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Mitigating Misfire and Fire-through Faults in Hybrid Renewable Energy Systems Utilizing Dynamic Voltage Restorer

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Abstract: Recently, there was a great focus on integrating renewable energy sources (RESs) into electrical power systems (hybrid systems) due to their many environmental and economic advantages. The output of most of these RESs is DC; some power electronic devices, including inverters, must be used to integrate these RESs into the electrical grid. Any maloperation, faults, or improper control in these power electronic devices will enormously affect these hybrid systems' performance. This paper aims to mitigate the misfire and fire-through faults that occur at the switching of the inverter that connects three renewable sources: PV, wind, and the fuel cell to the grid. This mitigation of such inverter faults (misfire and fire-through) is performed through optimal tuning of the PI controller driving a dynamic voltage restorer (DVR) connected at the system's AC side. The optimization technique used is particle swarm optimization (PSO). While mitigating these two inverter faults using the PI-PSO controller for the DVR, improved system performance through voltages, currents, and powers waveforms is achieved. Besides, the three renewable sources were kept in continuous operation without disconnection from the system during these faults.

Keywords: particle swarm optimization; dynamic voltage restorer; fuel cell; hybrid power system; misfire; fire-through; photovoltaic (PV); wind turbine

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1. Introduction

Renewable energy sources (RESs) have recently become a focus of attention in electric energy production due to their economic and environmental advantages. Renewable energies are characterized by their low prices, improving public health by reducing water and air pollutions; also, they are accessible compared to traditional energy sources [1,2]. The hybrid renewable energies have an influential role in feeding different regions, whether these areas are on-grid or off-grid.

Many researchers recommended incorporating various RESs such as PV, wind, the fuel cell (FC), and biomass into the electrical grid. These incorporations are presented to overcome the problems that arise when using fossil fuel [3,4].

Most of RESs always generate DC with different DC voltage values, so DC-DC choppers are exploited to tie the DC output of these RESs into a common DC bus to the grid, hybrid power systems (HPSs) [5]. For both on- and off-grid applications, DC-AC inverters are also needed to connect the common DC bus to the grid. The power electronics switches of the inverters have larger and significant effects on the HPSs' performance [6]. Many faults may take place in the power electronic switches; 53.1% of these faults are due to malfunctions in the control circuit, while nearly 37.9% of them are for power parts of the switches [7,8]. These power electronic switches' faults would cause some problems, which will lead to some negative effects on power quality [9].

Two internal faults may occur in the inverter switches, misfire, and fire-through faults [10]. Misfire is the disappointment of a converter change to power over conduction at the planned time frame, while the fire-through is the disappointment of a converter change to switch-off during a planned non-conducting period. These two internal faults are due to glitches in power electronic switches' firing control circuits [10]. Serious problems can occur due to these faults in essential systems, especially in inverter stations [11]. To overcome these internal faults, some devices would be used and connected to the systems.

Some flexible devices were added to the power systems, especially integrated with RESs and HVDC systems to improve the performance and overcome different faults [12–14]. STATCOM and the unified power flow controller (UPFC) were presented for enhancing the efficacy of the wind energy conversion system (WECS) [6,15]. Superconductors were introduced to improve the WECS against wind gusts and different faults [16]. The dynamic voltage restorer (DVR) was utilized for supporting the low voltage ride-through the capability of WECS [17–19]. The DVR was introduced for enhancing the performance of HPS through attaining the following: (1) power quality improvement, (2) continuous operation of the three RESs (PV/wind/FC) during faults, (3) supporting the low-voltage ride-through capability, (4) improving the rotor speed profile of WECS generators, and (5) reducing the harmonics [20–22].

To the authors, only super magnetic energy storage (SMES) and UPFC from the flexible devices were introduced to mitigate the misfire and fire-through faults in WECS; however, the very high cost of SMES and the complexity of the structure of UPFC are issues [23,24]. Misfire and fire-through faults in HPSs were not introduced in many research work.

This paper presents the mitigating of misfire and fire-through faults that occur at the inverter used to connect three RESs (PV, Wind, and FC) to the grid. The three RESs are tied together to a common DC link. The inverter is used for connecting this DC link to the electrical grid. The optimal size of the three RESs was calculated based on some economic features, namely, net present cost and the cost of energy. Mitigating these two faults (misfire and fire-through) is achieved by adding a DVR. This DVR is controlled by two optimized PI controllers tuned by particle swarm optimization (PSO).

The main contribution of this paper may be outlined as:

- Improving the integration of three renewable energy sources (PV, wind, and FC) to the grid through mitigating misfire and fire through faults.
- Using a controlled DVR to alleviate the misfire and fire-through faults that may take place at the point of common coupling between the three renewable sources and the grid.
- Optimal tuning of the most commonly used controller in the industry (PI controllers) for the DVR.
- Keeping the continuous connection of the hybrid renewable energy sources without disconnection during some grid faults.

The paper is outlined as: Section 1 is the introduction; Section 2 represents the system description, while Section 3 exemplifies the Controller Design and optimization algorithm. Sections 4 and 5 represent the results and the conclusions, respectively.

2. System Description

The HPS presented in this paper contains three RESs (PV/Wind/FC). Two DC-DC converters (one for the PV system and the other one for the FC system) are used to regulate the DC voltage of both PV and FC at 780 V to tie them to the common DC bus. The generator used in the WECS is a permanent magnet synchronous generator [20–22]. The output voltage of WECS is converted to DC through the AC-DC converter. A third DC-DC is used to regulate the WECS output after the inverter to 780 V, DC, and connecting it to the common DC bus. The DC bus is tied to the grid via an inverter, two transformers, and a transmission line. The three RESs are connected to the network at the point of tying (POT).

The DVR is used to mitigate the misfire and fire-through faults that take place at the inverter. The DVR is connected between the POT and the grid as shown in Figure 1a. The system data are given in [20,22].

