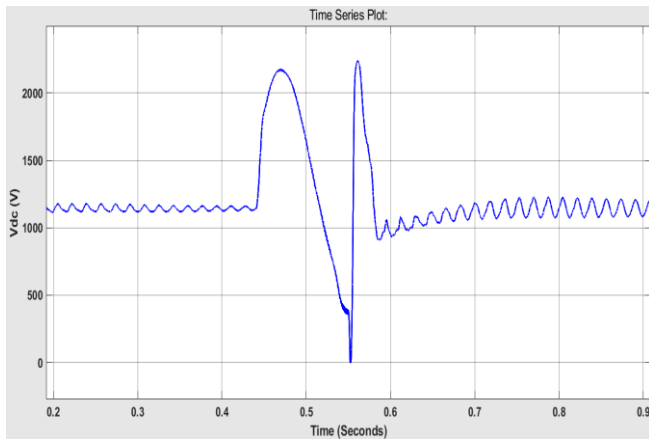
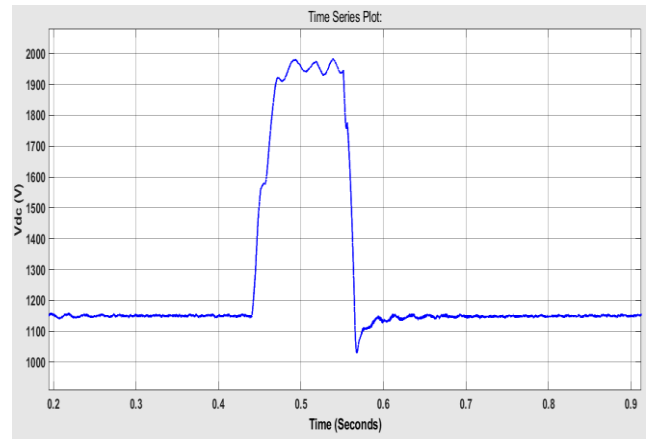
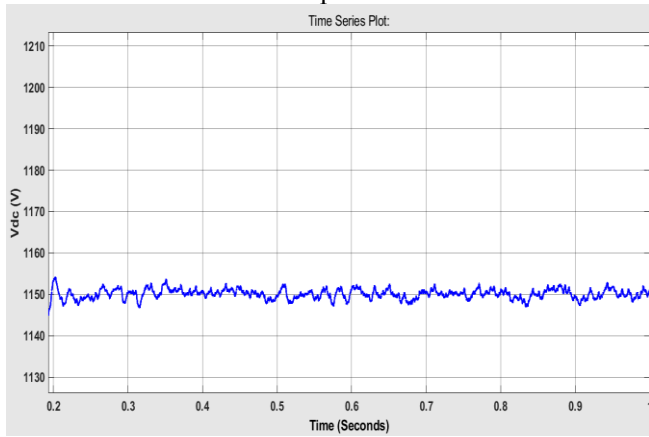


