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A New Method for Direct Power Control of DFIG-Based Wind Turbines under Voltage Disturbances

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Abstract

Doubly-fed induction generator (DFIG) is too sensitive to the terminal voltage reduction. Thus, it is essential to choose an appropriate controller for converters in order to have stable voltage as well. In this article, double-fed wind turbines is controlled by vector proportional integrated regulator. For this purpose, a test network using vector proportional integrated (VPI) regulator is applied. Therefore, the stability is examined by evaluating the considered grid under different fault conditions. In addition, the performance of this grid is evaluated in the case of adding DFIG. Next, the effect of VPI regulator is analyzed on performance of this grid. The results showed that application of vector proportional integrated regulator improves grid stability to a further degree than direct vector regulator.

Keywords: Doubly-fed induction generator, vector proportional integrated regulator, fault, wind turbine, direct power control.

1. INTRODUCTION

Doubly-fed induction generator (DFIG), compared to fixed-speed induction generators or synchronous generators, have various advantages including variable speed and capabilities to take advantage of four-phase active and reactive power, lower cost of the convertor and power losses [1], [2].

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In these regards, several new control methods have been proposed to improve the performance of DFIG operation, such as voltage oriented control (VOC), direct power control (DPC) and predictive current control (PCC) [3]- [6]. So far, steady and transient response of DFIG-based wind power generation system has been widely discussed under balanced and unbalanced conditions. Researchers proposed unbalanced control strategy by vector-oriented control technique, in which the harmful effect caused by negative component of the grid voltage was analyzed on DFIG system [4].

In [5] Lie Xu used the direct vector control for DFIG. It was based on the direct control of active and reactive power by selecting the appropriate voltage vector applied to the rotor. As the initial rotor flux does not influence the active and reactive stator power, only the stator flux is used to eliminate the problems of estimating rotor flux. Although this method did not provide comparable results with other techniques, no certain method has been already proposed to control the voltage harmonic distortions; the same is true for VOC and PCC methods. Vector oriented voltage control acts based on the idea of simultaneous composition and application of direct and squared components of the injected current and the relevant calculations are conducted in the reference voltage space vector.

In [6] Dawei Zhi used the predictive current control for DFIG. The method predicts the changes of the rotor current in the synchronous reference of rotor flux during a certain period. In order to eliminate the current fault, the voltage required by the rotor is to be calculated directly. Obviously, this method depends on simultaneous calculation of rotor current and its voltage; an optimal result may not be acquired by appearing some faults which change the ratio of current changes and voltage.

Several alternate control objectives focus on eliminating the negative component of the stator and rotor current as well as volatility of the active/reactive power and electromagnetic torque. Various studies clearly expressed the unbalanced control technique using DPC by compensating for different parts of the stator power to improve function of the DFIG under unbalanced transient grid voltage. An analysis and an improved VOC have been provided for DFIG, which suggested the alternate control objectives to maintain the three-phase sinusoidal stator current or eliminate fluctuations in both active and reactive stator power or omit the fluctuations in electromagnetic torque [7]-[10]. In addition, apart from the usual loop of rotor current control, an independent and distinct loop of stator resonant current control was successfully presented to remove harmonic components of the stator current [4].

Accordingly, the studies noted above focused on a DFIG system under VOC-based harmonic voltage, which need to separate essential and harmonic components of the grid voltage; as a result, stability of the closed loop and dynamic response of the system would be worried. DPC technique could improve DFIG control such as simple implementation, fast dynamic response, stability against parameter change and grid disturbance [5]. In order to overcome the old DPC method drawbacks, the variable switching frequency, integrated DPC by space vector modulation (DPC-SVM) are used to reduce the broadband harmonic injections into the grid and so simplify the filter design. Multiple regulators used in some research for precise tracking of real signal with respect to a criterion include: hysteresis regulator, resonance proportional regulator, traditional PI regulator, resonance proportional integral regulator and vector PI synchronous regulator [5], [6].

According to some studies based on zero-pole eliminating to prevent unexpected increase, VPI regulator can be used to eliminate components of the oscillations in active and reactive stator power of DFIG due to the difference in closed-loop phase suitable for exact tracking of the AC signal [7].
Considering voltage harmonics, this paper used a DPC control by VPI regulator in order to focus on the exact tracking of steady state, dynamic performance analysis, stability of the closed-loop performance as well as the ability to remove the deformed grid voltage (voltage distortion) and compensation of the back EMF.

The previous studies used some controllers which may cause grid instability in some cases, while vector proportional regulator is always stable with 90° phase limit. In addition, the compliance of this regulator is higher than other controllers and it can be used by a variety of grids [11]- [15]. Many researchers put their efforts on optimizing the turbines, as well as their controllability under critical conditions [14]- [18].

This paper used a vector proportional integrated regulator to control DFIG wind turbine. The results showed that vector proportional integrated regulator is stable in both closed- and open-loop modes and does not cause grid instability itself. To achieve the most optimal case proportional to the intended application of regulator, coefficients of the optimal regulator should be determined. Grid instability will considerably drop if the DFIG-based wind turbine is added to the grid. In this case, the vector proportional integrated regulator considerably improves the grid stability; therefore, it largely compensates disturbances related to grid voltages.