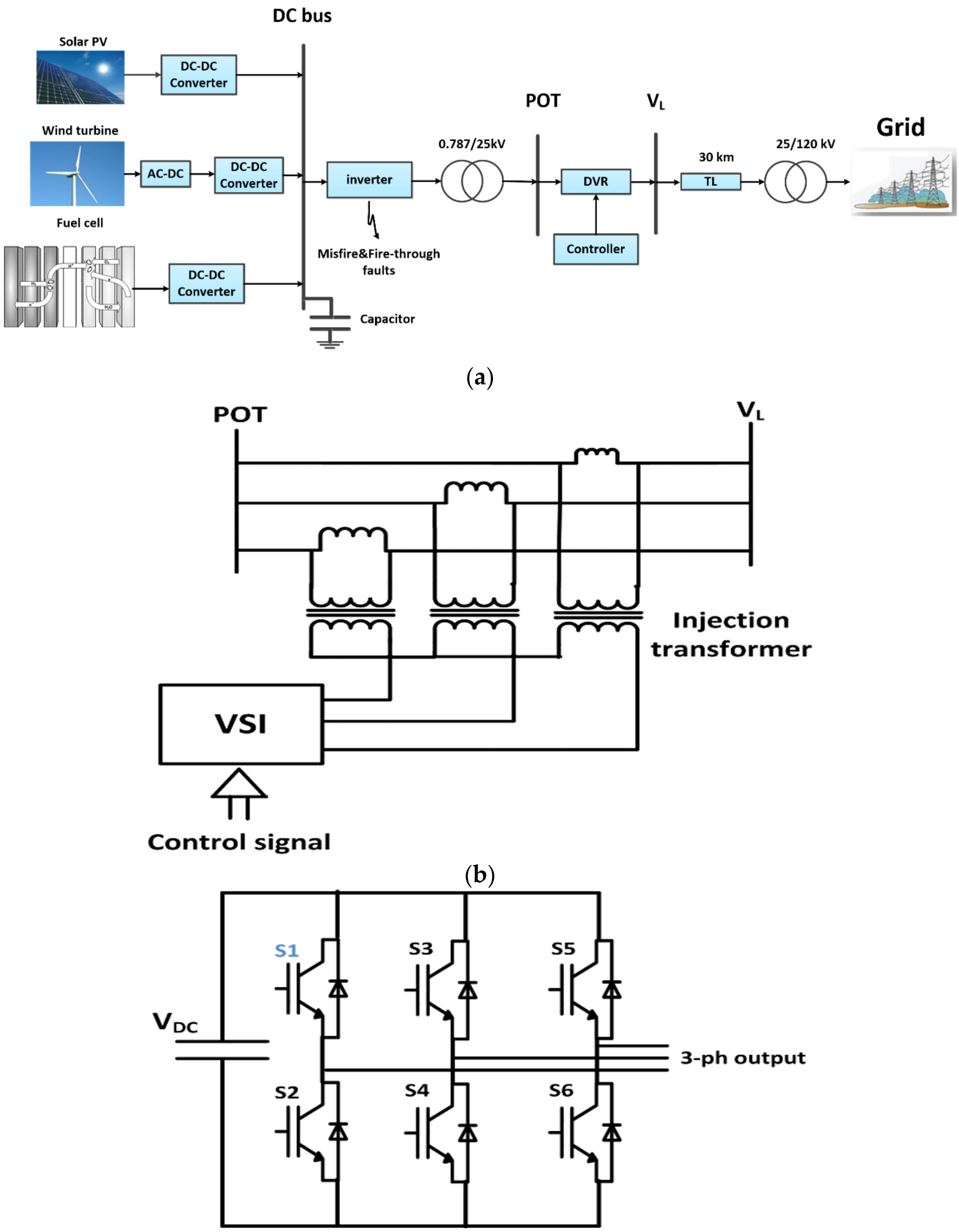

Figure 1. System under study. (**a**)—Hybrid power system, (**b**)—DVR, (**c**)—The main circuit of the 3-ph inverter.

The DVR is connected in series with the system to inject a controlled voltage during misfire and fire-through faults as illustrated in Figure 1b. At normal operation, the DVR operates at zero MVAr to keep a unity power factor at the POT. The main circuit of the 3-ph inverter used for tying the three RESs to the grid is shown in Figure 1c.

3. Controller Design and Optimization Algorithm

This paper aims at using the DVR to alleviate the misfire and fire-through faults that occur at the inverter that connects RESs to the grid. The PSO technique is utilized for optimal tuning of two PI controllers driving the DVR.

3.1. Particle Swarm Optimization

Many optimization algorithms were presented for finding the optimal PI controller parameters. From them, PSO is considered along with the genetic algorithm as a benchmark for the optimal tuning of PI controller parameters. PSO is introduced in this paper to determine the optimal controller parameters of two PI controllers used for controlling the DVR. The optimal tuning of the two PI controller parameters is performed offline using PSO. The obtained optimal PI controller parameters will be used online for regulating the DVR to mitigate some faults and consequently improve the system performance.

In order to control the flow of reactive power between the hybrid system and the DVR to alleviate misfire and fire-through faults, PSO is primarily taken into account when defining the optimal PI controller gains. These two PI controller parameters were used for driving the DVR that are K_{pd}, K_{id}, K_{pq}, K_{iq}. This optimal tuning process for the PI controller parameters using PSO is achieved through minimizing the objective function that is defined in (7). As shown in Figure 2, the DVR is controlled by two separate PI controllers. These two PI controllers are assigned for regulating the direct and quadrature axis voltages separately.

The goal function is computed using the starting values as the initial pollutants for the two controllers' parameters. Each particle's position and velocity are updated. The new objective function is defined as a result. Such a process is repeated with continuous updates until either the maximum number of iterations or the nearly ideal answer is reached. The best population that produces the smallest objective function is then calculated. The flow chart of PSO is given in Figure 2 [22].

3.2. DVR Control by PI-PSO Controllers

The main parts of the DVR are: the DC capacitor, voltage source inverter (VSI)-based IGBT, control circuit, and injection transformer, Figure 1b. The role of the DVR is injecting an appropriate voltage in series to the system during disturbances through controlling the VSI. The control of the DVR contains a closed loop in the DQ frame. At any disturbance, the load voltage (V_L) is affected and converted from the ABC frame to DQ voltages in the D-Q axis (V_d, V_q), respectively. PLL is utilized for measuring the system frequency.

