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RESEARCH ARTICLE

Transmission and Distribution Smart Grid System Based on Self-Hailing Controllable Crowbar

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ABSTRACT The smart grid system is an ideal solution to overcome the limitations of traditional grid systems. A system is considered smart if it has smart in all its parts such as smart generation, smart transmission and distribution, smart control, smart metering, and … etc. In this paper, smart transmission and distribution have been presented to achieve the requirements of the smart grid system. By transferring to the smart grid, all utilities catch a lot of benefits such as increasing reliability, efficiency, and safety. On other hand, the operation cost will be decreased. In addition, fast dynamic response for fault detection and isolation based on automatic Internet of Things (IoT) and wireless control can be achieved. It should be noted that in the smart grids, the security of the system and occupational safety will be greatly increased. The system has been validated under different kinds of faults such as single-line to ground fault, and double-line to ground fault. In addition, the theoretical operation has been tested via MATLAB Simulink software.

INDEX TERMS PV, wind, smart grid system, smart transmission and distribution system, controllable crowbar, fault.

NOMENCLATURE

DFIG	Doubly Fed Induction Generator.
WECS	Wind Energy Conversion System.
CBFT	Crowbar Based on Fault Type.
PCC	Point of Common Coupling.
FRT	Fault Ride Through.
ANFIS	Adaptive neuro-fuzzy inference system.
PV	Photovoltaic.

I. INTRODUCTION

The electrical systems became complex and contained many components, which was due to the increasing demand for energy, which led to an increase in generation stations and thus increase the need to develop and raise the efficiency of transmission and distribution systems. These traditional systems suffer from many problems related to the system's ability to restore its stability after any kind of fault occurs.

Recently, many researchers and large companies have turned to using modern systems in controlling all components of the system, and the system has been called the smart grid. The use of a smart grid allowed reliability, security, demand side management system, metering, self-healing, connection with micro-grids, and integration of renewable resources [1], [2], [3], [4], [5].

The system can be called smart if one part or all parts of it became smart and the parts are generation, transmission, distribution, control, and metering. in [1]. New smart grid monitoring has been used which led to develop and increase the electric utility, three-step control has been presented to optimize the overall efficiency in [2] the automatic solving of the energy fluctuations has been presented in addition, the effect of smart grid on the physical power grid has been analyzed, in [3] the effects of smart grid on the national grids have been proposed. besides, it presented several effective proposals to transform the traditional grid into a smart grid.

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in [4] a smart grid model has been presented and it discusses the benefit of a smart grid for the long term, in [5] only the smart generation is interested has been presented. In this paper, the smart transmission and distribution system has been presented under different faults to achieve the requirements of smart grid systems. These requirements have been presented in detail in [5].

The different feature of the smart grid over the traditional grid has been listed in Table 1 [6], [7], [8], [9].

TABLE 1. The different features of the smart grid over the tradition.

	Proposed system based on Smart grid	Traditional grid
power distribution system	The infrastructure for the distribution system is used optimally with high efficiency	Minimum level of efficiency for the power infrastructure
transmission system	The infrastructure for the transmission system is used optimally with high efficiency	Minimum level of efficiency for the power infrastructure
power generation capacity	represent an alternative to investment	Lose its importance due to the development of the technology
Control aspects	Use an efficient automatic protection control based on the proposed self-hailing protection control	Tradition protection control may use without any automatic control
Cost-benefit analysis (CBA)	Low cost	High cost
Reliable	More reliable	Less reliable
Self-healing from power disturbance events	Solve the problem of blackouts	The probability of this problem has a high percentage of occurs
Enabling active consumers participation and operating resiliently against attack	Available	Not available
Providing power quality and optimizing assets	Can be strongly achieved	Low level of power quality
Future generations	Accommodating all generations and enabling new products, services, and markets	Networks cannot accommodate modern development
Load Reduction	it may restrict all individual devices, or another larger customer, to reduce the load temporarily	the overall load is not a stable, slow varying, average power consumption
Elimination of the demand fraction	By using control systems, power grid systems have varying degrees of communication	uncontrolled blackout
Exchange of measurement data and control signals	Available	Not available
Communication	Two way	One way
Metering	Advanced	Traditional devices

It is worth mentioning that all kinds of faults have a direct effect on the power system generation, hence the smart grid has been proposed to give a good solution for the system under faults, in addition, the system has a good dynamic response under the dynamic change of the system wither was a fault or load change. A lot of electrical systems have been studied based on different faults [10], [11], [12], [13], [14]. In [10] effective algorithms have been presented to locate the fault for the two-parallel transmission line. In [11] the behavior of the system voltage and load currents have been studied based on different faults with linear and non-linear loads, in [12] a novel method of the single-phase-to-ground fault has been presented. In [13] double line to the ground has been applied, in addition, Fault resistance values are determined, In [14] the tripping of the line without fault has been discussed and this tripping is more dangerous than a three-phase permanent ground fault, the criterion used in this previous study showed that the inertia time constants, transfer impedance angle and initial relative phase angle between two machines are the important items to determine any machines most effected by fault.