2. VECTOR PROPORTIONAL INTEGRATED (VPI) REGULATOR

For power systems stability, various methods can be used. Many of these techniques influence the phases of power, voltage, and other components of the grid and some change sizes [15]. Vector proportional regulator acts in a way that not only avoids additional instability load to the grid under any circumstances, but also considerably improves stability by 90° phase limit for different values of the coefficients, in the case of voltage distortions. This regulator is also applicable to other compensators such as SVC, STATCOM, etc. The equation governing VPI regulator is,

$$C_{VPI} = K_p + \frac{K_i}{s} + \frac{K_{pr}s^2 + K_{ir}s}{s^2 + \omega_c s + \omega_0^2} \tag{1}$$

where K_p and K_i are proportional and integral coefficient for regulating the dc component, ω_c, ω_0 are the resonant bandwidth, and resonant frequency, K_{pr} and K_{ir} are proportional and integral coefficient of VPI for regulating the harmonic components, in which $K_{ir}=K_{pr}R_r/\sigma L_r$ should be achieved based on the rule of pole-zero cancellation [15].

For the purpose of better investigating the proposed DPC strategy, it should be pointed out that K_{pr}, K_{ir}, and ω_c are the only parameters of the VPI regulator that can be adjusted in the control loop, while the other parameters such as ω_0 and DFIG machine parameters are fixed. Usually, ω_c should be set about 10–20 rad/s to improve the resonant peak gain and the robust performance to the grid frequency variation, and K_{pr}, K_{ir} should be obtained based on the rule of pole-zero cancellation to achieve 30–50 dB peak gain at the resonant frequency to eliminate ac signal tracking error [15].

The controller is composed of a fixed part, an integrator and a function with second-order numerator and denominator including two zeros and two poles; rewriting as a single polynomials in Eq. (2),

3. SIMULATION AND RESULTS

The conversion function of this regulator involves three zeros and three poles. Fig. 1 shows a block diagram of VPI regulator.

$$C_{VPI} = \frac{K_p \times \left(s^3 + \omega_c s^2 + \omega_0^2 s\right) + K_i \times \left(s^2 + \omega_c s + \omega_0^2\right) + K_{pr} s^3 + K_{ir} s^2}{s^3 + \omega_c s^2 + \omega_0^2 s} \qquad (2)$$

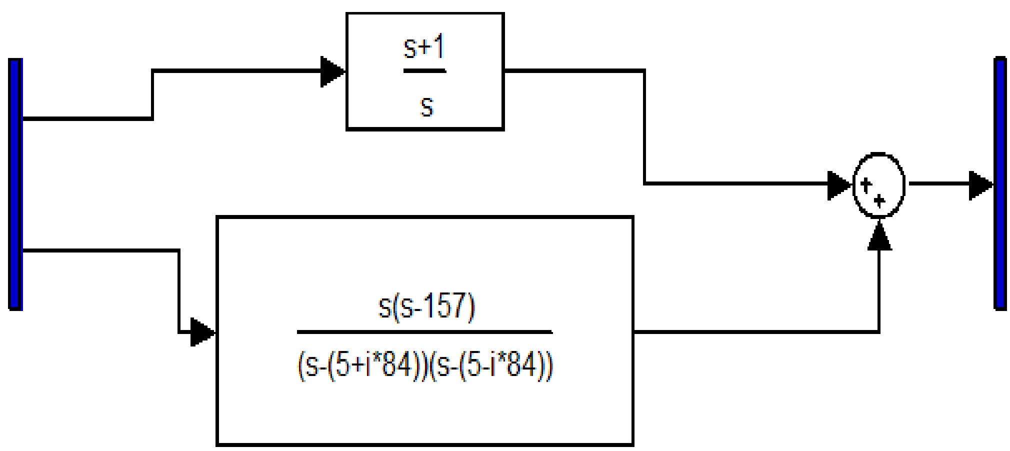

Fig. 1. Block diagram of VPI regulator.