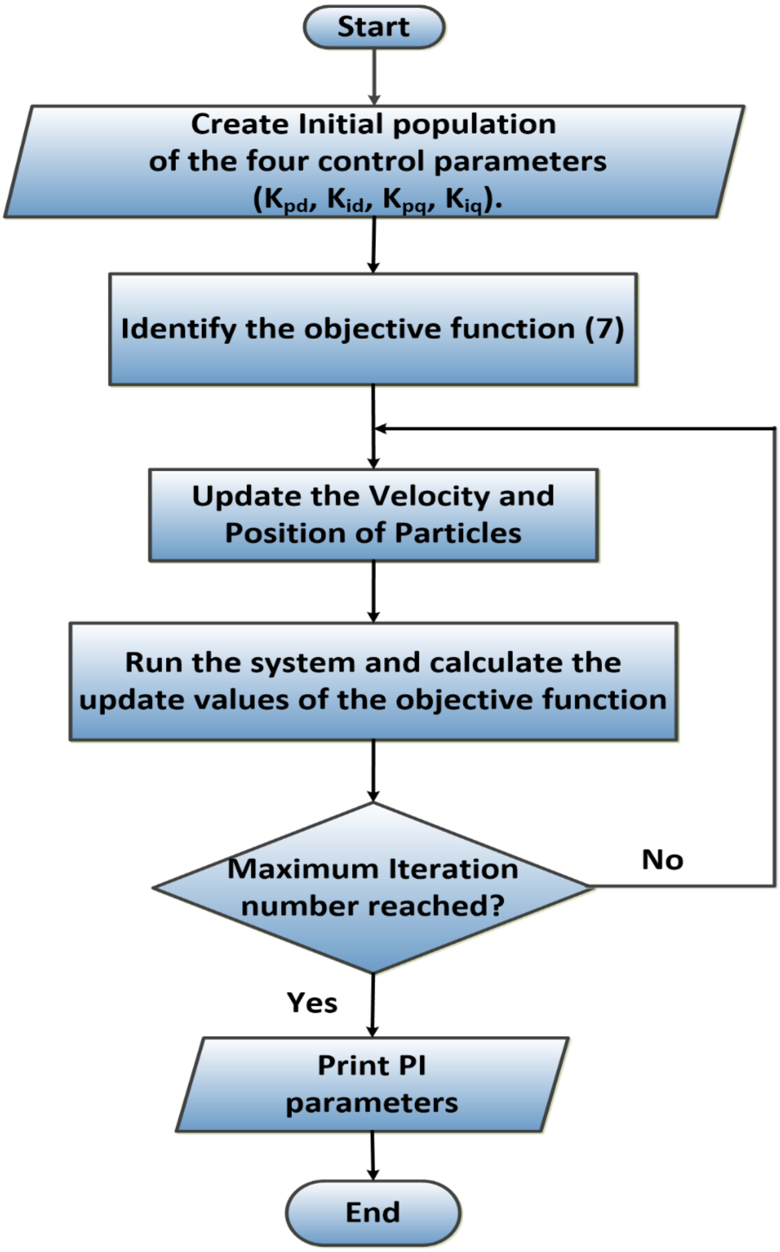

Figure 2. Flow chart for PSO.

The ABC three-phase frame is converted to the DQO frame as:

$$V_d = \frac{2}{3}\left[V_a \sin wt + V_b \sin\left(wt - \frac{2\pi}{3}\right) + V_c \sin\left(wt + \frac{2\pi}{3}\right)\right] \quad (1)$$

$$V_q = \frac{2}{3}\left[V_a \cos wt + V_b \cos\left(wt - \frac{2\pi}{3}\right) + V_c \cos\left(wt + \frac{2\pi}{3}\right)\right] \quad (2)$$

$$V_0 = \frac{1}{3}[V_a + V_b + V_c] \quad (3)$$

The two voltages resulting from converting the load voltage to the D-Q frame (V_d, V_q) are compared through two reference voltages in the D-Q frame (V_{d_ref}, $V_{q\text{-}ref}$), respectively. These reference voltages are set to 1 p.u for V_{d_ref} and 0 for $V_{q\text{-}ref}$. These two errors in the D-Q frame ($error_d$, $error_q$) represent the input to the two PI controllers and can be calculated as:

$$error_d = V_{dref} - V_d \quad (4)$$

$$error_q = V_{qref} - V_q \quad (5)$$

The total error is the sum of these two errors is:

$$e = error_d + error_q \quad (6)$$

Many objective functions, as a controlled efficacy, were presented for optimal tuning of the PI controller parameters from the integral-time of absolute of error (ITAE) and integral of the square of error (*ISE*). For the applications in which the time speed recovery and control are required, the time is too short, and the ITAE may be applicable as the *ISE*. From these applications of using *ISE*, optimal tuning of PI controller parameters to support the low-voltage ride through within a short time without disconnecting wind and PV renewable sources can be achieved as in [25]. In addition the *ISE* can be used for supporting the wind energy conversion systems against some faults that are characterized by short times such as the three-phase fault [26] and ferroresonance faults [27].

The *ISE* is used to determine the optimal PI controllers for the two loops [20–22] and can be defined as:

$$ISE = \int_0^\infty e^2(t)dt \quad (7)$$

The output of the D-axis control loop is V_d^* and for the Q-axis is V_q^*. These two voltages (V_d^*, V_q^*) are then transformed to the ABC farm to produce the PWM signal driving the IGBT of VSI to inject the appropriate voltage in series to the system to alleviate the misfire and fire-through disturbances. The block diagram of the DVR controller is illustrated in Figure 3.

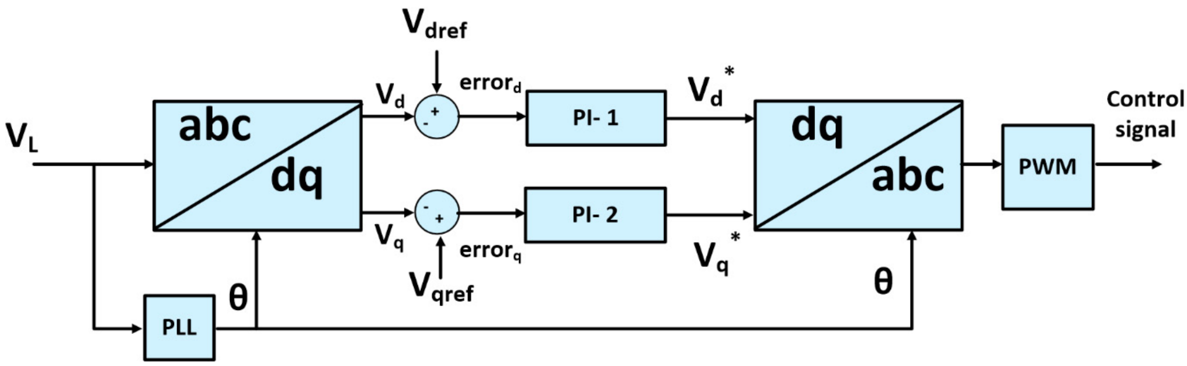

Figure 3. DVR control block diagram.

4. Results and Discussions

The hybrid system, depicted in Figure 1, is utilized to assess the proposed DVR-based PI-PSO controller's cogency for enhancement of the performance against misfire and fir through faults taking place at the inverter.

To determine the proposed system's ratings, some economic features, namely, the net present cost and the cost of energy of the hybrid proposed system, were investigated considering the Egyptian code [22,28,29]. In this case study, the optimal grouping of integrated RESs is the 30.687 MW PV-array, 13.5 MW wind turbines, 46 MW fuel cell, and system converter (32.911 MW) with a dispatch strategy of the load.