Figure 18. DC-Link Voltages under voltage dip a)
without protection



(b) Crowbar



(c) DVR+ANFIS

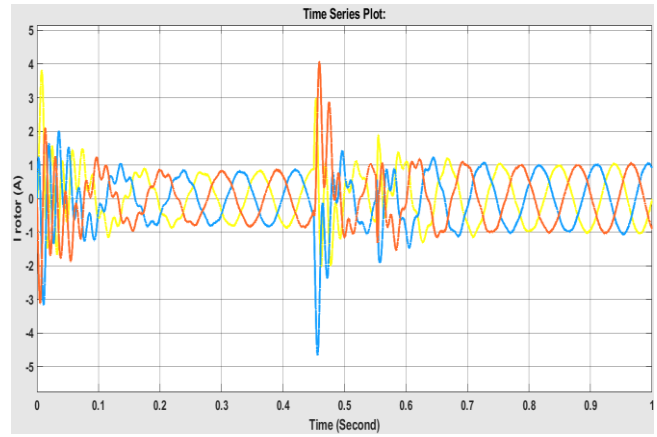
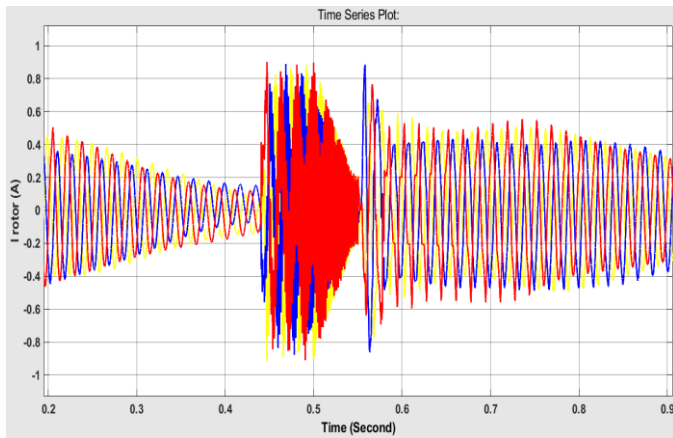
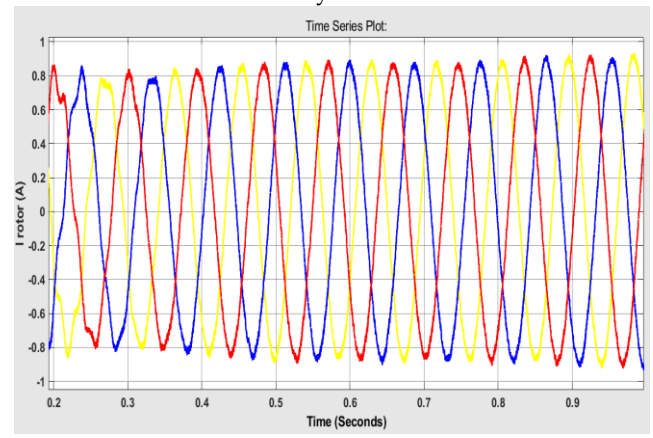


Figure 19. The rotor-currents under voltage dip a)
without any method



(b) Crowbar



(c) DVR+ANFIS

The rotor current during the fault exceeded the nominal value by four times (4.3 A). During a fault, the current not only increases but also becomes distorted and non-sinusoidal. As the fault's end time approaches, the current decreases and returns to its nominal value, but it continues to fluctuate for a few cycles, figure (19 a). By applying conventional protection Crowbar, it is observed that the rotor current during the fault reduced to 0.90 A. However, the distortions and imbalance in the waveform increased during the fault. This is because activating the crowbar leads to a short circuit in the RSC and a loss of control. After the fault clears, it is observed that the current remains unbalanced and high

for several consecutive cycles, figure (19 b). Figure (19 c) shows the best performance of the controllers during fault cases and the current becomes more sinusoidal.

Figure 20 explains the resulting electromagnetic torque in the three conditions. Figure 20-a shows how the voltage dip at $t=0.44$ sec experiences a negative peak, this peak occurs due to the sudden increase in the rotor current. After that the torque's value becomes zero (0), at $t=0.55$ sec T_{em} starts to decline, and returns to the normal value. After the fault is removed. It can be seen that the torque needs several cycles to stabilize. Figure (20 b) represents that the Crowbar results in greater torque distortion, although it reduces the fault current value it leads to excessive torque ripples. It can be noted that the current distortions and imbalance during the fault led to the torque wave being shifted to positive values. Therefore, the machine in this case works as a motor and consumes power from the grid instead of providing power. The proposed strategy performed effectively in this case, treating torque oscillations during the fault and resulting in a waveform that was almost free of oscillations and within negative limits, meaning that the machine during the fault remained in its working state as a generator and reliably supplied its power to the grid. Table 4 summarizes the results of the DFIG's parameters in the three conditions in the case of symmetric voltage-dip (90%) as following.