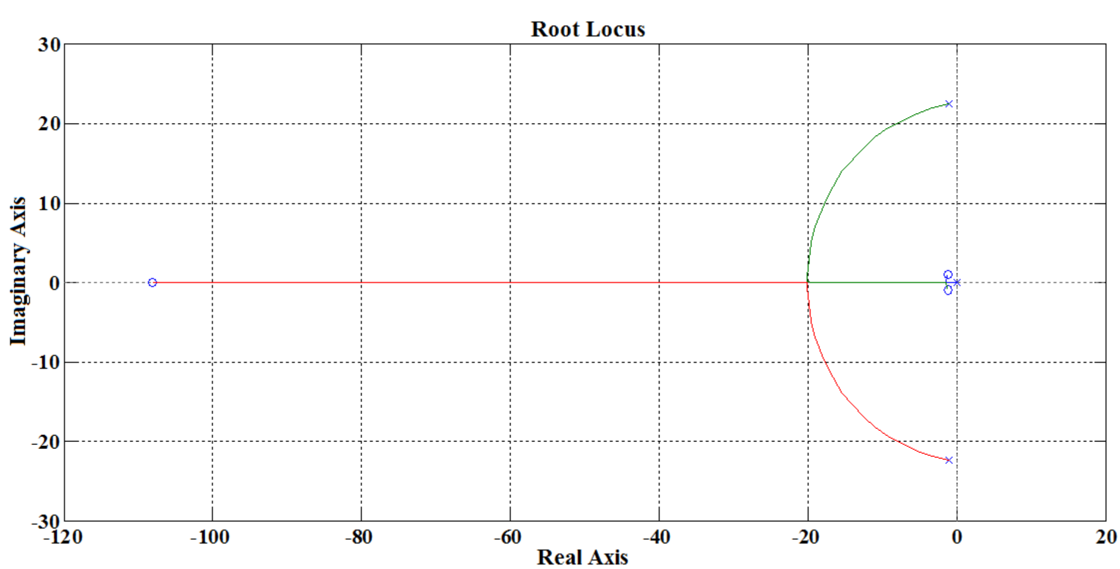

Fig. 2. Open-loop locus of the VPI poles.

In this paper, the coefficients of VPI regulator in the block diagram are supposed according to Eq. (3).

$$\begin{aligned} &K_p = 2 \\ &K_i = 2 \\ &\omega_c = 14 \\ &\omega_0 = 200\pi \\ &K_{ir} = 160 \\ &K_{pr} = 2 \end{aligned} \qquad (3)$$

Fig. 2 shows locus of the open-loop poles for values suggested in Eq. (1).

As seen in Fig. 2, the regulator will be stable in open-loop mode, because all points of the locus are located on the left axis jω. Fig. 3 shows the locus related to poles of the closed-loop function. According to Fig. 3, the closed-loop function of VPI regulator is stable for all different frequencies and thus their corresponding poles.

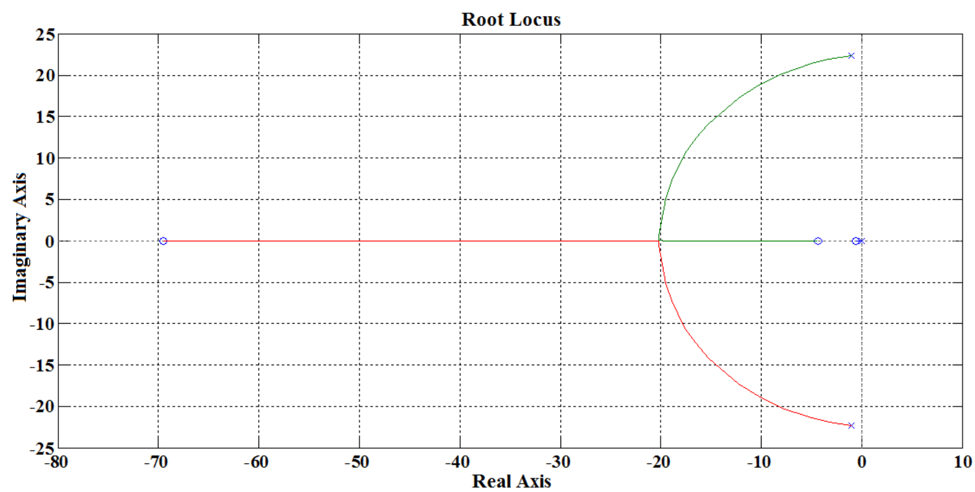

Fig. 3. Closed-loop locus of the VPI poles.

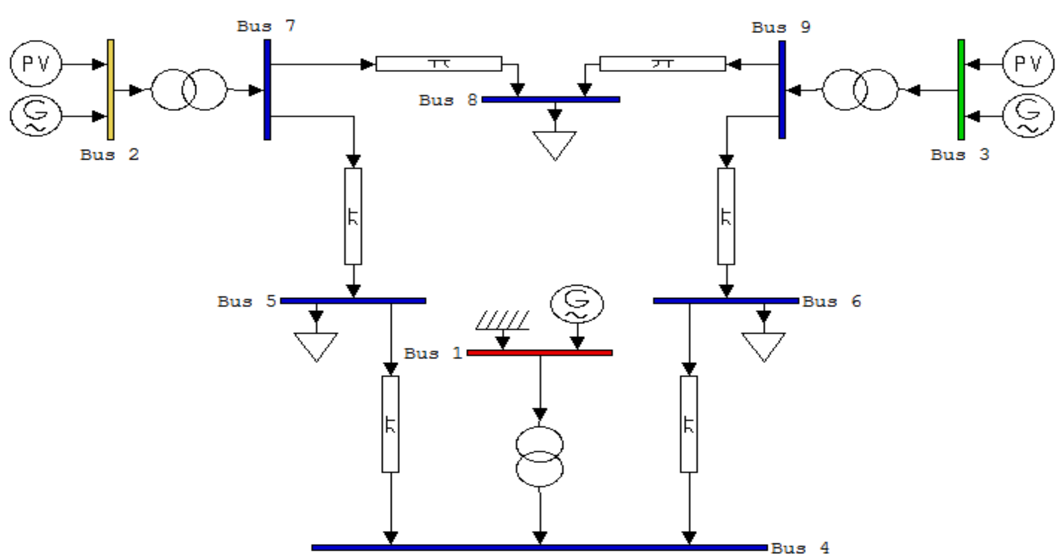

Fig. 4. The studied test network.