The faults in the transmission and distribution system can be solved by different methods like the fault current limiter in [15] which improve the transient stability of a grid and the (FRT) by using the proposed shunt resonance fault current limiter. And crowbar resistance [16], [17], [18], [19], [20]. In [16] study the influence of crowbar resistance on the stability of DFIG with (FRT) has been presented. In [17] the crowbar has been designed to the grid voltage dip to limit rotor fault current, DC-link over-voltage, and protect the rotor converter effectively. In [18] the maximum crowbar resistance has been used to protect the over-voltage of the rotor side converter from high rotor currents, and also avoid high currents flowing through the rotor side converter to the DC-link capacitor. In [19] the influence of various types of faults on grid-connected with (DFIG WECS) with and without crowbar resistance has been presented. In [20] the study the crowbar protection system has been presented. In addition, the crowbar resistance value is calculated.

All previous techniques for using crowbars used the traditional method to allow the crowbar to catch in the system which depends on the manual adjustable of the time that the crowbar works as a protection device. Some papers put a control system to the electronic switches of the crowbar system to catch in and out from the grid automatically like in [21], [22], [23], [24], and [25]. Presents in [21] different control strategies of the crowbar protection used with DFIM during a voltage dip in the grid. Grid faults in [22] used a designed (ANFIS) crowbar protection strategy for DFIG. Proposed in [23] a novel controllable (CBFT) protection technique for DFIG WECS connected to the grid. For the problem in rotor current and DC bus voltage in DFIG in [24] showing adaptive control strategy and the resistance setting method, With the proposed scheme both the rotor current and DC-bus voltage can be controlled inside the restriction.

Self-controllable crowbar in [25] proposed to improve the reliability of the BDFRG under faults. In [26] using a hybrid fuzzy-PI controller to create a control signal for an electronic switch(IGBT) of the crowbar system.

In [25] a new control strategy for the crowbar has been used which the crowbar has been automatically catching in and out of the system without any manual adjustable. In addition, the system used in [25] was wind only. in this paper, the control strategy used in [25] has been modified to be suitable for a smart generation system, and the main motivation in this paper can be summarized as:

- Convert the traditional transmission and distribution system to a smart system by using a simple controllable crowbar simple with self-hailing.
- Using controllable crowbar not only with wind generation but also with hybrid generation.

II. SYSTEM UNDER STUDY

The smart generation system shown in Fig. 1 has been selected to be a case study for the proposed control method. The system contains a wind generation station connected with the grid, beside the PV generation station and the load used is RL load.

The electric equations for DFIG of wind generation station in (1):

$$\begin{cases} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = -R_s \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{1}{\omega_s}\frac{d}{dt}\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} + \begin{bmatrix} -\psi_{qs} \\ \psi_{ds} \end{bmatrix}, \\ \begin{bmatrix} v_{dr} \\ v_{qr} \end{bmatrix} = -R_r \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + \frac{1}{\omega_s}\frac{d}{dt}\begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} + s\begin{bmatrix} -\psi_{qr} \\ \psi_{dr} \end{bmatrix}, \\ \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \end{bmatrix} = -\begin{bmatrix} X_s i_{ds} + X_m i_{dr} \\ X_s i_{qs} + X_m i_{dr} \end{bmatrix}, \\ \begin{bmatrix} \psi_{dr} \\ \psi_{qr} \end{bmatrix} = -\begin{bmatrix} X_r i_{dr} + X_m i_{ds} \\ X_r i_{qr} + X_m i_{ds} \end{bmatrix}, \end{cases} \quad (1)$$

where v_{ds}, v_{qs} are voltages of the stator winding of the generator in d, q axises. v_{dr}, v_{qr} are voltages of the rotor winding of the generator in d, q axises. R_s is stator resistance. R_r is rotor resistance. i_{ds}, i_{qs} are currents of the stator winding of the generator in the d, q axes. $\mathrm{i_{dr}}$, $\mathrm{i_{qr}}$ are currents of the rotor winding of the generator in d, q axes. ψ_{ds}, ψ_{qs} are the flux linkages of the stator in d, q axes. ψ_{dr}, ψ_{qr} are the flux linkages of the rotor in d, q axes. X_s is stator reactance. X_r is rotor reactance. X_m is the mutual reactance between the stator and rotor.