The DVR, integrated into the HPS, is controlled by two PI-PSO controllers to alleviate misfire and fire-through faults at the inverter. These faults are simulated at switch 1 (S1) in Figure 1c. PSO is presented for optimal tuning of the two PI controller parameters by minimizing the objective function that is the *ISE* given in (7). The values of the optimized

PI controller parameters are given in Table 1. In the next sections, the role of the proposed PI-PSO for the DVR to mitigate the misfire and fire-through faults taking place at the inverter will be investigated. Moreover, the effects on the system performance including the load voltages profile and rotor wind speed, and keeping the three RESs in continuous operation during faults, will be examined.

Table 1. Optimal PI-PSO controller parameters.

Cases	D-Axis		Q-Axis		D-Axis	Q-Axis
	K_{pd}	K_{id}	K_{pq}	K_{iq}	V_d	V_q
Misfire	8.350	180.29	70.2	182.3	250.4	258.9
Fire through	10.45	202.01	79.4	195.7	265.3	274.8

4.1. Faults within the Proposed System

In this part, the performance of the proposed HPS at misfire and fire through intermittent faults within the VSI of the inverter is studied. The two faults are assumed to occur at switch S1-IGBT1 (Figure 1c) at 0.5 s and lastly for 0.05 s. The pulses of the switch (IGBT-1) during the misfire fault and the switch (IGBT-1) pulses during the fire-through fault are depicted in Figure 4a,b, respectively.

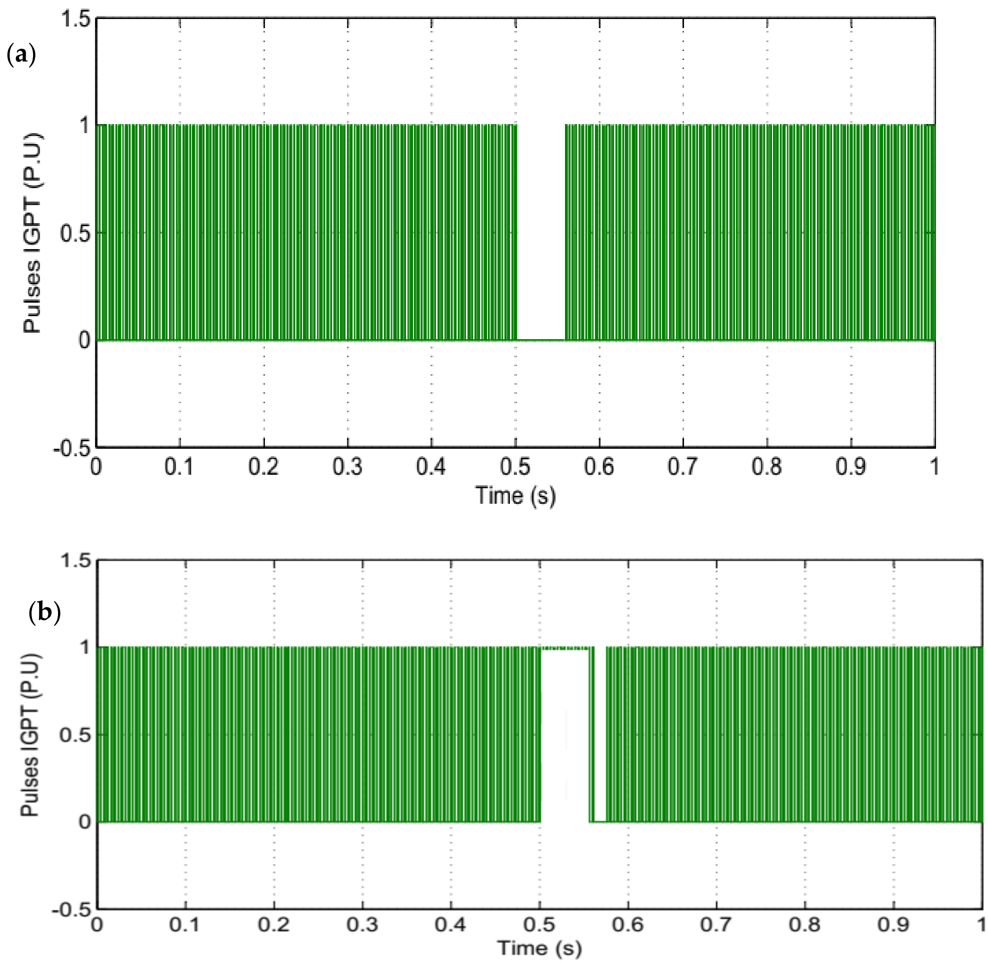

Figure 4. Intermittent faults at S1 of the inverter. (**a**)—Misfire fault, (**b**)—Fire-through fault.

The performance of the hybrid renewable energy system during the switch faults is studied. As shown in Figure 5, the fire-through fault causes the voltage at the PCT to decrease to 0.6 p.u, with a nominal effect on the voltage at the POT as depicted in Figure 5.

During the fire-through fault, a significant change in the DC capacitor occurs; the DC link is dropped to zero as indicated in Figure 6. This sharp and rapid drop in DC link voltage may destroys the DC-link capacitor if it is not disconnected. The protection devices will operate to disconnect the DC link capacitor to avoid these problems; consequently, the RESs will be disconnected. Reconnecting these RESs to the grid is not an easy issue and requires some difficult and complex procedures and precautions.

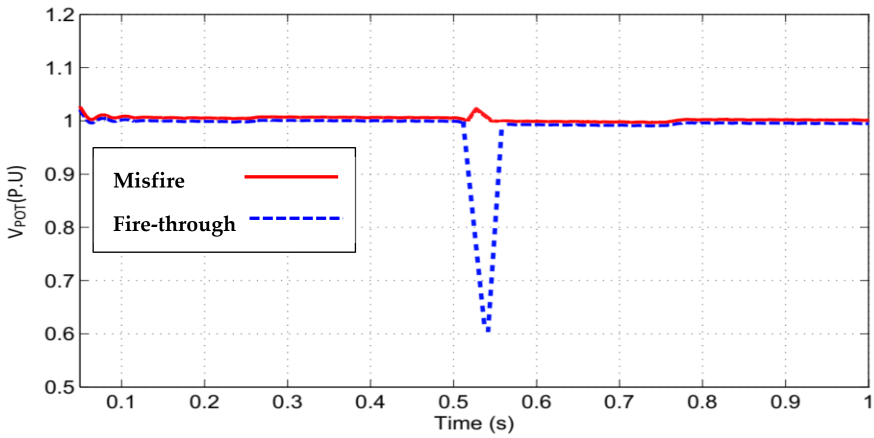

Figure 5. Point of Common Coupling (POT) voltage.