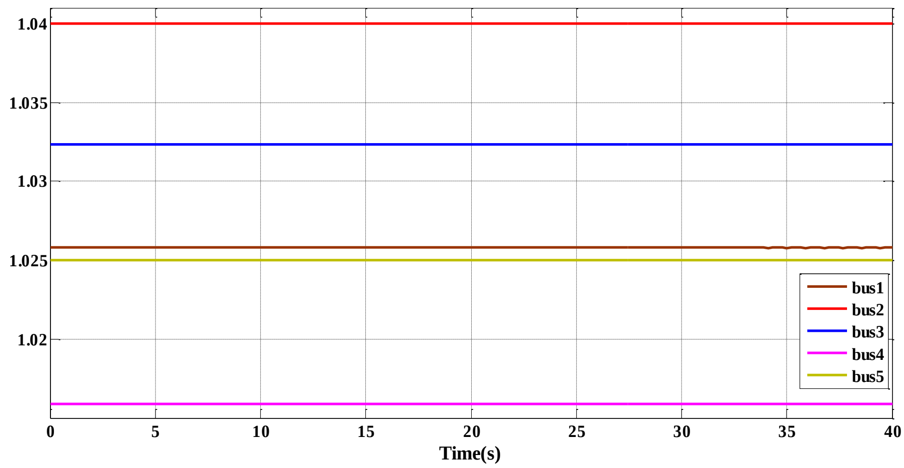

Fig. 5. Voltage of buses.

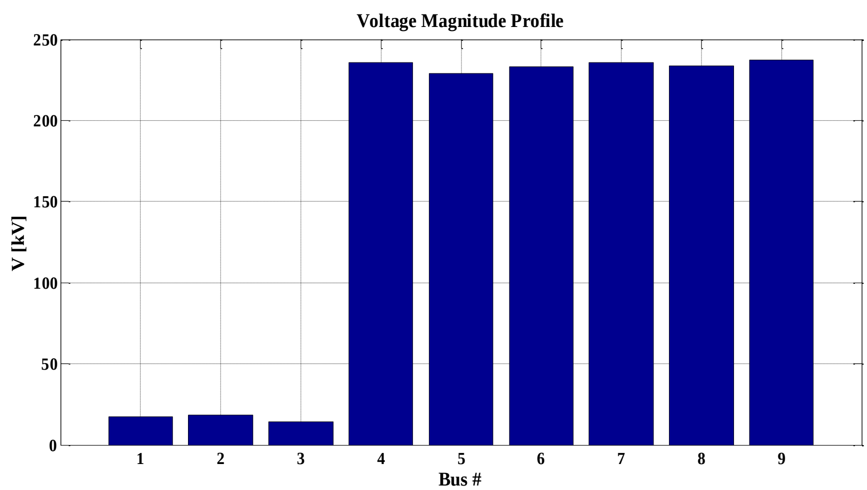

Fig. 6. Voltage of the faultless buses.

To evaluate the performance of VPI controller, the test network shown in Fig. 4 was used. The voltage of line that used in grid is 230 kV which is injected by three energy generators. Tables 1 and 2 present specifications of the transformers and loads.

Figs. 5 and 6 show voltages of the buses. As shown in Fig. 5, the grid is stable for the initial conditions.

If any fault occurs on a Bus 7 for 0.2 seconds, the bus voltages will be in the form of Figs. 7 and 8.

As the Fig. 7 shows, although the gird obviously changes for 0.2s fault and shorter, the fault will not lead to instability.

Table 1. ***Specifications of the transformers.***

Trans-former	Re-sistance (p.u)	Reac-tance (p.u)	Voltage ratio
Connected to bus 1	0	0.0576	16.5/230
Connected to bus 2	0	0.0625	18/230
Connected to bus 3	0	0.0586	13.8/230

Table 2. ***Specifications of the loads.***

Number of bus related to load	Load (MVA)	The ratio of active power	The ratio of reactive power
5	100	1.25	0.5
6	100	0.9	0.3
8	100	1.00	0.35

As seen in Fig. 8, the voltage of some buses became less than the faultless case, but in small quantities and not zero. For better comparison, Figs. 9 and 10 represent the bus voltages for 0.25s fault.

Fig. 9 shows that the grid will be instable for such faults and faults with more time, because some bus voltages became zero.

Fig. 10 shows more clearly that the voltage of buses 7 and 8 became zero. Different methods can be used to stabilize instable grids under possibility. If SVC compensator is used, bus voltages will be like Figs. 11 and 12.