The relation among the output PV cell current as a function in the cell parameters can be formulated in (2) [23]:

$$I = I_{ph} - I_o\left(e^{\frac{q(V+IR_s)}{nKT}} - 1\right) - \frac{V + IR_s}{R_p} \quad (2)$$

where; the I_{ph} is the current generated by the incident light (it is directly proportional to the sun irradiation), I_o is the reverse saturation or leakage current of the diode, q is the electron charge (1.6 × e-19 C), K is the Boltzmann constant (1.38 × e-23 J/K), n is the idealization factor, T is the temperature of $(p-n)$ junction, R_s *and* R_p are the series and parallel resistance of the cell, respectively, I is the load current, and V is the cell voltage.

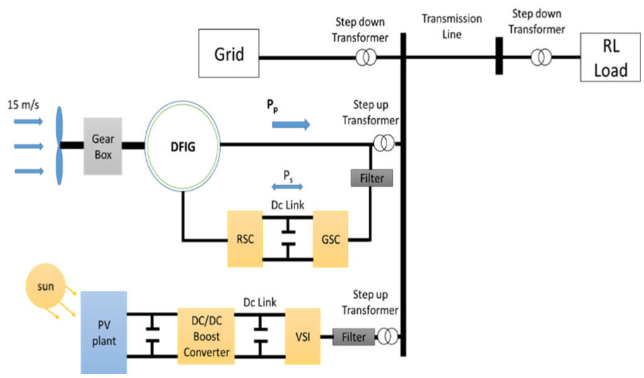

FIGURE 1. Smart generation system under study.

The protection crowbar has been used in the system and its location at transmission lines beside the generation stations is shown in Fig. 2.

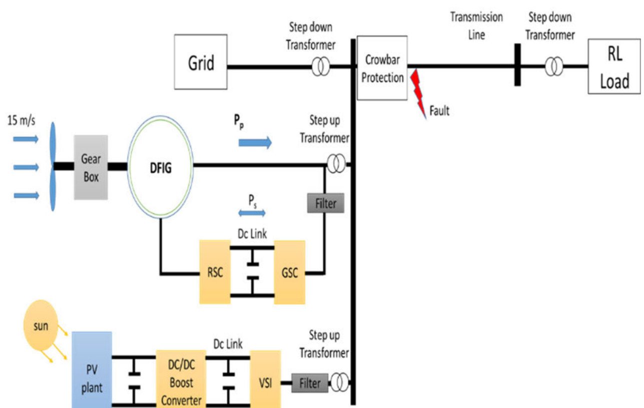

FIGURE 2. Smart generation system with smart transmission and distribution system.

III. AUTOMATIC CROWBAR RESISTANCE METHOD CONTROL

A. SIMPLE CROWBAR RESISTANCE CIRCUIT

The crowbar is a simple circuit that contains single resistance for each phase with an electronic switch to catch in/out from the system as shown in Fig. 3

In the crowbar resistance method, the value of the resistance considers the essential player for the system stability. This value has been chosen in this paper by trial and error according to the performance.

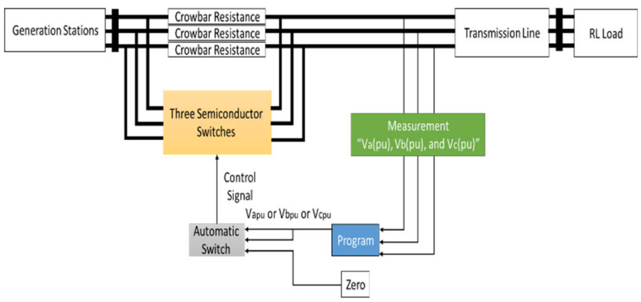

FIGURE 3. Crowbar circuit with control strategy.

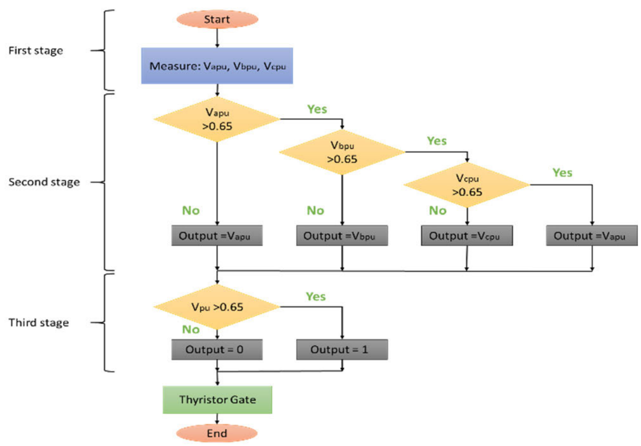

FIGURE 4. flowchart of crowbar resistance control.

