Investigation of Different Fault Ride Through Strategies for Renewable Energy Sources

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***Abstract*—The Fault Ride Through (FRT) capability of renewable energy sources (RES) for providing support to the power grid under several disturbances allows us to consider them not only as passive elements in the power system network, but also as ancillary services for the mitigation of evolving contingencies. In this paper, an investigation of the FRT operation of RES according to current grid regulations highlights some impacts on the system response that were not considered previously and require to be addressed. Slight modifications of the current grid codes are therefore necessary to solve these problems. A critical dead band zone modification for smother fault recovery is suggested. Moreover, this paper proposes the use of an adjustable parameter into the FRT strategy for a fair compromise of voltage and frequency support. The proposed FRT strategies are applied to a RES that is interconnected with the IEEE 14-bus test system and dynamic electromagnetic transient simulation results are provided.**

***Index Terms*—Fault ride through, power system operation, renewable energy sources, voltage and frequency stability.**

I. INTRODUCTION

The increasing price and the environmental impact of fossil fuels have grown the international attention on Renewable Energy Sources (RES). At the European level, RES have recently reached 14% of the total energy generation. Such an increased penetration of RES can have a significant impact on the operation of the power system. Therefore, RES should be enhanced with Fault Ride Through (FRT) capability in order to be able to provide support to the power grid under disturbances. The recent grid regulations regarding RES interconnection [1]-[5] define that under low-voltage grid faults, the RES should remain interconnected as depicted in Fig. 1. Additionally, the RES should provide a proper voltage and frequency support to the power system as shown in Fig. 2 [1]-[5].

In the literature, several studies have been undertaken for investigating the FRT operation of RES. In general, these investigations are performed from two different perspectives. On one hand, researchers who focus their studies on the RES side are using advanced dynamic renewable models on the RES side, but they consider weak power systems with no dynamics on the grid side [5]-[8]. In this case, the investigation of FRT operation of RES is based on ElectroMagnetic-Transient (EMT) simulations, providing instantaneous values of voltages and currents in the grid. On the other hand, researchers who focus their studies on the grid side consider full dynamic models for the power system components but simplified renewable models [9]-[10]. The analysis is usually based on Root Mean Square (RMS) simulations. The advantage of using RMS simulations is that the simulation speed can be increased significantly, but the simulations omit the fast electromagnetic transients.

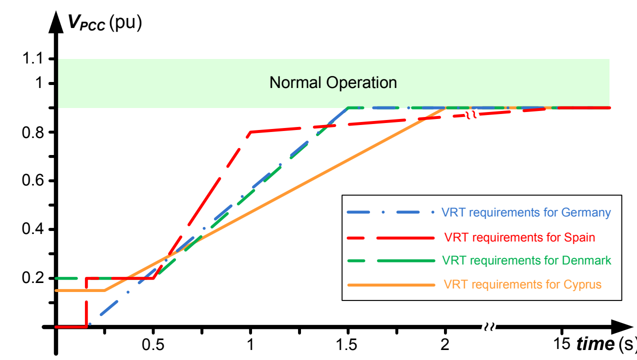

Figure 1. Low-voltage ride through requirements according to several grid codes. The RES should remain inteconneced when operate above the characteristic line.

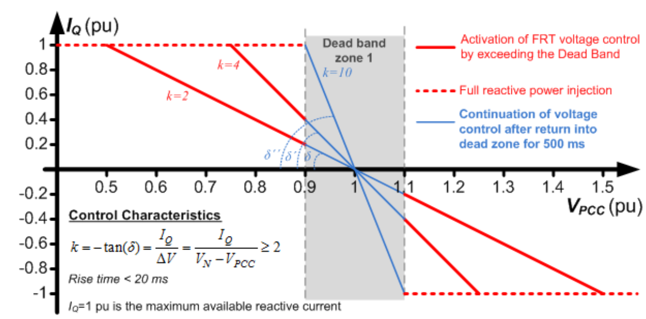

Figure 2. Reactive power support characteristics of RES for proper FRT operation according to grid regulations.