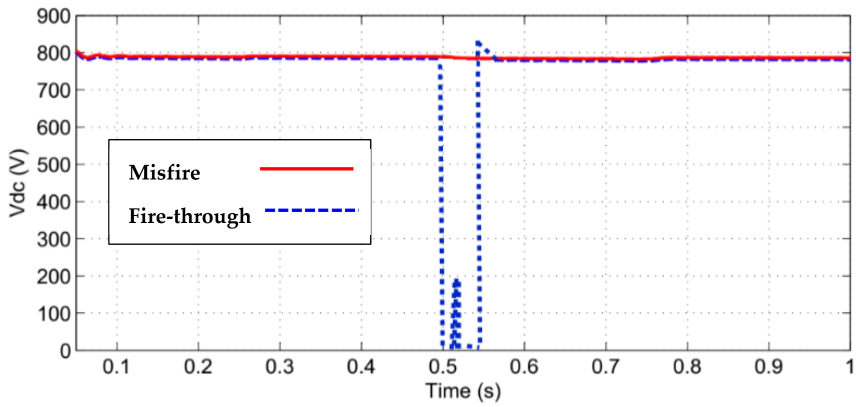

Figure 6. DC-link voltage.

With these internal faults (misfire and fir-through) in the VSI of the inverter, a change in the power of each generation source occurs. The power of the PV system is affected by the fire-through fault to drop down to less than 0.5 p.u, but, at the misfire fault, a small change in power occurred, and this change is insignificant; see Figure 7a. The FC generation source is affected by these faults, as shown in Figure 7b; the power of the fuel cell through the fire-through vibrates up and down causing a loss of power from this generation source so that the protection must be interconnected. However, with the misfire fault, the power is slightly affected.

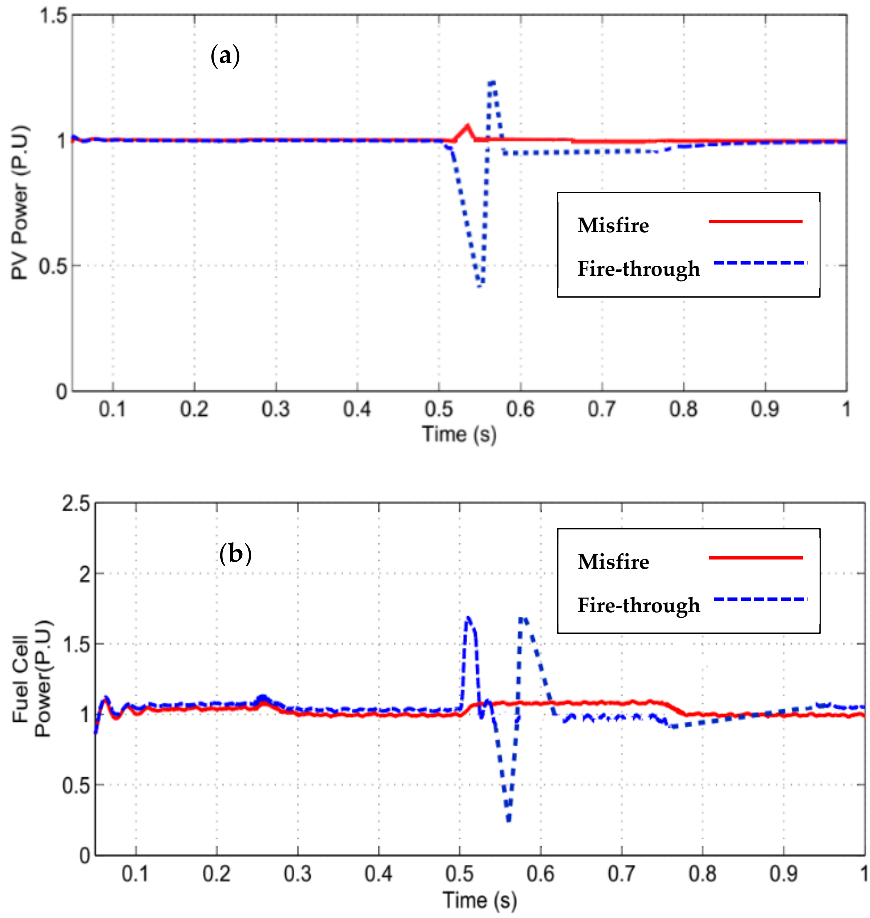

Figure 7. PV and FC power during faults. (**a**)—PV, (**b**)—FC.

The impact study of misfire and fire-through faults on the WECS will be investigated. As the misfire fault occurs, the wind power's power will be insignificant, but, in the fire-through fault, the wind power is dropped to 0.8 p.u as shown in Figure 8a. During this fault, the electrical torque thumps incorporate more motions with low-frequency esteem, and this may cause breakdown of the generator as a lot of vibrations on the mechanical part as depicted in Figure 8b. During the fire-through event, the wind turbine generator will absorb a large amount of the reactive power from the AC network as illustrated in Figure 8c, and the real power produced will be significantly decreased. On the other hand, the reactive and active powers are little bit affected during the misfire fault event. The decrease in wind power accelerates the shaft speed to recompense the power imbalance through these faults. The generator speed reached higher values (20%) without the DVR which will cause the disconnection of the generator from the system as the speed surpasses the maximum allowable cutoff of 17% [20] as in Figure 8d.

From these results summarized in Figures 7 and 8, the two intermittent faults mainly affect the three RESs used and may cause damage and disconnection to all/one of the RESs from the network. Of course, reconnecting one/all of these sources is a complicated and challenging process that requires many procedures to reconnect. That requires adding some flexible, controllable devices to alleviate these harmful effects and consequences of such faults.

