Improved Fault Ride Capability in DFIG based Wind Turbine using Dynamic Voltage Restorer and Firefly Technique

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Abstract - This paper investigates fault ride through (FRT) capability in doubly fed induction generator (DFIG) based wind turbine using a dynamic voltage restorer (DVR). FRT capability in the wind turbine has been received more attention in recent years due to its ability to maintain the grid stability during faults. The performance of FRT can be improved by using DVR. DVR can be controlled using Proportional and Integral (PI) controllers. In this research, a novel DVR model based on the optimization algorithms is introduced. The aim of the optimization problem is to improve the performance of the PI controller and therefore minimize power losses in the power grid. Finally firefly algorithm is used to solve this problem. The performance of the proposed method is evaluated by using simulation examples in the MATLAB environment. Simulation results indicate the proposed algorithm can improve stability of the grid during faults in the wind turbines.

Keywords - doubly fed induction generator, fault ride through, dynamic voltage restorer, PI controllers, Firefly optimization algorithm

I. INTRODUCTION

In the recent decade, renewable energy has received a great deal of attention due to the growing demand power. Due to the low cost of production and maintenance of wind farms, wind farms play a vital role in the supply of electricity. The capacity of wind farms has grown by an average of 25% per year since 2000, while the global economy has grown by no more than one to two percent per year. With the expansion of wind farms, the expectation from them has increased, and it is expected that wind farms, like fossil power plants, can produce stable energy. However, similar to other renewable power plants, generating electricity from wind farm has different challenges. One of the most important challenges is maintaining the stability of the power grid when the wind farm encounters to faults [1].

Many requirements must be considered in wind farms that one of the most important of them is Fault ride through (FRT), which has attracted the attention of researchers in recent years. Wind farms are expected to support the grid during system failures and be recovered as soon as possible. Grid-connected wind power plants are required to be connected to power grid even in the event of a balanced or unbalanced voltage drop and to support the grid by generating reactive power during a fault [2]. Lack of network support or sudden shutdown of wind farms during faults can lead to severe network consequences and produce extremely problems. Hence, the ability to use wind turbines has been attracted more attentions, especially in countries that are greatly increasing wind energy capacity and companies have begun to implement FRT capability on the wind farms. Figure 1 (a) indicates that when the voltage is dropped, the turbine must be connected in the specified curve. Fault correction should also be at a slope of 20% of rated power per second. In addition, figure 1 (b) indicates wind turbines must support the network voltage through reaction current support and this must be done within 20 milliseconds after the fault [3].

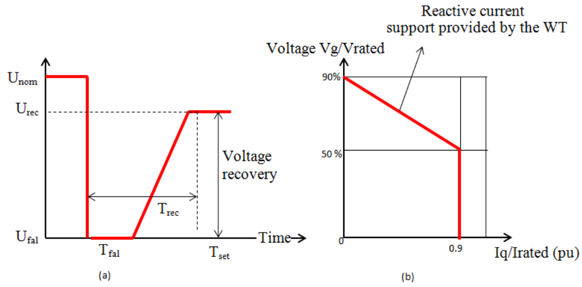

Fig. 1. (a) Fault Ride Through grid code ; (b) Reactive Power requirement grid code

The double-powered induction generator (DFIG) has several advantages such as reduces cost, losses, weight, and size compared to a fully converted power converter system due to its capability to work with both active and reactive power control. However, DFIG-wind turbine (DFIG-WT) is very sensitive to voltage disturbances, especially voltage drop, and if proper protective equipment is not provided, a sudden voltage drop can cause overvoltage and overcurrent in the rotor windings, which can destroy the crowbars [4]. Usually crowbars are installed to protect the rotor windings, but, the installation of crowbar leads absorbs reactive power and also stops generation of active power, which further contributes to the fall of the network in the event of a voltage drop. Excessive current in the rotor during a voltage drop causes an increase in voltage across the DC bus, fluctuations in the stator and rotor current, as well as disturbances in the active and reactive power of the DFIG-WT. In some researches, a static synchronous compensator (STATCOM) was proposed for FRT to generate reactive power and support DFIG-WT [5]. However; STATCOM cannot protect the rotor side converter (RSC) and must work with the crowbar to protect the RSC from excessive rotor current during network fault. Some other solutions that have been introduced by researchers include Series Dynamic Resistance (SDR) on the stator or rotor side or the use of a network side converter (SGSC) [6]. Nevertheless, none of these methods have been able to solve the problem of maintaining the network in the event of an error.