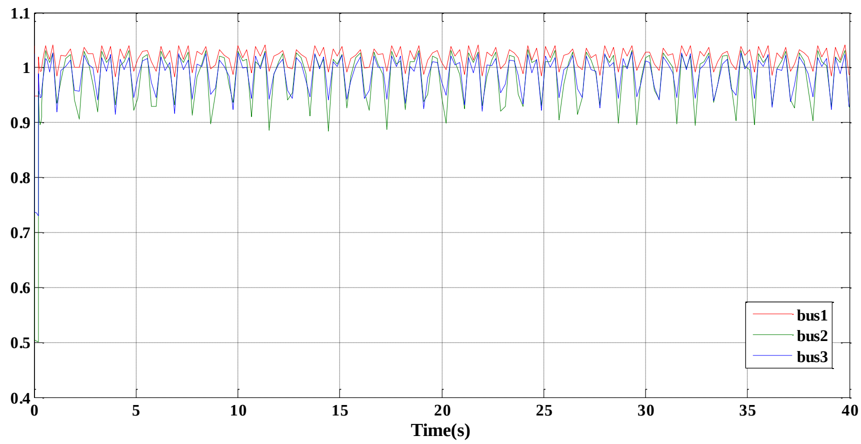

Fig. 7. Voltages of some grid buses in 0.2s fault.

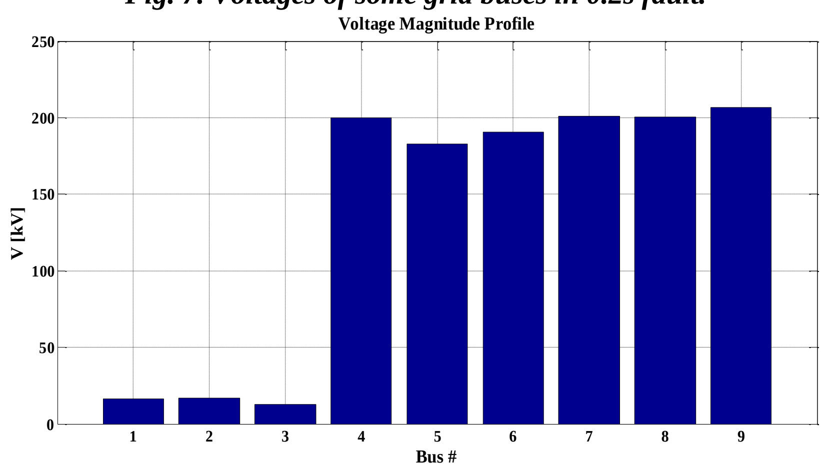

Fig. 8. Voltages of the buses in 0.2s fault

Fig. 9. Voltages of some buses in 0.25s fault.

As the Figs. 11, 12 show, the grid acts as a faultless grid using compensator.

Adding double-fed wind turbine to the grid, the results show that:

DFIG-based grids demonstrate different behaviors than available grids; however, the governing equations and evaluation of these grids are similar to other power systems.

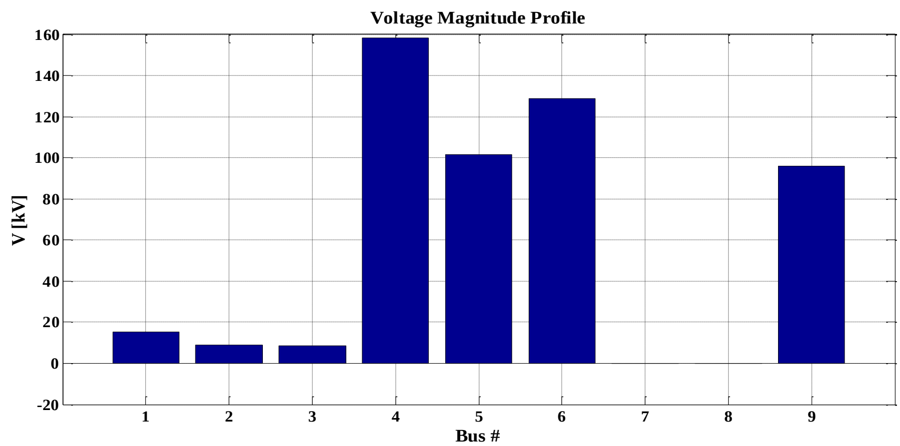

Fig. 10. Voltage of buses in 0.25s fault.

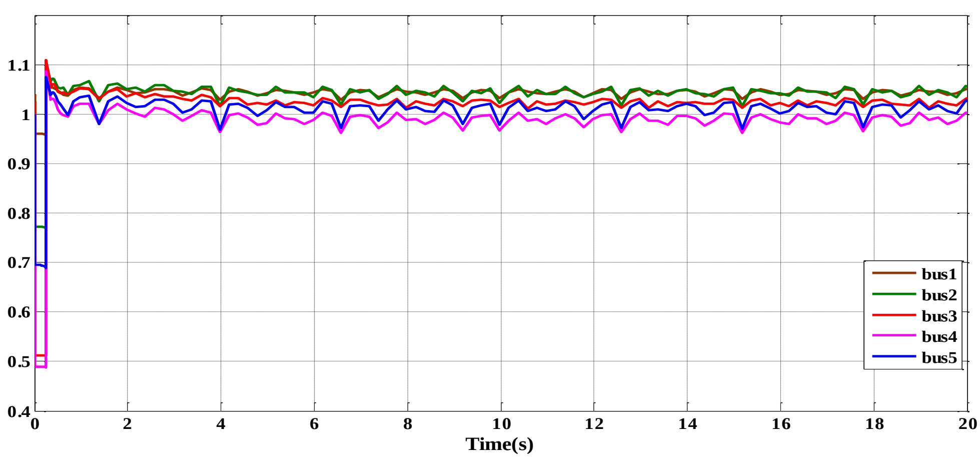

Fig. 11. Voltages of some buses in 0.25s fault using SVC compensator.