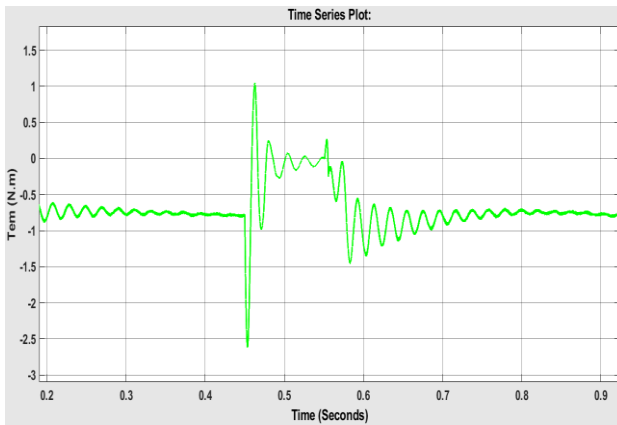
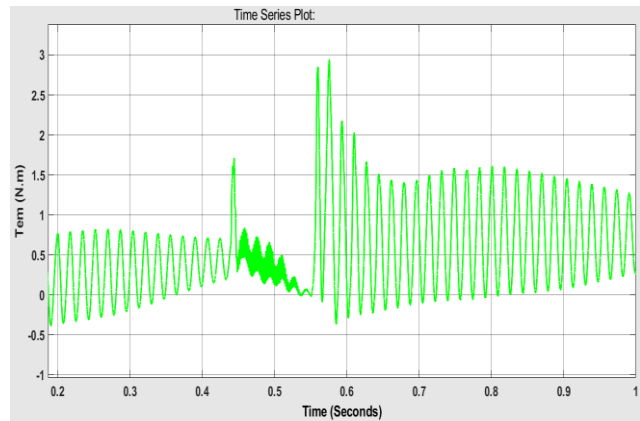
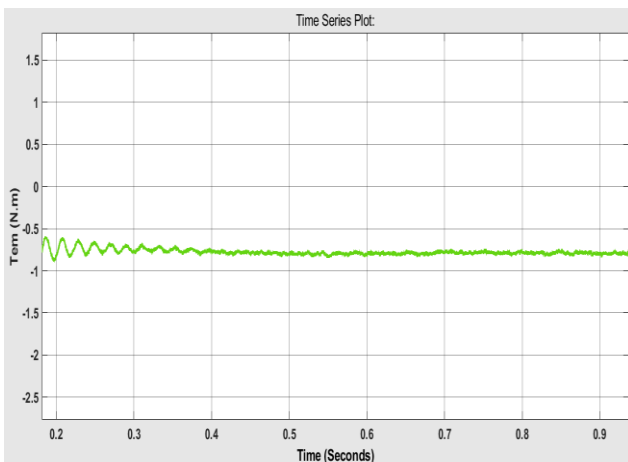


Figure 20. Electromagnetic-Torque for DFIG with a) without any method



(b) Crowbar



(c) DVR with ANFIS-controllers

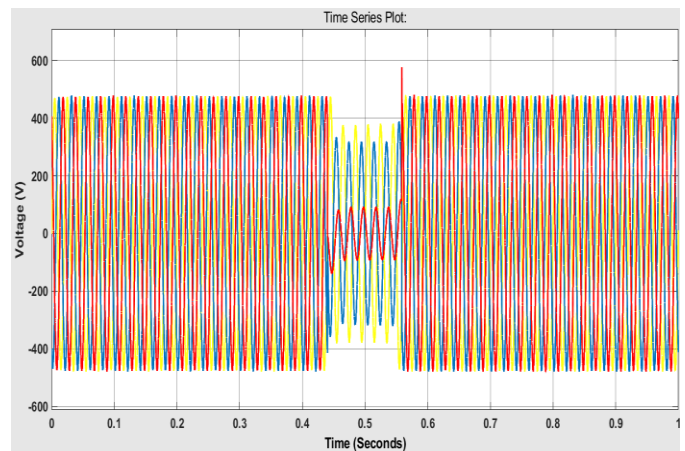


Figure 21. The stator-voltage with Asymmetric voltage-dip occurring between 0.44 to 0.55 sec

Table 3. Comparison between the two applied methods in the symmetric 50% voltage-dip

	I_{rotor}	Vdc	THD%	Tem ripples
Without any Protection Method	3.4 A	1634 V	78.70%	96.73%
With Crowbar	0.9 A	1200 V	11.74%	142.34%
With DVR+AN-FIS	0.89 A	1151 V	0.99%	10%

Table 4. Comparison between the two applied methods in the symmetric 90% voltage-dip

	I_{rotor}	Vdc (V)	THD%	Tem Ripples
Without any Protection Method	4.3 A	2235 V	102.94%	85.71%
With Crowbar	0.90 A	1950 V	89.77%	190.80%
With DVR+AN-FIS	0.89 A	1151 V	1.03%	11.39%

Case 3: Asymmetric-dip

In this case, the asymmetric voltage-dip is applied from $t=0.44$ sec to $t=0.55$ sec. Figure 21 shows the voltage that is applied to the DFIG.