Recently, dynamic voltage restorers (DVRs) have been used to FRT in wind farm. A DVR is a series compensating device that injects the appropriate compensating voltage to correct a faulty mains voltage. One of the advantages of DVR is its ability to inject reactive power due to the load voltage limitations that have recently been used to compensate for faulty grid voltage [7]. The advantage of this system is that it does not need any additional protective equipment for DFIG-WT is eliminated. DVR for FRT capability is typically used to reduce voltage and compensate for wind turbine inflation in distribution systems. The DVR is also capable of sagging, swelling and harmonic compensation. However, design a controller for DVR is an important challenge. DVR performance can be improved based on the control and compensation techniques. Due to advantages of DVRs, this paper uses it to improved fault ride through capability in DFIG based wind turbine. The performance of the DVR is optimized based on the optimization algorithm. Firefly algorithm is used to minimize power losses in the system.

The rest of the paper is organized as follows; DFIG based wind turbine system is modeled in the section 2. In the section 3, the DVR is introduced. Proposed optimization algorithm and firefly optimization algorithm are introduced in the section 4. Simulation results and conclusion are expressed in the section 5 and 6, respectively.

II. DFIG Based on Wind Turbine System Modeling

Figure 2 shows the structure of a wind farm. It can be seen that the DFIG-WT stator is connected directly to the power grid and the rotor is connected to the power grid via RSC and GSC via slip loops. The converter is connected to the RSC and rotor and is connected to the GSC network, which in total accounts for only 30-35% of the total capacity of the device. The controllable voltage and frequency provides variable operation of the generator speed, so the constant output of the generator is stable when the wind speed fluctuates and the stator remains constant at the grid frequency, even when the generator is operating at different speeds. This type of generator produces more power, therefore, it be very popular in the power industry. It can increase the slip to ±0.3 pu and therefore can generate power without falling on the nonlinear part of its characteristic curve [8].

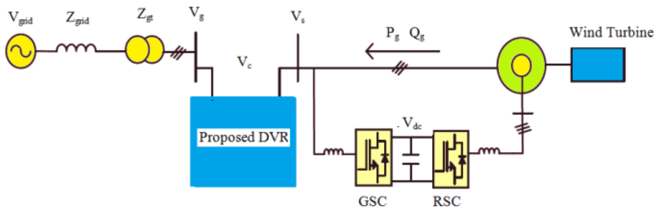

Fig. 2. Black Diagram of FRT capability in DFIG based on the proposed method

Figure 3 shows the "T-form" equivalent circuit of DFIG-WT. This circuit operates in the stator-flux-oriented-vector, which is built on a two-pack loop form. Outer power control can control the active and reactive power, and internal power control with edible disconnecting parts can control the rotor current. The d-axis of the synchronous specified frame is aligned with the stator-flux space vector in the field-oriented control, which rotates counterclockwise ωs.

It is important to consider stator voltage, rotor current and DC connection voltage when DFIG-WT is dropped. When balanced fault is accrued, DFIG-WT dropping causes too much current and it produces transient overshoot. In this scenario, the RSC controls current and regulates it to the pre-fault value. In addition, excessive current causes a sudden increase in the active power of the RSC, which is not transmissible by the GSC due to its partial rating, thus increasing the DC bond voltage to 1.2 pu. Also, the transmission power through GSC is reduced due to low voltage during failure.

The transitions that occur during instantaneous fault clearance are less than the instantaneous fault due to the better GSC capability with nominal voltage availability. By passing the circuit breaker parameters, these transitions can be controlled while clearing the error. Also, recovering full voltage in one step using a circuit breaker causes a large change in the flux forced into the stator and requires a large natural flux.

The response of the system is different in the unbalanced fault conditions. There are no temporary cuts in the event of an instantaneous fault, but there is a large ripple current in the rotor winding and double-frequency fluctuations in the DC connection voltage. Any phase jump in the supply voltage when an unbalanced voltage drop due to a fault causes an excessive transient due to negative sequence components. Therefore, the modeling of DFIG-WT behavior during network fault is performed using the equivalent "T-form" circuit of the DFIG-WT form as shown in Figure 3 [3, 7, 8].