B. CROWBAR RESISTANCE CONTROL STRATEGY

As shown in the flowchart in Fig. 4, The control algorithm depends on measuring the pu rms voltage at PCC for each phase, then inter this voltage on an automatic switch, if the pu voltage reduces than 0.65 magnitude (preset value 0.65 choices from the previous studies according to the value of the pu rms voltage faulty phase, where in case of a fault with the ground the magnitude of the pu rms voltage near to zero, in case of fault without ground the magnitude of the pu rms voltage near to 0.5), The electronic switch used with the crowbar is connected in parallel, and this means that in the case of faults (Vpu >= 0.65), the switch does not work, which allows the crowbar resistance to be connected in series with the system and works to protect the system in this case. In the case that no fault occurs (Vpu < 0.65), the switch is turned on and leads to removing the resistance of the crowbar from the system, as the switch is connected in parallel with the resistance [25].

So the mathematic expression for the previous cases can be presented as:

$$\begin{cases} out = 1 & if\ (V_{apu} \text{ And } V_{bpu} \text{ and } V_{cpu}) \geq 0.65 \\ out = 0 & if\ (V_{apu} \text{ or } V_{bpu} \text{ or } V_{cpu}) < 0.65 \end{cases} \quad (3)$$

In Fig. 4, the flow chart contains three stages after the control signal inter the electronic switch. The first stage measures the value of the pu rms voltage for each phase. The second stage compares the value of the pu rms voltage for each phase with the preset value of 0.65 if any one of the phases has a fault becomes the output of this stage, if three phases don't have a fault any pu rms voltage becomes output in this flowchart choice phase an arbitrary. The third stage compares the output of the second stage with the preset value of 0.65 to known found fault or not in case of fault a value less than 0.65 output to thyristor zero means the parallel path is open and the crowbar resistance active with the system, in case of no-fault the value of output of second stage greater than 0.65 then output to thyristor one mean the parallel path closed and the crowbar resistance out the system.

IV. SIMULATION RESULTS

The system shown in Fig. 2 has been created based on MATLAB Simulink software. The transformer used to connect the grid is the step-down transformer from 500KV to 220KV. The wind station used has 6 turbines with 1.5MW for each one, moreover, it is connected to the busbar via a step-up transformer from 575V to 220KV. The system also has a PV station that supplied the system by 3MW, the PV transformer is a step-up transformer from 260V to 220KV. The system feeds RL load 10 MW across step down transformer from 220KV to 380 V. Two kinds of system faults at the transmission line (PCC) have been done (single line to ground fault, double line to ground fault). The crowbar resistance choice by trying and error according to the performance as occurs in most of the research related to the crowbar system, and the magnitude in this work is equal to 450Ω.

A. SINGLE LINE TO GROUND FAULT

Fig. 5 shows the PCC voltage with a single line to ground fault without a controllable crowbar. As obvious the faulty phase (a) becomes zero and still zero until the fault is removed. In addition when the fault was removed the voltage return its previous value after sudden overshoot as shown in Fig. 5. However, in Fig. 6 the system used a controllable crowbar which allow the system to return the original value during the fault after the small time (10 msec).

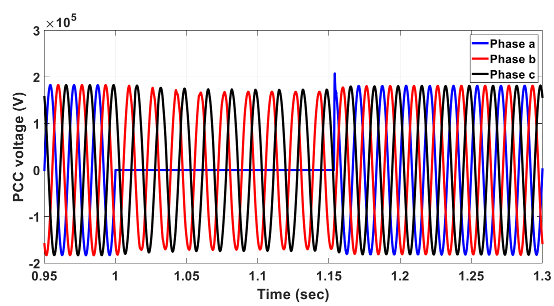

FIGURE 5. PCC voltage with a single line to ground fault without a controllable crowbar.

In Fig. 7 the grid active power with the crowbar and without the crowbar has been presented, which indicates that the waveform of the grid active power fluctuated during the fault without using the crowbar, however, the waveform with the

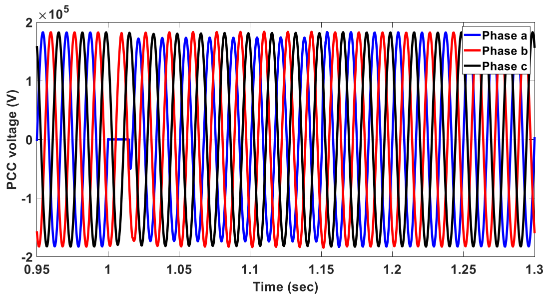

FIGURE 6. **PCC voltage with a single line to ground fault with a controllable crowbar.**

crowbar rapidly goes to the steady state value. in addition, there is power during the fault due to the resistance of the crowbar.