Figure (22 a) explains how the non-balance in the stator voltage impacts on the V_{dc} , at $t=0.44$ sec the V_{dc} increased to 1285 V. It remains distorted even after the fault has been removed after several cycles. Treating the fault using Crowbar protection also proved ineffective in this case as the entire resulting wave was distorted, full of ripples and exceeded the nominal values, figure (22 b). Figure (22 c) presented the resulted voltage in the DC-Link due to using the proposed technique

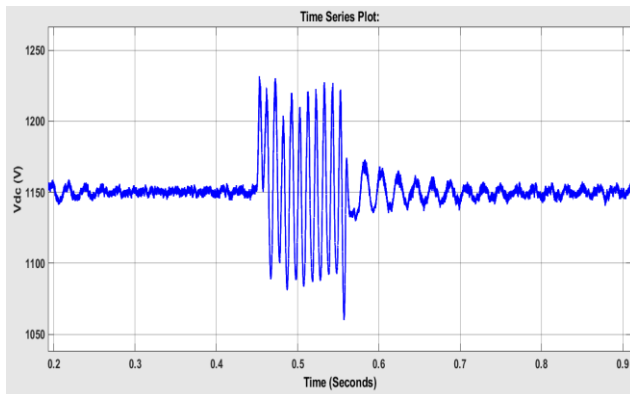
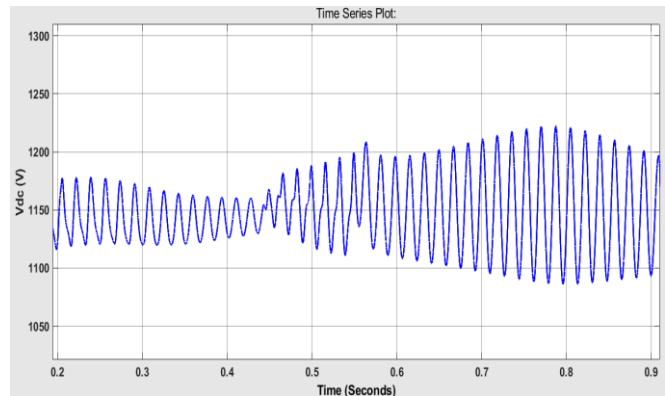
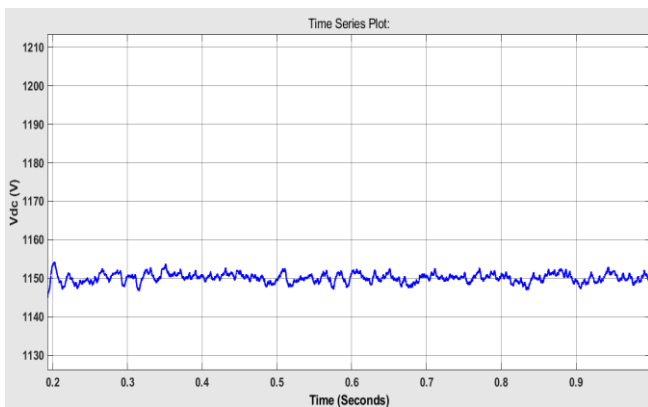