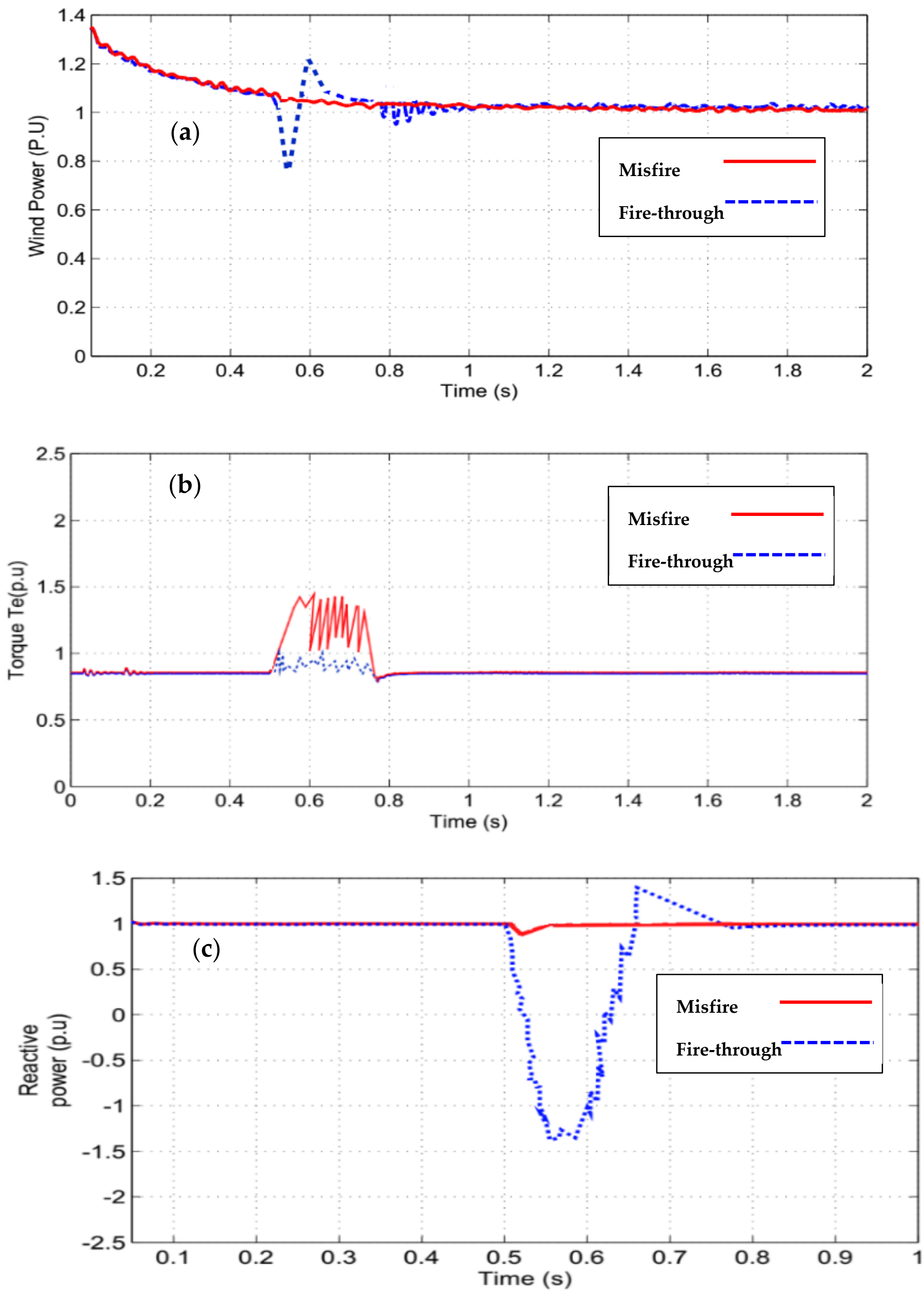

Figure 8. *Cont.*

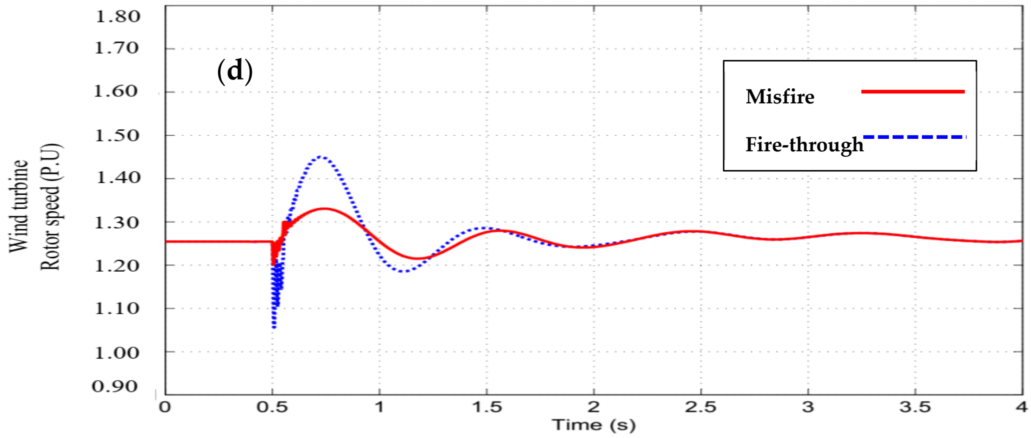

Figure 8. WECS efficacy during misfire and fire-through. (**a**)—power, (**b**)—torque, (**c**)—reactive, (**d**)—wind rotor speed.

4.2. Impact of DVR during Fire-through Faults

To mitigate the effects of misfire and fire-through faults on the HPS, the DVR is integrated to the system at the POT; see Figure 1a. The misfire has an insignificant impact from the above results, so it is not included in this part. On the other hand, the fire-through effect is included in connecting the DVR controlled by PI-PSO.

In this part, the fire-through fault occurs within the IGBT-S1; see Figure 1c; the voltage at the POT is decreased to 0.6 p.u without adding the DVR, but with connecting the DVR controlled by PI-PSO to the system, the decrease in this voltage is regulated to 0.8 p.u as depicted in Figure 9a thanks to the injection of a regulated voltage from the controller DVR.