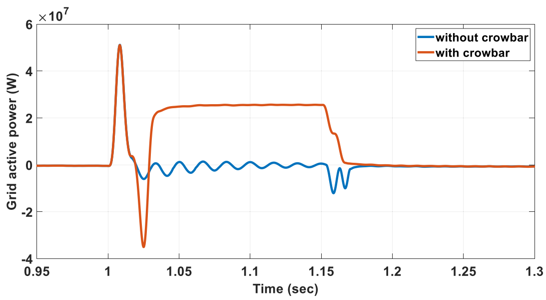

FIGURE 7. **Grid active power with single phase to ground fault with and without a controllable crowbar.**

Fig. 8 (a) shows the behavior of the wind's active power during the fault. However, the active power has a large overshoot (42.9%) but it rapidly reaches its steady state at 8.4e6 W, while without using the crowbar the value has oscillated around a value less than the original steady state value. The effect of clearing the fault has been shown in Fig. 8 which indicates that the waveform of the active power has a small undershoot while the using crowbar. But without using a crowbar the undershoot has a large value.

However, in [25] the active power in BDFRG under the crowbar for a single phase to a ground fault has been presented in Fig. 8 (b), the performance of the system under the crowbar fluctuated before the fault however during the single line to ground fault the system maintain the average value. in addition, the system has a large overshoot at clearing the fault.

In fig. 9 the PV active power has been shown. The PV active power oscillates around the steady state value after transient undershoot however, the PV active power decreases suddenly during the fault and is still around 2.25e6 W until the fault is clear.

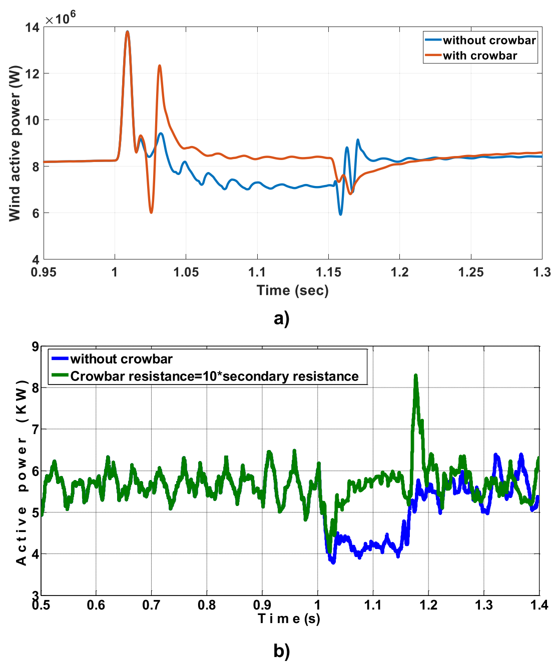

FIGURE 8. **a) Wind active power with single phase to ground fault with and without a controllable crowbar for the proposed system b) active power in BDFRG under the crowbar for single phase to ground fault.**

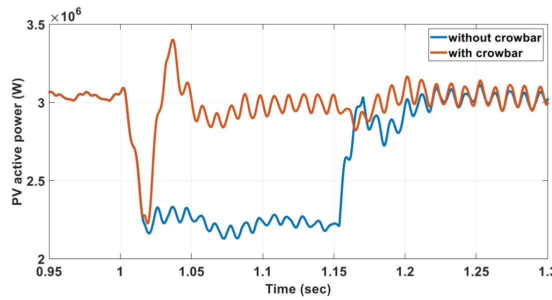

FIGURE 9. **PV active power with single phase to ground fault with and without a controllable crowbar.**

Fig. 10 shows the grid three-phase currents during the single-phase fault without using a crowbar, it is noticed that phase (a) has an instability value during the fault time. In addition, the current in this phase oscillates with a large value during the fault. However, using a crowbar phase (a) has an overshoot for a small time in the fault time, and then it oscillates with a small value during the rest of the fault time as shown in Fig. 11.

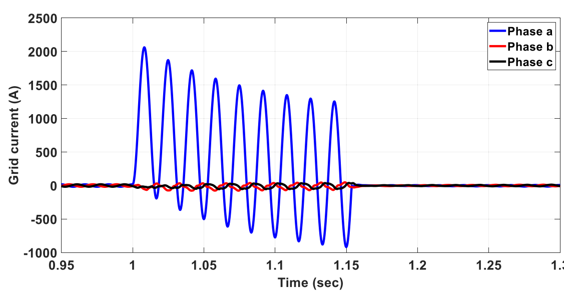

FIGURE 10. **Grid current with single phase to ground fault without a controllable crowbar.**

wind current with single phase to ground fault without controllable crowbar has been shown in Fig. 12. The three-phase currents have unstable large values during the fault. Small

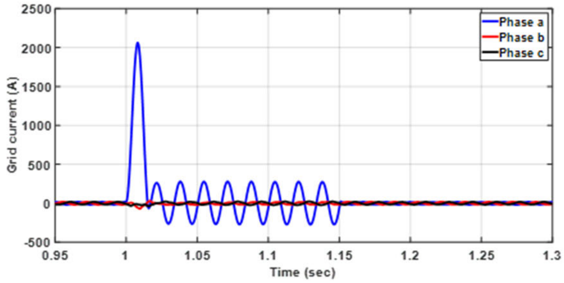

FIGURE 11. Grid current with single phase to ground fault with controllable crowbar.