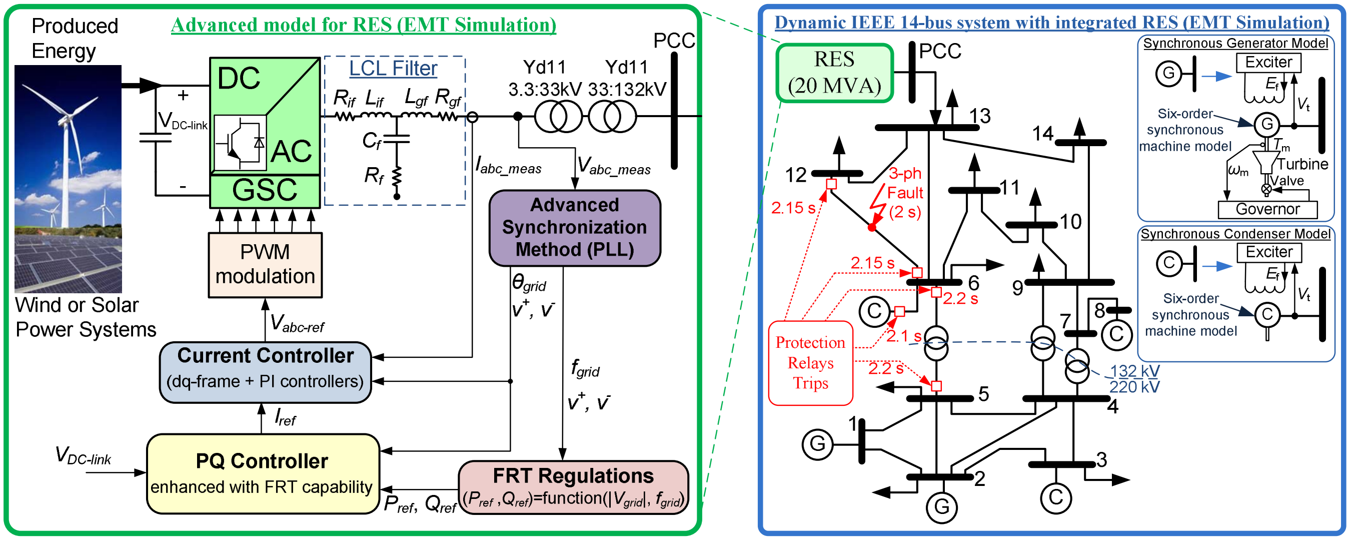

Figure 3. The dynamic system model setup that allows the evaluation of the impact of different RES FRT strategies on the power system operation.

In this paper, the FRT investigation is based on EMT simulations on the IEEE 14-bus test system implemented in PSCAD software, where a 20 MVA RES has been integrated at bus 13. Detailed and advanced EMT models have been used for both the synchronous machines and the power electronic Grid Side Converter (GSC) of the RES, allowing an analytical and transient study for the interactions between the RES and the power system. Furthermore, this implemented simulation model allows an in depth investigation of the current FRT strategies according to the grid regulations. The investigation indicates some issues on the current regulations that were not considered previously. Slight modifications of the current grid codes are therefore suggested for overcoming these problems. These modifications include the addition of a critical dead band zone for a smoother fault recovery and the introduction of an adjustable parameter $k_I(f_{gr})$ for a fair compromise of voltage and frequency support. The paper is organized as follows: the dynamic system model that is implemented for the investigation is presented in Section II. The FRT investigation is performed in Section III. In part A of this section, the operation according to the current FRT regulations is presented, while in part B, modifications of the current regulations are proposed for improving the FRT impact.

II. Dynamic System Model

The impact of the FRT strategies of RES on the operation of the power system requires the implementation of a dynamic power system model with integrated RES within the same simulation framework (Fig. 3).