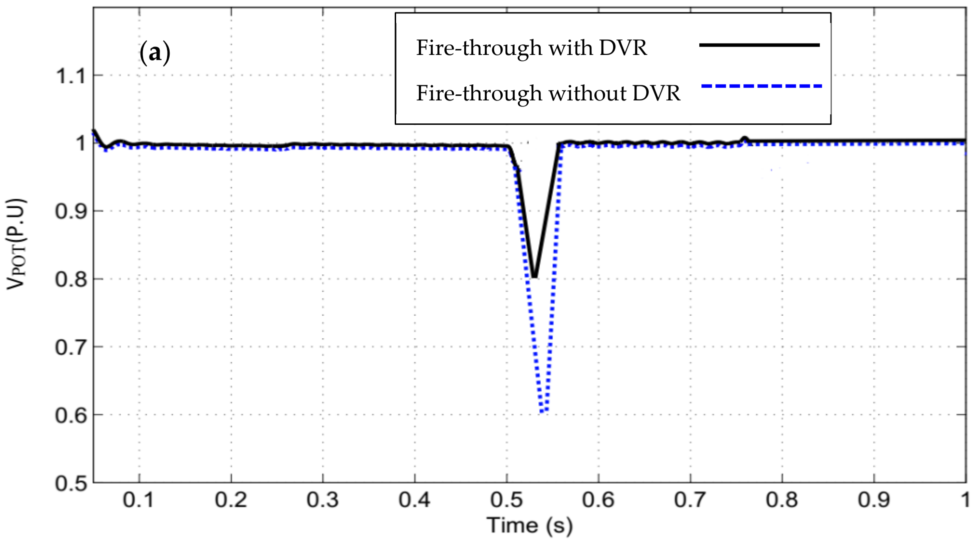

Figure 9. *Cont.*

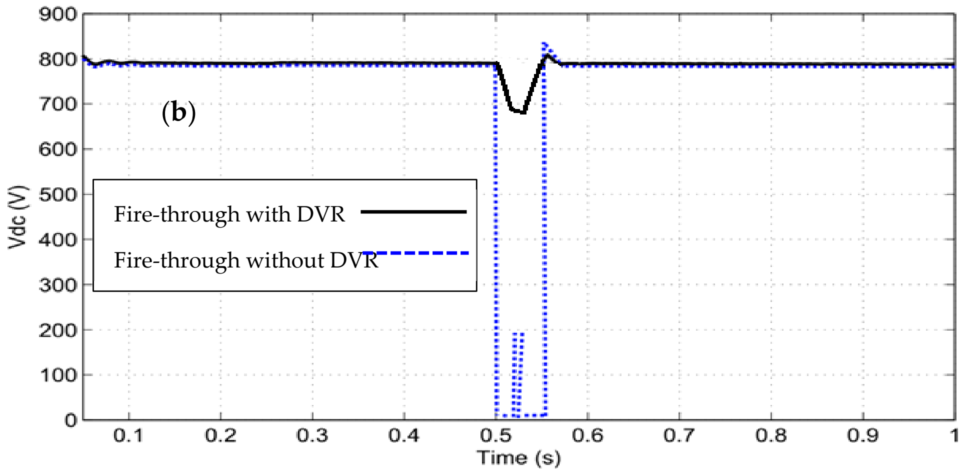

Figure 9. POT and DC link voltage during fire-through fault with and without using DVR. (**a**)—POT voltage, (**b**)—DC link voltage.

While injecting the regulated voltage from the controlled DVR, the DC link is protected and will not be disconnected from the network as the reduction in the DC link voltage is 82% only, as illustrated in Figure 9b.

As presented in the previous part, the generation sources' active power will be dropped without using any compensation process. Without using the DVR, the power of the PV is regulated as the maximum overshoot in 0.15% while 51% without using DVR as shown in Figure 10a. On the other hand, within the fire-through fault, the FC power is not regulated, leading to disconnecting the FC system from the HPS as the large oscillations (±60%) in the FC generated power take place. When using the DVR, the FC power is regulated but with small variations with a nearly 30% increase as in Figure 10b.

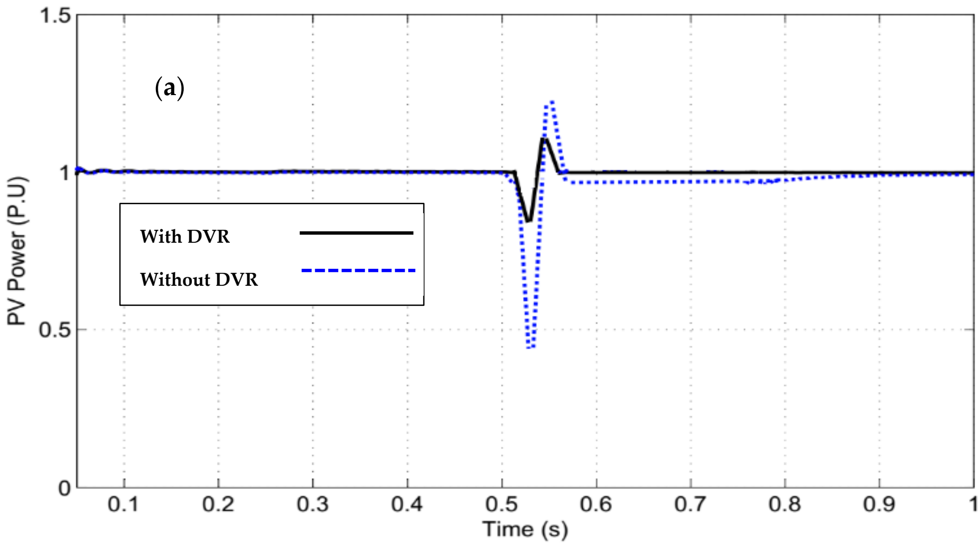

Figure 10. *Cont.*

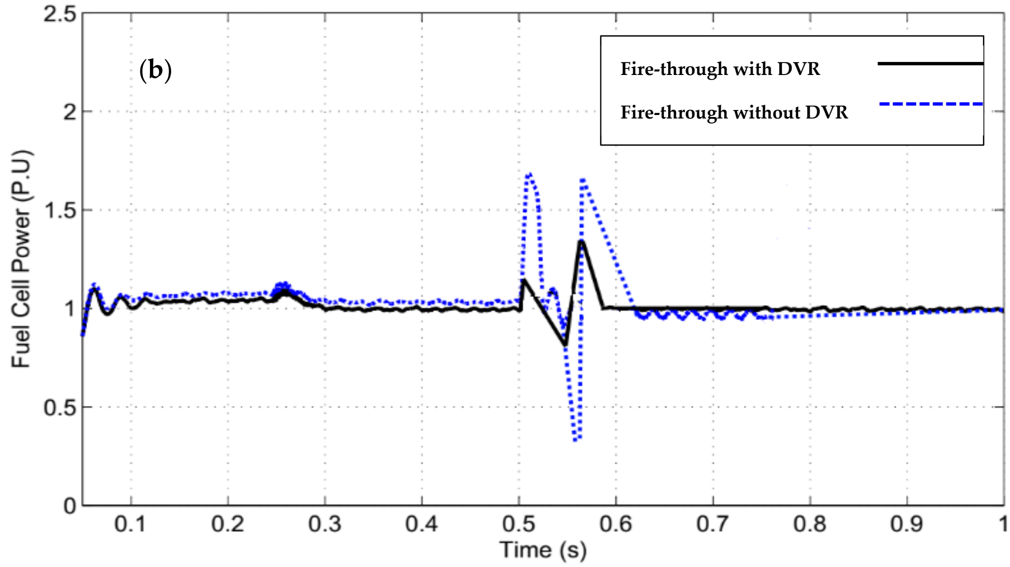

Figure 10. PV and FC power during fire-through faults while using DVR. (**a**)—PV, (**b**)—FC.

To mitigate the side effects on the WECS during the fire-through fault, the controlled DVR is connected. The wind power generated profile is improved as in Figure 11a.

Adding the DVR, the electromagnetic torque is significantly improved with fewer oscillations. The maximum overshoot is reduced from nearly 66% to 30% when using the DVR as depicted in Figure 11b. The wind generator's speed profile is also improved with a maximum overshoot of 10% that will keep the generator in service during this fault when using the DVR as in Figure 11c. The reactive power of the WECS is affected by the fire-through fault that occurred at the inverter, and the generator absorbed reactive power from the grid that will affect the stability of the system. When using the DVR, the reactive power profile of the WECS is enhanced without absorbing reactive power from the grid; see Figure 11d.