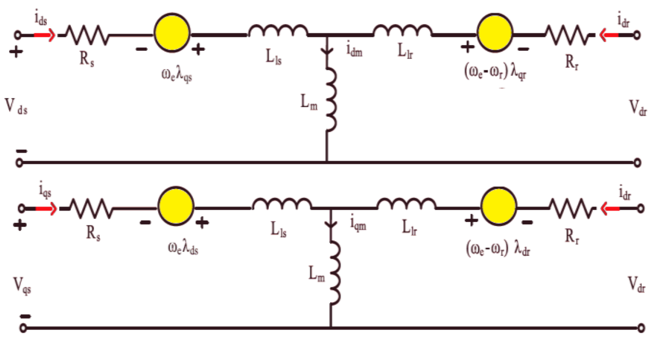

Fig. 3. “T-form” equivalent circuit for DFIG

Based on the figure 3, we have:

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega_e \lambda_{qs} \quad (1)$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} - \omega_e \lambda_{ds} \quad (2)$$

$$v_{dr} = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega_e - \omega_r)\lambda_{qr} \quad (3)$$

$$v_{qr} = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} - (\omega_e - \omega_r)\lambda_{dr} \quad (4)$$

In the above equations, v_{ds}, v_{qs}, i_{ds}, and i_{qs} are stator voltages and currents, respectively and v_{dr}, v_{qr}, i_{dr} and i_{qr} are rotor voltages and currents, respectively. ω_e and ω_r are the supply angular frequency and the rotor angular frequency, respectively. In addition, λ_{ds} and λ_{qs} are the d-q stator flux linkages and λ_{dr} and λ_{qr} are the d-q rotor flux linkages. R_r and R_s are the resistance of rotor and stator, respectively. In addition, we have:

$$L_s = L_{ls} + L_m \quad (5)$$

$$L_r = L_{lr} + L_m \quad (6)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (7)$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (8)$$

$$\lambda_{dr} = L_m i_{ds} + L_r i_{dr} \quad (9)$$

$$\lambda_{qr} = L_m i_{qs} + L_r i_{qr} \quad (10)$$

Where L_s, L_r, L_{ls},L_{lr} and L_m are stator inductance values , rotor inductance, stator leakage inductance, rotor leakage inductance and magnetizing inductance, respectively. Finally, the active and reactive powers for stator are calculated as follows [9]:

$$P_s = \frac{3}{2}\left(v_{qs} i_{qs} + v_{ds} i_{ds}\right) \quad (11)$$

$$Q_s = \frac{3}{2}\left(v_{qs} i_{ds} + v_{ds} i_{qs}\right) \quad (12)$$

Where P_s and Q_s are active and reactive powers. As illustrated in the previous works, the threshold value of the rotor current during fault is 1.5 pu to 2 pu values and the DC-link voltage rating is 1150 V and its threshold value is 1.35 pu.

III. DVR MODELING

As mentioned before, a DVR is a VSC that is connected in series to the power grid and DFIG-WT to the PCC to inject the enough compensating voltage to compensate for voltage drop, swelling or harmonic and to obtain the stator rated voltage. Switching signals are given to the VSC by the pulse width modulation (PWM) technique with the appropriate controller. The DVR compensates for the faulty voltage to allow the DFIG-WT to continue its nominal operation as requested by the network code. Normal phase locked loop (PLL), which is synchronous in the d-q reference frame, detects the network phase angle and is used for synchronization. The phase compensation method is used for power control and SRF DVR control. Since the network codes need to compensate for the complete voltage drop in fault conditions, the DVR is determined for wind turbine power. For voltage drop with zero phase angle jump, the power required by the DVR is obtained by :

$$P_{DVR} = \left(\frac{V_1 - V_2}{V_1}\right) P_{load} \quad (13)$$

DVR voltage rating depends on the voltage drop. The required voltage is obtained as follows:

$$V_{DVR} = V_{1\varepsilon} \quad (14)$$

$$P_{DVR} = \sqrt{3} V_{DVR} I^{*}_{1\varepsilon^{*}} \cos(\psi) \quad (15)$$

Where P_{DVR} is the active power.

The diagram of DVR based on in-phase compensation is shown in the figure 4. The injection transformer must be sufficiently designed and the appropriate transformer ratio selected. Higher rating of the transformer is necessary to avoid the risk of high currents and high saturation discussed. In the next section, the proposed DVR is explained [3, 8].