Thus, the IEEE 14-bus system has been implemented in PSCAD using detailed EMT models for each machine as shown in Fig. 3. The network parameters and the initial power flows of the system have been set according to [11]. The synchronous generators and condensers of the dynamic power system are modelled based on the sixth order machine model. The generator model is equipped with an associated exciter, turbine and governor while the condenser model is only equipped with an exciter as demonstrated in Fig. 3. The machine, turbine, governor and exciter parameters are set according to the typical parameters given in [12].

Additionally to the dynamic power system simulation, a full detailed EMT model for a RES (based on a 20 MVA central power electronic GSC) has also been developed in PSCAD. The RES is interconnected at bus 13 of the IEEE 14-bus system (Fig 3). Bus 13 is considered as the Point of Common Coupling (PCC). The GSC of the RES is actually a typical three-phase two-level Pulse Width Modulation (PWM) Voltage Source Converter based on six switching Insulated-Gate Bipolar Transistors (IGBT). The GSC injects high quality currents into the grid through an LCL filter and two step-up transformers (Fig. 3). The design parameters of the RES hardware are presented in Table I. The GSC controller is implemented in synchronous reference frame (dq-frame) using Proportional-Integral (PI) controllers and includes a synchronization method, a current controller and an active and reactive power controller (PQ Controller) enhanced with FRT capabilities. The sampling and switching frequency of the controller is set to 4.9 kHz. The synchronization of the GSC controller is achieved by an advanced phase-locked loop (PLL) algorithm [13]-[14] that tracks accurately and fast the voltage phase angle under any grid conditions. The current controller [15] ensures the high quality current injection under normal and abnormal operation. Table I provides the tuning parameters used in the PLL and the current controller. An advanced PQ controller enhanced with FRT capabilities has been developed according to [5, Ch. 10], [6], [14]. The PQ controller regulates the active and reactive power injection by considering the produced energy of RES (DC-link voltage

TABLE I

RES Dynamic Model - Design Parameters for the Central GSC

GSC nominal values	V_N=3.3. kV, f_N=50 Hz, S_N=20 MVA, $V_{DC\text{-}link}$=10.6 kV
LCL filter	L_{if}=1.5 mH, C_f=292 μF, L_{gf}= 86 μH R_{if}=45.8 mΩ, R_f=176.3 mΩ, R_{gf}= 2.7 mΩ
Sampling and PWM	$f_{SAMPLING} = f_{PWM}$ =4.9 kHz
PLL (tuning parameters)	k_P=92, T_I=0.000235
Current controller (tuning parameters)	k_P=1.3499 , T_I=0.0229

controller), and the amplitude and frequency of the grid voltage at the PCC (based on the FRT regulations). Hence, the implemented dynamic model described above enables the investigation performed in this paper.

III. Investigation of Fault Ride Through Operation

The implemented dynamic EMT model described in Section II (IEEE 14-bus system with integrated RES in PSCAD) allows a deeper evaluation of the RES FRT strategies on the operation of power systems. The power system operation when RES operate according to current FRT regulations is demonstrated. However, under specific circumstances, the operation based on current FRT regulations highlights some problems. Modifications for overcoming these problems are suggested within this paper.

A. FRT Operation Based on Current Regulations

According to the modern grid codes [1]-[5], when a RES senses a low-voltage grid fault at the Point of Common Coupling (PCC) it should ensure the synchronization, remain connected, and provide FRT support to the power system as already demonstrated in Fig. 1 and Fig. 2. The injection of reactive power (Q) is beneficial for the voltage (V) of the power system and correspondingly the injection of active power (P) for the frequency (f) of the system. The proper voltage support is defined in Fig. 2 according to [1]-[5]. The amount of reactive current (I_Q) that should be injected by the RES within less than 20 ms is defined by the grid codes as,