Figure 22. DC-Link Voltages under voltage dip a) without any method



(b) Crowbar



(c) DVR+ANFIS

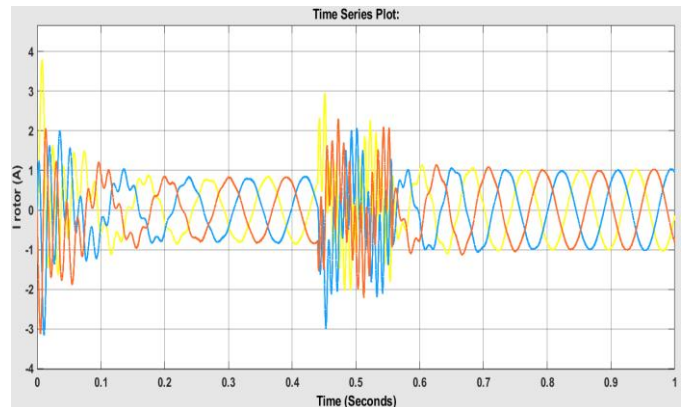
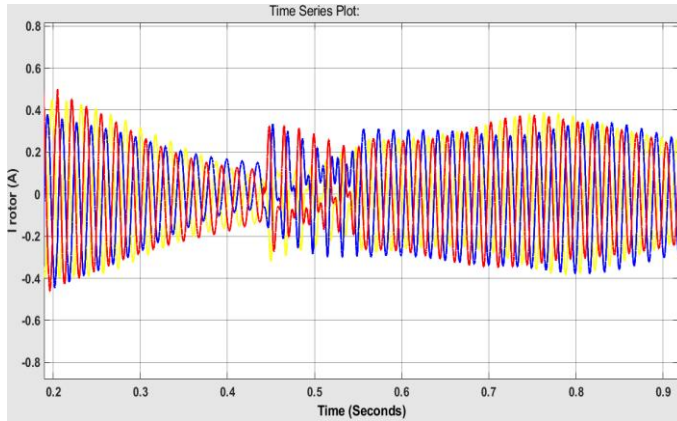
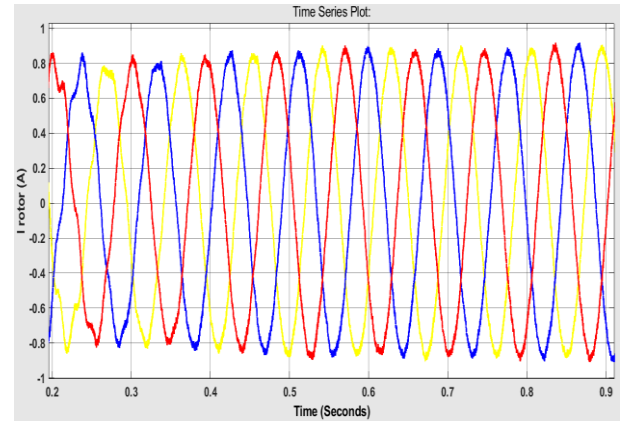


Figure 23. The rotor-currents under voltage dip a) without any method



(b) Crowbar



(c) DVR+ANFIS

As with other previous faults, the current increased to 3 A at $t=0.44$ sec, and remained unbalanced until the fault finished at 0.55 sec. The crowbar has not provided an acceptable performance in this case. The current suffers from non-balances and decreased to a non-acceptable value of 0.25 A, figure (23 b). The proposed technique provides in this case the best performance to process this type of fault effectively.

As in previous cases, it was observed that the asymmetrical fault led to clear distortions in the torque, in addition to a change in the torque signal to positive, which clearly indicates a defect in providing power to the grid and the machine's tendency to consume during this period until the fault is removed, and thus an abnormal operating condition affecting the machine on the one hand and the power provided to the grid on the other hand, figure (24 a). figure (24 b) shows that the crowbar performance was very poor for this type of fault, as the distortions increased due to the distortions that occurred in the rotor current, figure (24 b). By regulating the constant voltage, the DVR+ANFIS was able to reduce torque oscillations and keep the machine operating within the power supply mode to the grid (figure 24 c).