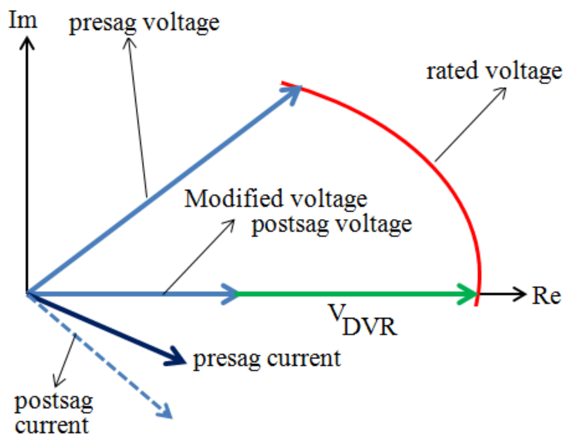

Fig. 4. Diagram of DVR based on in-phase compensation

IV. PROPOSED DVR CONTROL

In this section, the proposed method is described. The proposed DVR control is shown in the figure 5. This model is inspired from [10]. In this model, by using Park's transformation input voltages of PCC i.e. v_{Sa}, v_{Sb}, v_{Sc} are converted into the rotating reference frame voltage. In the converted voltage, the V_{Sd} has the component of the source voltage along d-axis in phase with source current and V_{Sq} is the component of the source voltage along q-axis in quadrature. V_{S0} is the source voltage. All output voltages arte orthogonal to each other. For the inductive reactive power load, the V_{Sq} will be negative, while for capacitive reactive power load, the V_{Sq} will be positive. Both V_{Sq} and V_{Sd} voltages have ac and DC components. The ac component is corresponding to harmonic voltages, while DC components are fundamental components of the voltages. In the figure 5, LPF is the low pass filter and reference DC voltage is constant. Voltage loss can be calculated by the Eq. 16 where Kp and Ki are PI controller coefficients.

$$V_{loss}(n) = V_{loss}(n-1) + K_{p1}\left(e_{dc}(n) - e_{dc}(n-1)\right) + K_{i1} e_{dc}(n) \quad (16)$$

Where

$$e_{dc}(n) = V_{dc\_ref} - V_{dc}(n) \quad (17)$$

This figure shows the voltage loss can be minimized by using PI controller. The coefficients of the PI controller should be determined such that the Eq. 16 will be minimized. Therefore, we use firefly algorithm to calculate the optimal values for Kp and Ki.

Terminal voltage can be calculated as follows:

$$V_{Lp} = \sqrt{\frac{3}{2}\left(v_{La}^2 + v_{Lb}^2 + v_{Lc}^2\right)} \quad (18)$$

Figure 5 indicates, we need two PI controllers for controlling DVR. The optimal Kp and Ki values may be different for these controllers. It is assumed the value of reference terminal voltage ($V_{Lp\text{-}ref}$) is constant.

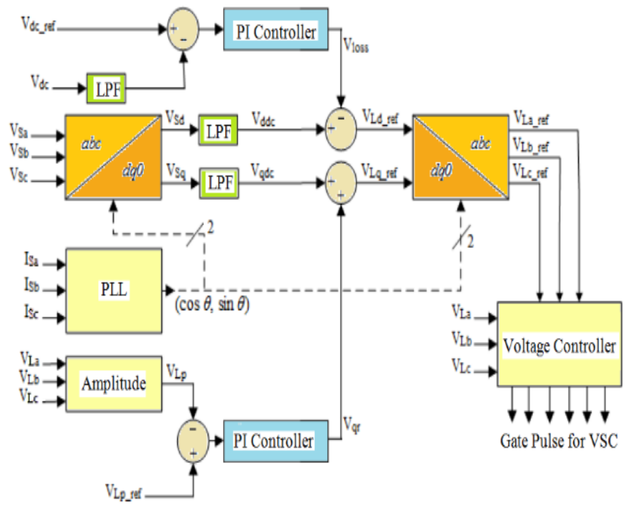

Fig. 5. Proposed DVR control model

The output of the second PI controller (Vqr) is used to regular the quadrature component of the load terminal voltage at the n[th] sampling instant and can be calculated as follows :

$$V_{qr}(n) = V_{qr}(n-1) + K_{p2}\left(e_{Lp}(n) - e_{Lp}(n-1)\right) + K_{i2} e_{Lp}(n) \quad (19)$$

Where

$$e_{Lp}(n) = V_{Lp\_ref} - V_{Lp}(n) \quad (20)$$

Now, the objective functions are Eq. 16 and Eq. 19 and problem constraints are maximum and minimum allowable values for active and reactive powers, ac and DC voltages. We employ firefly algorithm to solve this problem.