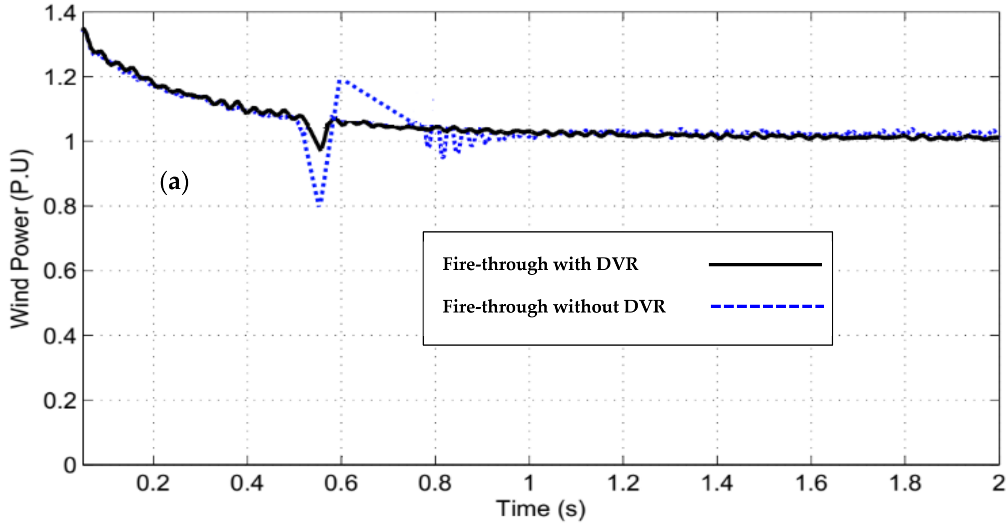

Figure 11. *Cont.*

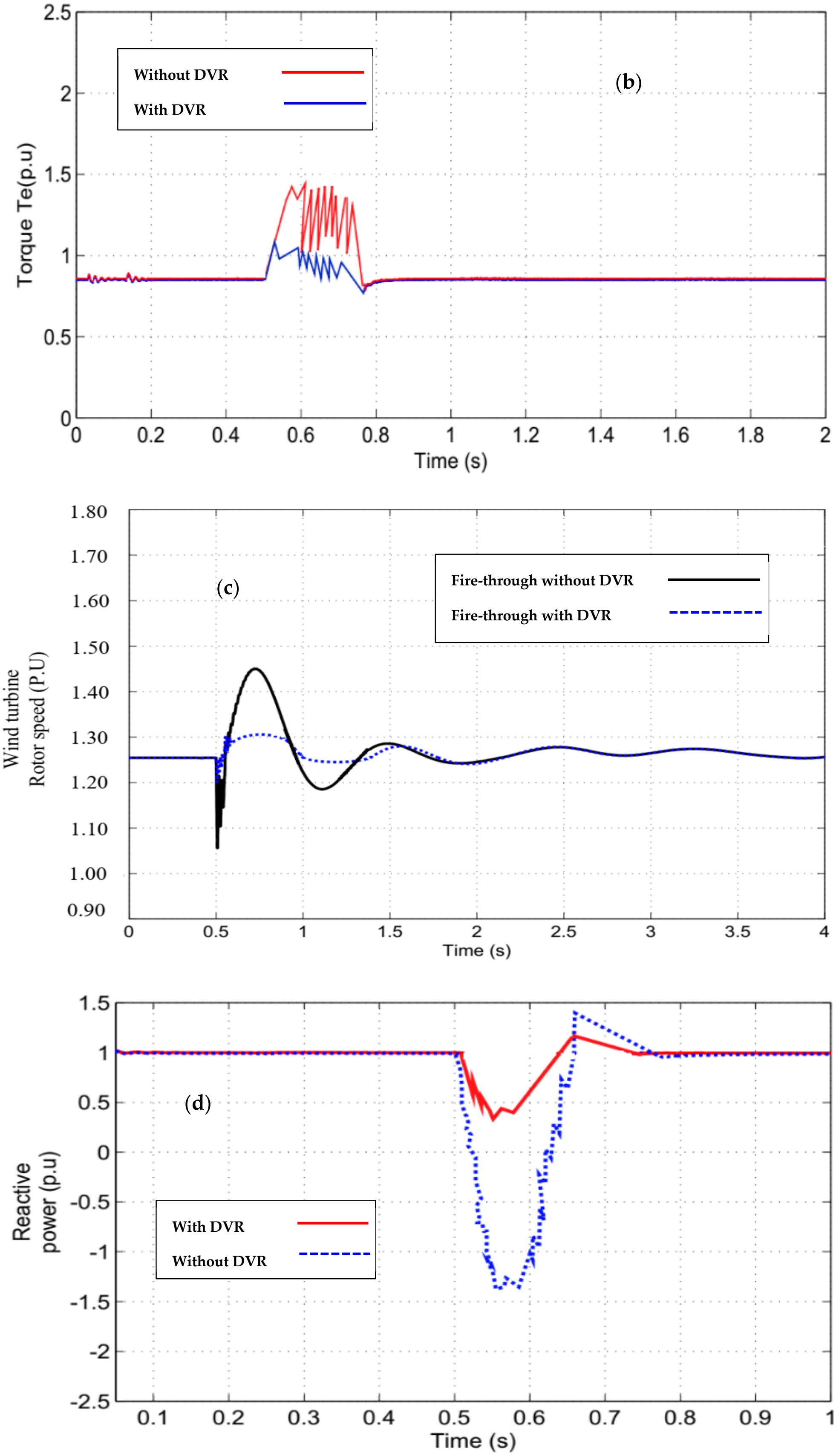

Figure 11. WECS efficacy during faults. (**a**)—power, (**b**)—torque, (**c**)—wind rotor speed, (**d**)—reactive power.

The performance of the DVR during fire-through can be examined through the above Figures, which reduced the vibration and overshooting of the wind turbine generator with the regulation in the power of generation sources (PV/wind/fuel cell). On the other hand, the regulation voltage at POT is applied.

5. Conclusions

This paper introduced two PI-PSO controllers to stimulate a DVR for enhancing the on-grid hybrid system under misfire and fire-through faults. The PI-PSO controllers' goal is to force the system voltage at the POT to control the voltage between the DVR and the load and consequently enhance the performance of the system during misfire and fire-through faults. The proposed PI-PSO controller showed a better performance concerning the system voltage, RESs' powers, and the WECS speed, electromechanical torque, and power. The proposed controller for the DVR also succeeded at keeping the continuous connection of the PV/wind/fuel cell to the system without disconnection for longer fault clearing times. The implementation of the hybrid system with the DVR makes an advantage that can ameliorate the efficacy of the on-grid HPS. In the future, this work may be implemented in a real hybrid power system.

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