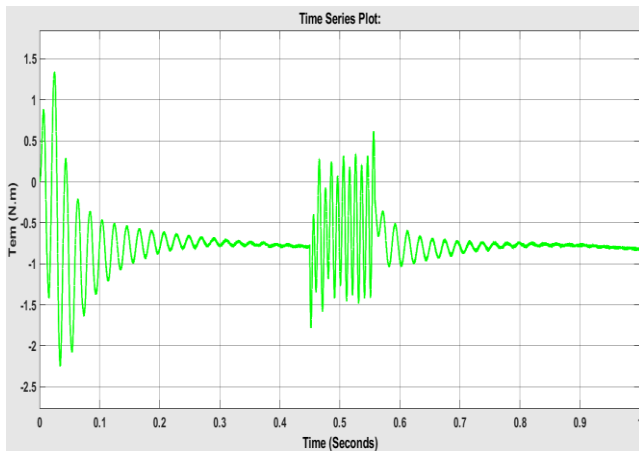
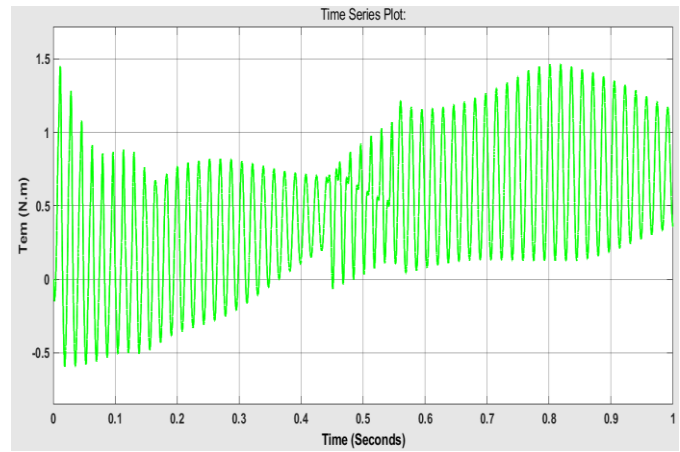
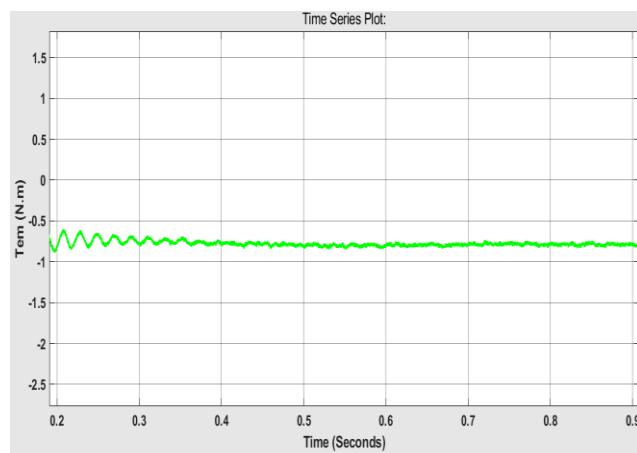


Figure 24. Electromagnetic-Torque for DFIG with a)
without any method



(b) Crowbar



(a) DVR with ANFIS-controllers

Table 5. Comparison between the two applied methods in the asymmetric voltage-dip

	I_{rotor}	Vdc	THD%	Tem Ripples
Without any Protection Method	2.9 A	1285 V	76.80%	114.1%
With Crowbar	0.25 A	1208.5 V	22.69%	140.42%
With DVR+ANFIS	0.89 A	1152 V	1.02%	10.25%

In table (6), there is a comparison is made between the results obtained in this study using the proposed method and the results obtained by previous reference studies using other methods. The comparison shows that each method addressed one type of fault without focusing on the other types. These methods were limited and did not improve the performance of the entire machine. The proposed method, however, was more flexible and able to adapt to all the situations that the grid was exposed to.

($\emptyset$) means that the fault type is non studied, ($\times$) means that the applied method the faults results have not improved, ($\checkmark$) means that the faults results have improved.

Table 6. Comparison between the results of the current study and the results of previous studies

Ref	Method	I_{rotor}			Vdc			Tem Ripples		
		S (50%)	S (>50%)	AS	S (50%)	S (> 50%)	AS	S(50%)	S (> 50%)	AS
[6]	Crowbar+ANFIS	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	$\times$	$\checkmark$	$\emptyset$	$\emptyset$	$\emptyset$
[8]	Minithreshold Crowbar	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
[9]	Crowbar	$\emptyset$	$\times$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
[10]	STATCOM	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$	$\times$	$\emptyset$	$\emptyset$	$\times$
	SVC	$\emptyset$	$\times$	$\emptyset$	$\emptyset$	$\times$	$\emptyset$	$\emptyset$	$\times$	$\emptyset$
[11]	STATCOM	$\emptyset$	$\times$	$\emptyset$	$\emptyset$	$\times$	$\emptyset$	$\emptyset$	$\times$	$\emptyset$
	SDSC	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\checkmark$	$\emptyset$
[12]	DVR+FUzzy	$\emptyset$	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\emptyset$
[13]	DVR+PSO	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\checkmark$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
[10]	ADRC+DVR	$\checkmark$	$\checkmark$	$\emptyset$	$\checkmark$	$\checkmark$	$\emptyset$	$\times$	$\times$	$\emptyset$

This study	DVR+ANFIS	✓	✓	✓	✓	✓	✓	✓	✓	✓
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×the faults results have not improved.