Firefly algorithm was introduced in 2007 by Xin-She Yang and that is inspired by the flashing behavior of fireflies. Tis algorithm has two main advantages than other optimal algorithms: automatical subdivision and its ability to deal with multimodality. This algorithm is developed based on the three main rules [11]:

1. Fireflies are unisexual; therefore, they will be attracted to other fireflies regardless of their sex.
2. The attractiveness is proportional to the brightness. The value of the brightness is dependent to distance. Always, less bright firefly is attracted to high brighter firefly. Firefly move randomly if there is no brighter one than a particular firefly.
3. The brightness of a firefly is determined by the landscape of the objective function.

Figure 6 indicates the flowchart of the firefly algorithm.

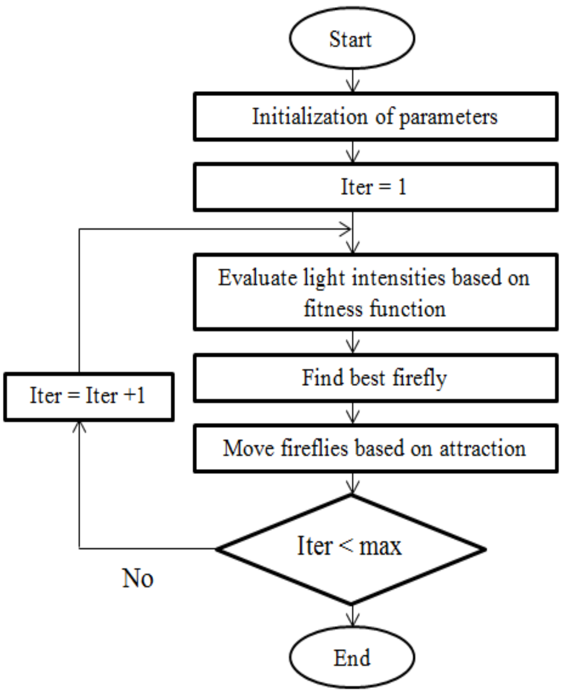

Fig. 6. Flowchart of the firefly algorithm

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, the performance of the proposed algorithm is evaluated by using the numerical examples. The simulations are run in the MATLAB software. It is assumed a 1.5 MW wind turbine is connected to the grid. The wind farm is used FTR to compensate faults effects on the grid.

The FTR is based on the DVR. In this section, we investigate the performance of the system in the two scenarios; in the first scenario, it is assumed the DVR system is used the feedback control system to manage the system. In the second one, the DVR is controlled by using the PI controller that its caffeinates are calculated by using the firefly algorithm. It is assumed the fault is accrued as t=0.2 sec of the simulation. Table 1 indicates the simulation parameters.

Table 1. Simulation parameters.

DFIG power	1.5 MW
Cut-in speed	5 m/s
Cut-out speed	30 m/s
Average wind speed	10 m/s
Network frequency	50 Hz
Stator Voltage	575 V
R_s	0.02 pu
R_r	0.002 pu
DC bus voltage	1150 V
DVR capacity	1.5 MVA
DVR inductance	0.1 mH
DVR capcitance	1.5 µF

Figure 7 indicates the stator current for both scenarios. It is observed after t=0.2 sec, fluctuations are occurred in the current signals. In the both scenarios, DVR can eliminate these ripples. But, this figure shows the system includes the DVR with firefly algorithm has less fluctuations and can reach its stable state in a shorter time.

Similarly, figure 8 indicates the stator voltages for both scenarios. In this figure, we observed the system that has DVR with PI controller has the better performance than other system.