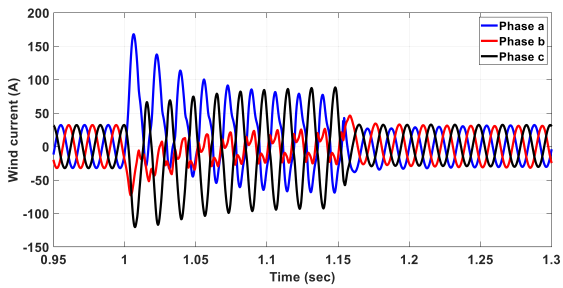

FIGURE 12. Wind current with single phase to ground fault without a controllable crowbar.

unstable values currents during the fault with a controllable crowbar have been presented in Fig. 13.

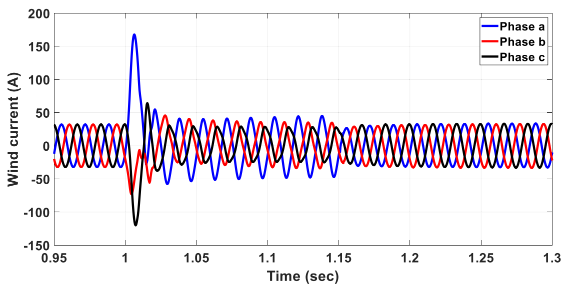

FIGURE 13. Wind current with single phase to ground fault with a controllable crowbar.

PV current with single phase to ground fault without a controllable crowbar has been shown in Fig. 14, all currents have unstable large values, however in the second case which is shown in Fig. 15 with a crowbar, all currents are stable but with large values in comparison of the normal value.

B. DOUBLE LINE TO GROUND FAULT

PCC voltage with a double line to ground fault without a controllable crowbar has been shown in Fig. 16. It is noticed that the double line voltages for phase (a)and phase (b) have disappeared under the fault without a crowbar. On the other hand, when the crowbar has been used all voltage has normal values except for a small time at the action of fault and clearing of fault as shown in Fig. 17.

Grid active power with double phase to ground fault with and without a controllable crowbar has been shown in Fig. 18.

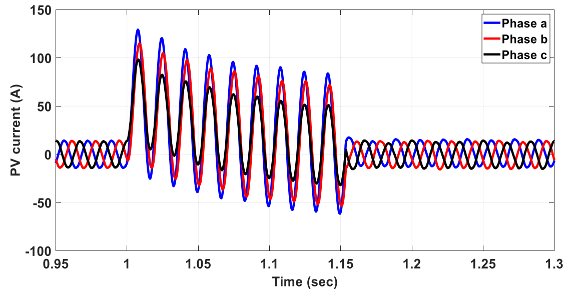

FIGURE 14. PV current with single phase to ground fault without a controllable crowbar.

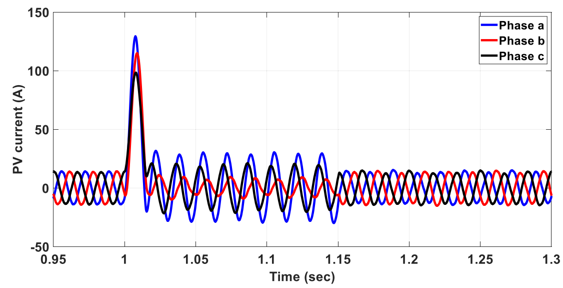

FIGURE 15. PV current with single phase to ground fault with a controllable crowbar.

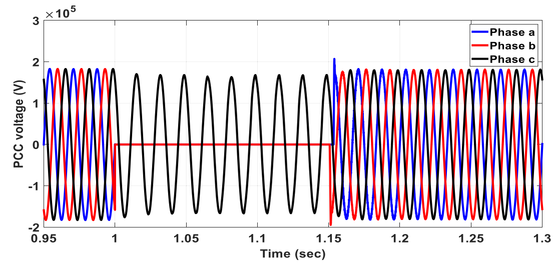

FIGURE 16. PCC voltage with a double line to ground fault without a controllable crowbar.