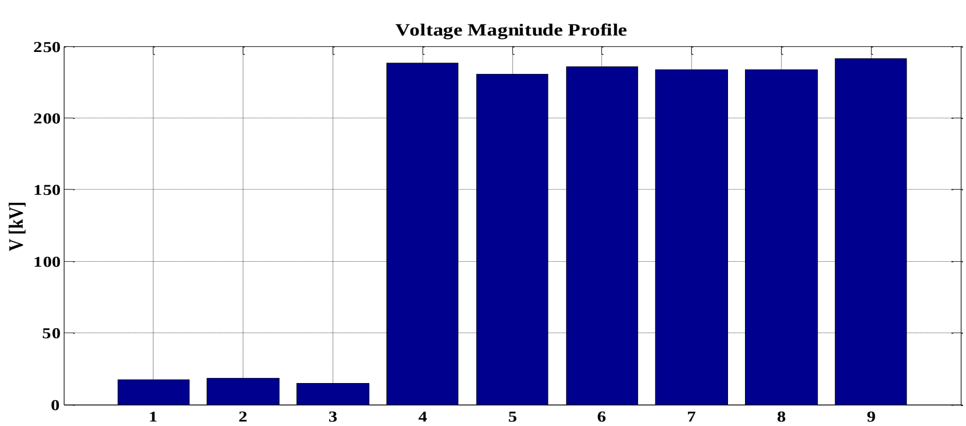

Fig. 12. Voltages of buses in 0.25s fault using SVC compensator.

Fig. 13 shows the grid examined in the presence of double-fed wind turbine (DFIG).

Figs. 14 and 15, show the bus voltages in this case.

In this case, the network is stable, but it is largely far from the usual.

In order to control and optimize the performance of DFIG-based grid, a VPI regulator can be used as shown in Fig. 16.

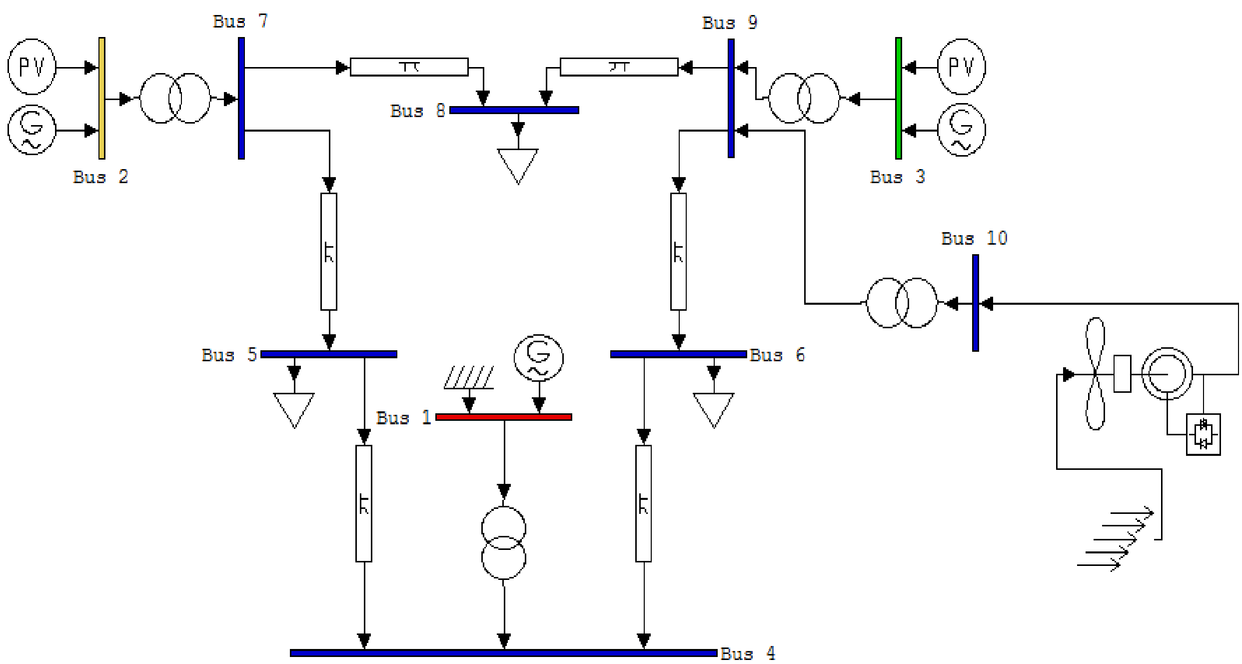

Fig. 13. The studied grid in the presence of DFIG.