✓ the faults results have improved

∅ : non studied

Practical considerations

Designing a DVR for the DFIG protection is expensive due to the need for complex electronic devices. Also, implementing ANFIS controller increases the complexity of the DVR and thus increases the cost of implementing the method. Despite its complexity and cost, its flexibility and ability to maintain the required performance led to avoiding damage to electronic circuit breakers in the molds, destruction of the insulation of the coils in the machine, damage to the capacitor, and other potential damages resulting from grid failures.

4. Conclusions

In this study, two topologies are implemented to investigate the DFIG transient performance improvement. The space-vector PWM is applied to the RSC with the two studied topologies. The DFIG nominal power is 3 MW. Crowbar and DVR integrated with ANFIS controllers are implemented and compared. Three fault conditions are applied to the DFIG in order to test the DVR with ANFIS flexibility and ability to adapt to faults.

The variations of DFIG parameters and their effects on the transient performance are discussed. The simulation outcomes are presented that the measured DFIG's parameters are stable during the voltage-dip when the proposed solution is applied. Moreover, the oscillations in the T_{em} and the V_{dc} are also mitigated. Furthermore, the need to short the RSC during the voltage-dip is also eliminated. The limitations of the methods discussed in previous studies, which were summarized and compared with the proposed method (Table 6) in this study showed that designing a controller (ANFIS) and training it on network data for various faults and integrating the resulting controller with (DVR) effectively enhanced the performance of the (DFIG). In addition, the proposed method improved the electromagnetic torque by reducing its ripples, which was not addressed by previous studies.

The model designed in this study is the basis for building a robust and strong system to protect the DFIG and develop its performance to ensure the reliability of the energy supplied to the grid via the wind system. For future work, this study recommends combining the DVR with other example algorithms such as the (PSO), or (genetic algorithm) and comparing their performance with the ANFIS that is applied in this study.

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Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest."

Appendix

1. If (input1 is in1mf1) and (input2 is in2mf1) then (output is out1mf1) (1)
2. If (input1 is in1mf1) and (input2 is in2mf2) then (output is out1mf2) (1)
3. If (input1 is in1mf1) and (input2 is in2mf3) then (output is out1mf3) (1)
4. If (input1 is in1mf1) and (input2 is in2mf4) then (output is out1mf4) (1)
5. If (input1 is in1mf1) and (input2 is in2mf5) then (output is out1mf5) (1)
6. If (input1 is in1mf2) and (input2 is in2mf1) then (output is out1mf6) (1)
7. If (input1 is in1mf2) and (input2 is in2mf2) then (output is out1mf7) (1)
8. If (input1 is in1mf2) and (input2 is in2mf3) then (output is out1mf8) (1)
9. If (input1 is in1mf2) and (input2 is in2mf4) then (output is out1mf9) (1)
10. If (input1 is in1mf2) and (input2 is in2mf5) then (output is out1mf10) (1)
11. If (input1 is in1mf3) and (input2 is in2mf1) then (output is out1mf11) (1)
12. If (input1 is in1mf3) and (input2 is in2mf2) then (output is out1mf12) (1)
13. If (input1 is in1mf3) and (input2 is in2mf3) then (output is out1mf13) (1)
14. If (input1 is in1mf3) and (input2 is in2mf4) then (output is out1mf14) (1)
15. If (input1 is in1mf3) and (input2 is in2mf5) then (output is out1mf15) (1)
16. If (input1 is in1mf4) and (input2 is in2mf1) then (output is out1mf16) (1)
17. If (input1 is in1mf4) and (input2 is in2mf2) then (output is out1mf17) (1)
18. If (input1 is in1mf4) and (input2 is in2mf3) then (output is out1mf18) (1)
19. If (input1 is in1mf4) and (input2 is in2mf4) then (output is out1mf19) (1)
20. If (input1 is in1mf4) and (input2 is in2mf5) then (output is out1mf20) (1)
21. If (input1 is in1mf5) and (input2 is in2mf1) then (output is out1mf21) (1)
22. If (input1 is in1mf5) and (input2 is in2mf2) then (output is out1mf22) (1)
23. If (input1 is in1mf5) and (input2 is in2mf3) then (output is out1mf23) (1)
24. If (input1 is in1mf5) and (input2 is in2mf4) then (output is out1mf24) (1)
25. If (input1 is in1mf5) and (input2 is in2mf5) then (output is out1mf25) (1)

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