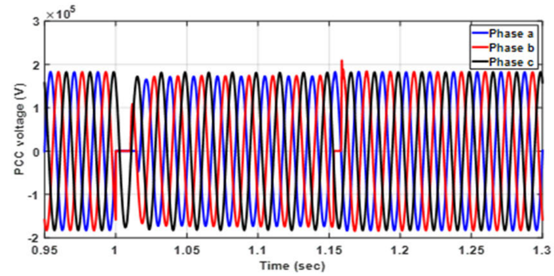

FIGURE 17. PCC voltage with a double line to ground fault with a controllable crowbar.

the active power on the grid side appears due to the resistance of the crowbar. While the value of the active power without a crowbar is zero.

Wind active power with double phase to ground fault with and without controllable crowbar has been shown in Fig. 19. the value of active power is within the range 8.4*10e6 W during the fault using a crowbar.

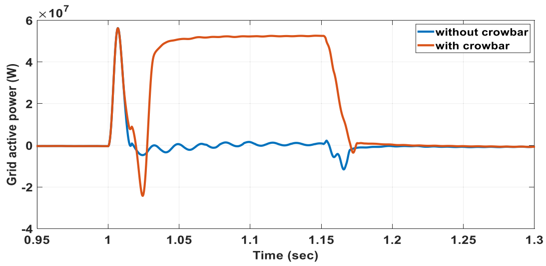

FIGURE 18. Grid active power with double phase to ground fault with and without a controllable crowbar.

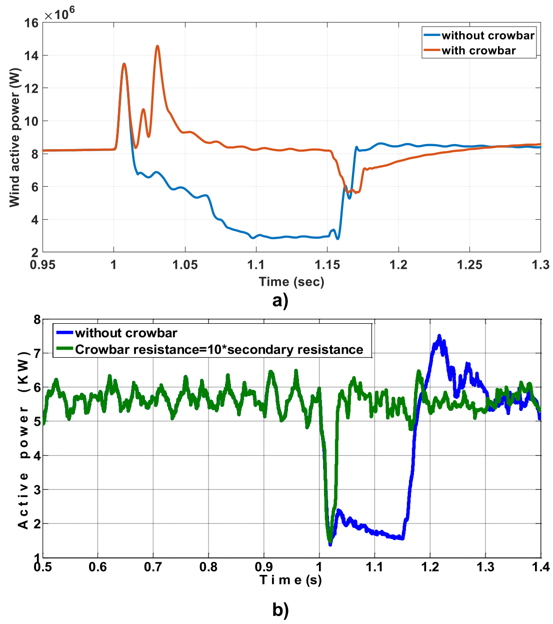

FIGURE 19. Wind active power with double phase to ground fault with and without controllable crowbar for the proposed system b) active power in BDFRG under the crowbar for double phase to ground fault.

In [25] the active power in BDFRG under the crowbar for double phase to a ground fault has been presented in Fig. 19 (b) which indicates that the system has large active power undershoot as a percentage of its average value (30%).

PV active power with double phase to ground fault with and without controllable crowbar has been presented in Fig.20. where the value of PV active power oscillated around the value of 3*10e6 after undershoot at the fault beginning and clearing.

Grid current with double phase to ground fault without controllable crowbar has been shown in Fig. 21. two phases have unstable values during the fault time. However, with using a crowbar the two phases appear with stable large values during the fault as shown in Fig. 22.

wind current with double phase to ground fault without controllable crowbar has been shown in Fig. 23, the three-phase currents during the faults are unstable with large values. in Fig. 24 wind current with double phase to ground fault with a controllable crowbar has been shown. the currents are unstable with small values as a comparison to the previous case.

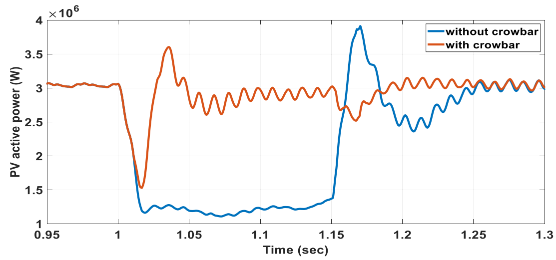

FIGURE 20. PV active power with double phase to ground fault with and without a controllable crowbar.

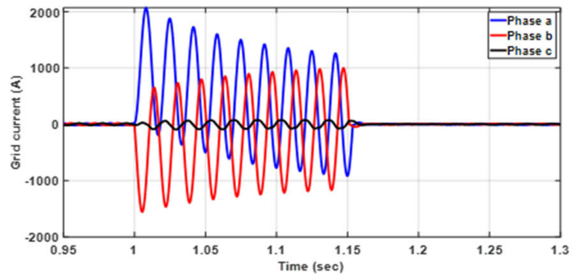

FIGURE 21. Grid current with double phase to ground fault without a controllable crowbar.