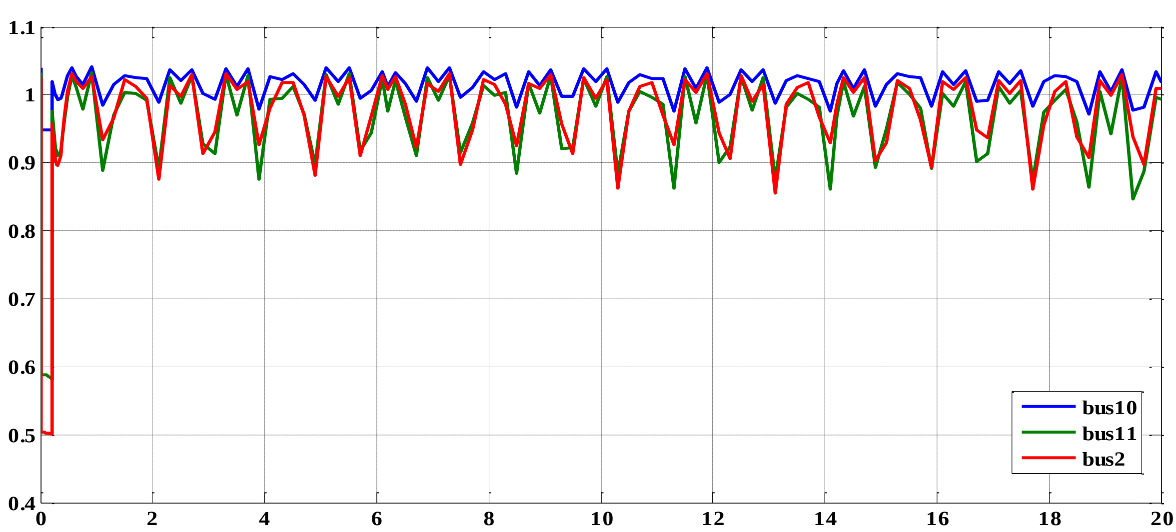

Fig. 14. Voltage of some buses using DFIG.

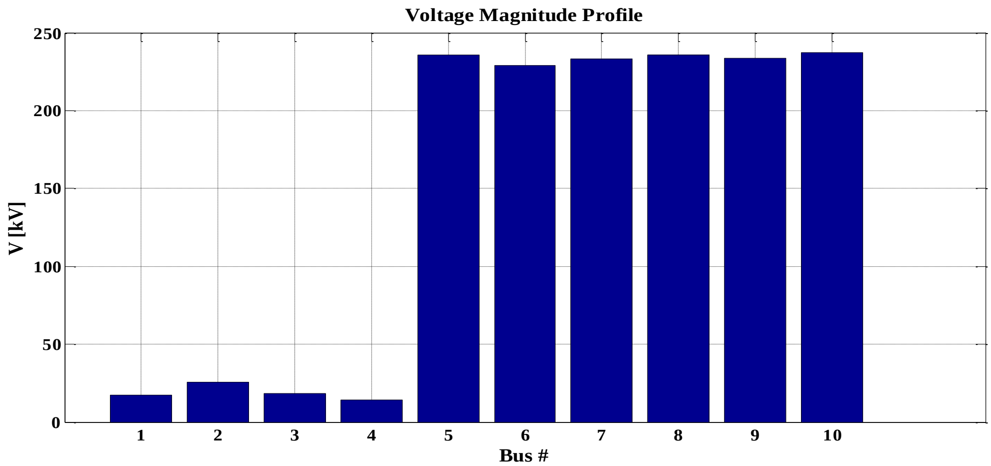

Fig. 15. Bus voltages in the presence of DFIG.