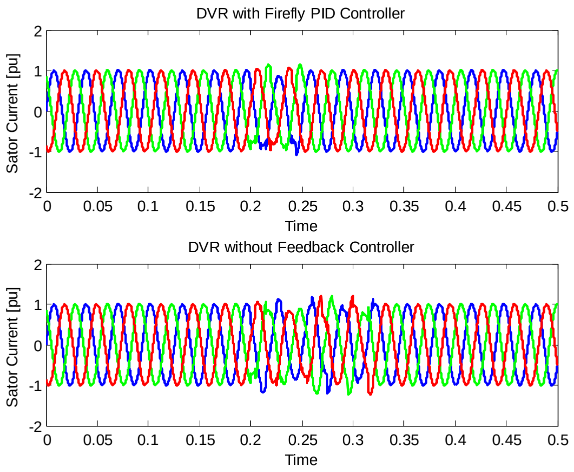

Fig. 7. Stator current in the simulation

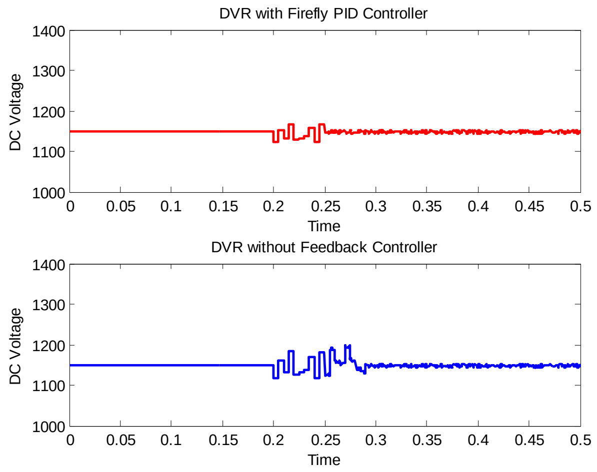

Fig. 9. DC voltage of the grid in the simulation

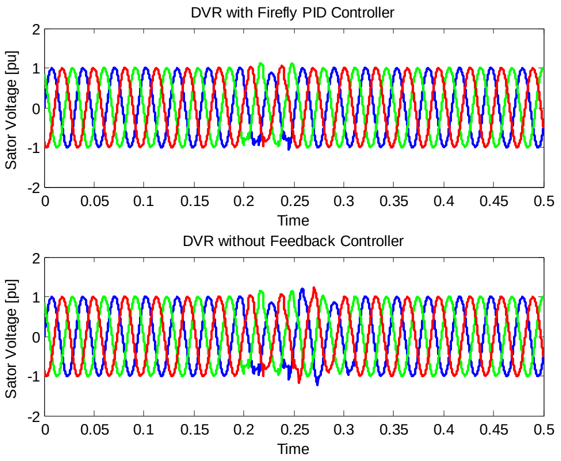

Fig. 8. Stator voltage in the simulation

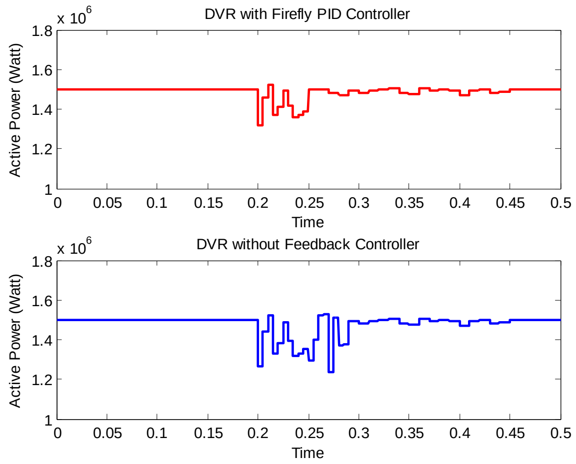

Fig. 10. Active power grid in the simulation

The DC voltage is affected, when fault is occurred in the grid. By compensating the effect of the fault, the DC voltage returns to stable value. Figure 9 shows, the DC voltage has some ripples after t=0.2 sec. However, the amount of ripples in our proposed method is less than traditional DVR systems. In addition, figures 10 and 11 show active and reactive powers of the wind farm during faults, respectively. These figures show the PI controller can improve the performance of the power grid by improving the performance of the DVR. It is observed, during fault, DVR produces reactive power and injects it to the grid. Rotor speed also is shown in the figure 12. It is observed, that the occurrence of fault in the network, regardless of its type, can affect the entire network and its components.