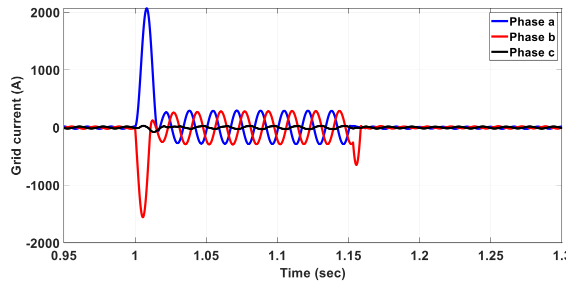

FIGURE 22. Grid current with double phase to ground fault with controllable crowbar.

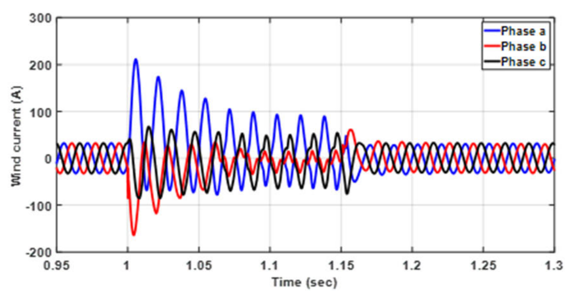

FIGURE 23. Wind current with double phase to ground fault without a controllable crowbar.

PV current with double phase to ground fault without controllable crowbar has been shown in fig 25. All currents have large unstable values during the fault. The behavior after clearing the faults is also shown in Fig. 25 where it needs time to be stable. However, the behavior of the three-phase currents using a crowbar is shown in Fig. 26. During the faults the currents have a small unstable value as compared to the

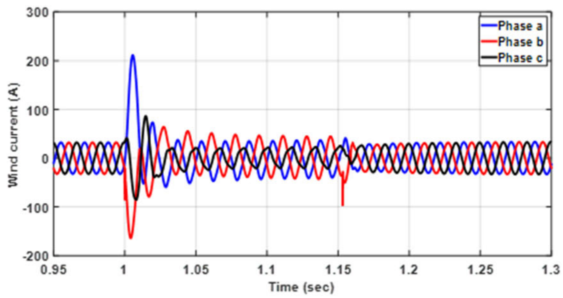

FIGURE 24. Wind current with double phase to ground fault with a controllable crowbar.

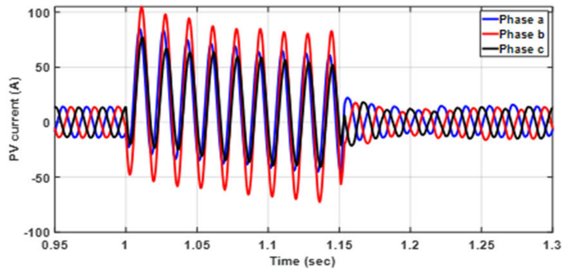

FIGURE 25. PV current with double phase to ground fault without a controllable crowbar.

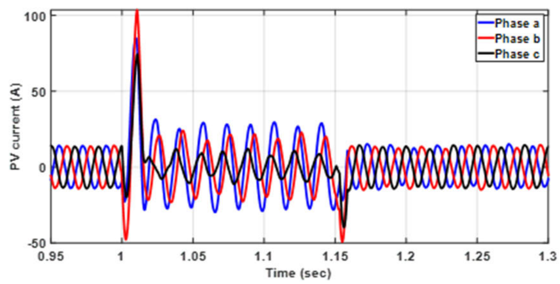

FIGURE 26. PV current with double phase to ground fault with a controllable crowbar.

last case in Fig. 25. In addition, the currents have rapidly reached its steady state value as shown in Fig. 26.

V. CONCLUSION

controllable crowbar has been used in this paper to protect the system against the faults such as a single and double line to ground fault, not only with WECS but also with all types of generation. Although only two types of faults have been discussed based on the proposed controllable crowbar, this proposal controllable crowbar method can be applied to all types of faults. With using crowbar, the currents have been rapid to reach its steady state value. The proposed controllable crowbar has a good dynamic performance under different faults (single line to ground and double line to ground fault) as comparison of the previous controllable crowbar. The active power for wind station under different faults has been compared for the proposed controllable crowbar has small change at clearing the fault while the old one has large value. However, the active power has a large overshoot at fault (42.9%), but it rapidly reaches its steady state at 8.4e6 W. The position of the controllable crowbar led to transfer the transmission and distribution system to be smart with smart generation and achieving the aims of the smart grid from self-healing, reliability, and other aims of smart grid make up the traditional grid as smart grid.

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