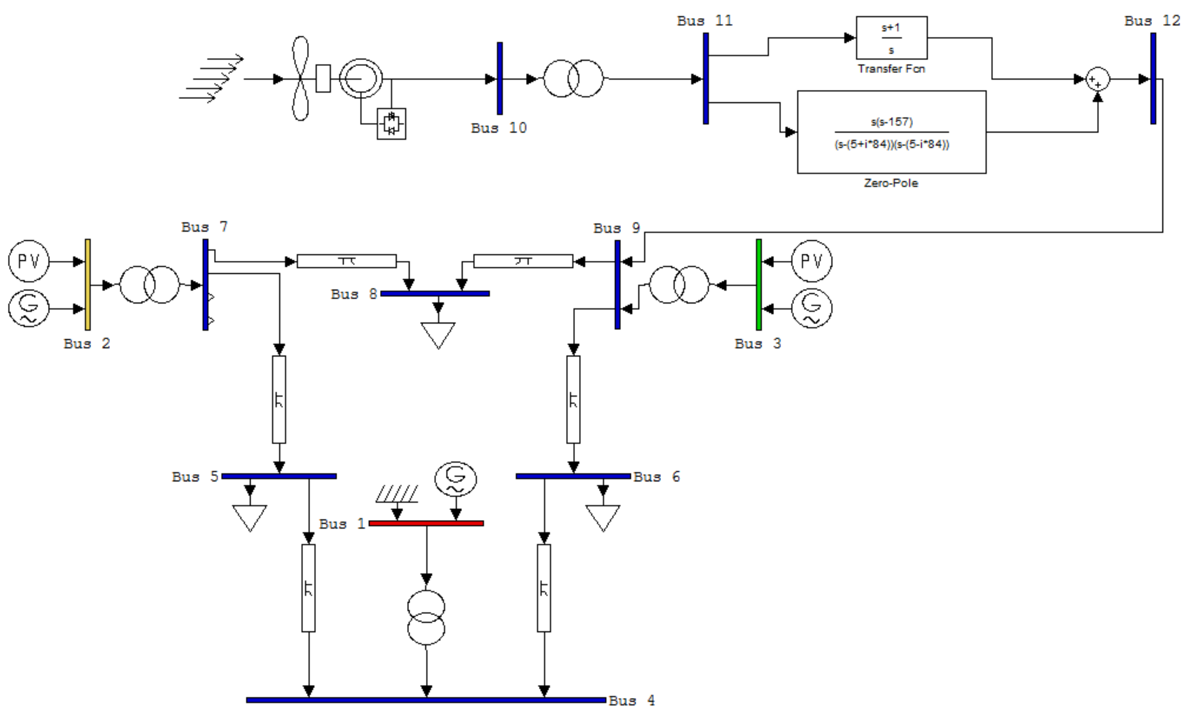

Fig. 16. View of the DFIG-based grid and VPI regulator.

If the VPI regulator is used, bus voltages are in the form of Fig. 17 and 18.

According to the results shown in figures, VPI regulator could considerably improve the grid and made it resistant against other changes. This controller can be also used in other power networks. Proportional to the studied grid, other possible parts can be added and used. As the results show, the present approach achieves better results compared to VOC, PCC and DPC methods. With regard to stability of the closed loop and open loop, it is applicable in more cases than other controllers. In addition, distortions and voltage drop considerably reduced by vector proportional integrated regulator compared to other methods.

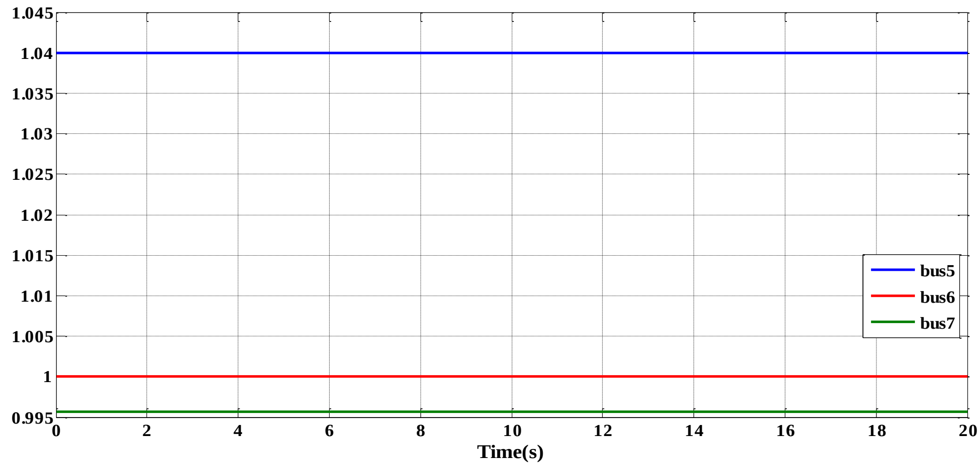

Fig. 17. Voltage of some buses in the presence of DFIG and VPI regulator.

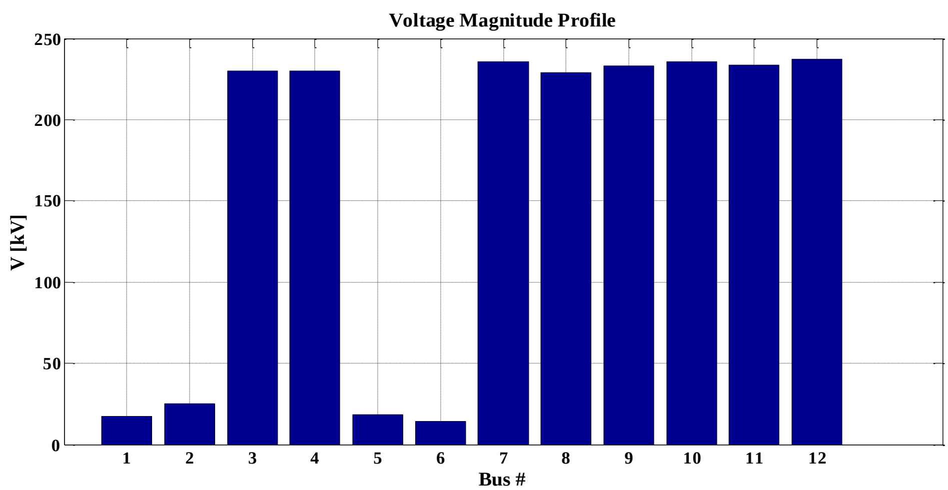

Fig. 18. Bus voltages of the DFIG-based grid and VPI regulator.

4. CONCLUSION

This paper investigated the direct power control of DFIG-based wind turbines under distorted voltage using a vector proportional integrated regulator. The results of simulation shown that the vector proportional integrated regulator is stable in closed-loop and open-loop grid as well. Adding a DFIG to the grid, stability of the grid is decreased and the grid may be close to instability. Using vector proportional integrated regulator, therefore, the studied system will be well stable. The system maintains stability under faults with periods less than 0.2s.

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