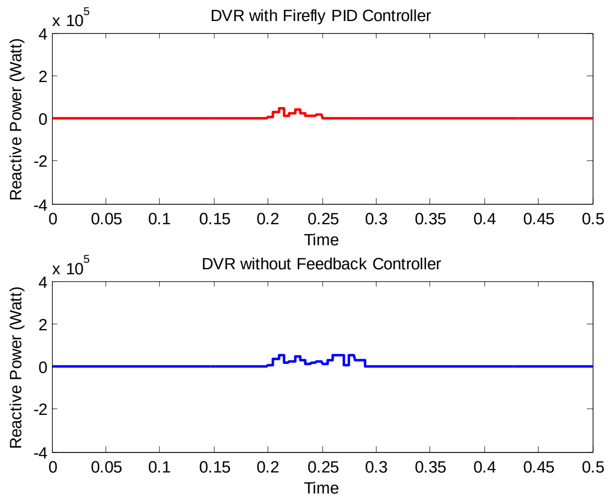

Fig. 11. Reactive power grid in the simulation

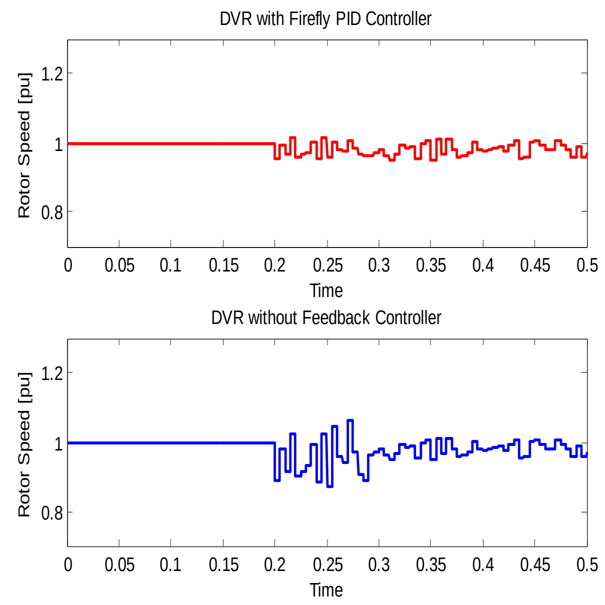

Fig. 12. Rotor speed during faults

As mentioned before, the DVR should inject voltage to grid to compensate negative effects of the faults. Figure 13 shows the injected power to the grid. It is observed, by occurring fault in the grid, the DVR starts to inject voltage.

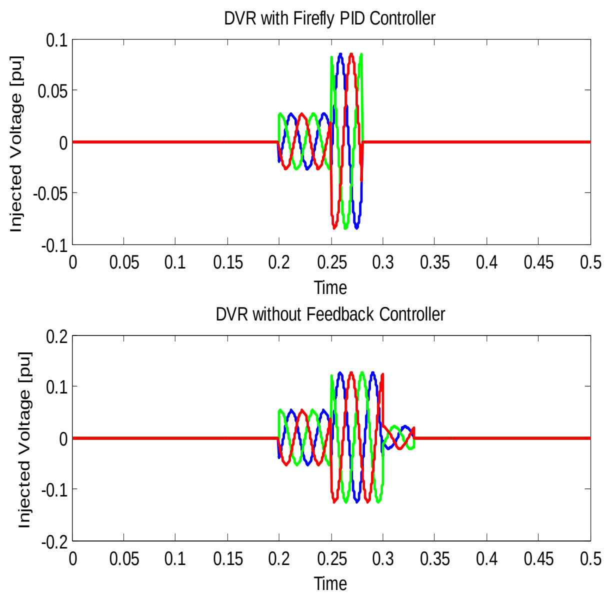

Fig. 13. Injected voltage to grid from DVR

VI. CONCLUSION

The performance of the DVR for DFIG wind turbine is investigated in this paper. The aim is to improve FRT in DFIG-WT based on the DVR. DVR can inject voltage and generate reactive power for grid during faults. These activities are necessary for guarantee the stability of the power grid. To improve the performance of the DVR, this paper introduces a novel control system for DVR. In fact, although majority of DVR control systems, used PI controller, but they did not use optimal PI controller. We used optimal PI controller to minimize the error in the system. In addition, we employ firefly algorithm to calculate optimal values for PI caffeinates. Simulation results show the proposed algorithm has a proper performance and can eliminate negative effects of faults on the power grid.

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