$$I_Q = k \cdot (V_N - V_{PCC}) = k \cdot \Delta V \tag{1}$$

where V_N is the nominal voltage (1 pu) and V_{PCC} is the voltage at the PCC. The parameter k determines the FRT type between voltage and frequency support. Regulations define this parameter as $k \geq 2$. Thus, for k=2, the FRT support is a compromise between Q and P. On the other hand, for k=10, when the V_{PCC} exits the Dead Band (DB) zone 1 (defined as 90<V_N <110%) the FRT operation provides only Q. Since the reactive current is defined by regulations, the active current injection (I_P) by the RES should also be adjusted correspondingly. In case where the GSC current ratings ($I_{GSC\text{-}ratings}$) are not violated, then the instant active current should keep delivering all the produced energy by the RES to the grid. Otherwise, in case where there is a violation on the GSC current ratings, then the active current should immediately decrease for maintaining the converter operation as,

$$I_P = \sqrt{{I_{GSC-ratings}}^2 - {I_Q}^2} \tag{2}$$

As a result, the delivery of the produced energy by the RES will also be decreased.

An investigation is performed to study the impact of the FRT operation of RES on the power system and the results are summarized in Table II. The investigation examines a three-phase short-circuit event that occurs at the middle of line 6-12. The three-phase fault causes the tripping of the protection relays of: the line 6-12, the condenser at bus 6, and the transformer 5-6 within 200 ms to clear the fault as presented in Fig. 3.

Table II

Summary of the Results for different FRT strategies

RES operation under low-voltage grid fault		Lower V_{Bus} (pu)	Number of buses out of limits	Comments
Disconnection of RES		0.73	6	-Deeper voltage sag -Causes further disturbance
FRT according to current grid regulations	k=0	0.81	5	- V and f support -For k=0: only frequency support -For k=5, 8, 10: Undesired repetitive small voltage dips (5-10%) due to the disconti-nuity character of DB 1 For k=10: High P and Q variations can negatively affect the dynamic behavior of the machines
	k=2	0.84	5	
	k=5	0.86	3	
	k=8	0.87	3	
	k=10	0.88	3	
Critical DB zone modification	k=2	0.83	5	- V and f support -Avoid the repetitive voltage dips near DB1 due to the insertion of critical DB2 -Smooth fault recovery
	k=5	0.85	3	
	k=8	0.86	3	
	k=10	0.87	3	
Adjustable $k_1(f_{gr})$ + Critical DB modification	$k_1(f_{gr})$	0.87	3	-V and f support -Smooth fault recovery (DB2) -Fair compromise between voltage and frequency support, especially during under-frequency conditions

The first case study of Table II presents the results when the RES loses the synchronization and is disconnected from the grid when the event occurs. This is the worst-case scenario (since it causes further disturbance to the system) which forces six buses of the system to be outside the regulation limits with the lower operating voltage at 0.73 pu.

The second case study of Table I focuses on the FRT operation according to the current grid codes (for k=0, 2, 5, 8, 10). The results show that, in general, by increasing the value of parameter k, the provided voltage support is increased and thus, fewer buses are violating the voltage limits (the lower operating voltage of the system is also increased).

The second case study begins with k = 0, even if this is not a current practice (since regulations define $k \geq 2$). This case represents an operation where the RES remains interconnected and synchronized with the grid, and provides only frequency support by injecting active power (P) to the power system. However, the results in Table II (five buses outside the voltage limits, lower bus voltage at 0.81 pu) show that this is a more desirable solution rather than disconnecting the RES during a grid fault. By increasing the value of k to 2 (current practice), a more compromising voltage and frequency support is applied, as presented in Fig. 4 and Table II (five buses outside the voltage limits, lower bus voltage at 0.84 pu). It is to be noted that all the results presented in this Section demonstrate only the voltages at all 132 kV buses, since the voltage at all 220 kV buses always lies within the limits during fault recovery. Further improvement on voltage stability can be achieved by increasing the value of parameter k as shown in Table II.

However, under specific circumstances where the RES FRT support is sufficient to maintain the voltage at PCC within the limits, serious problems may be caused, especially as the value of k is increasing. These problems occur due to

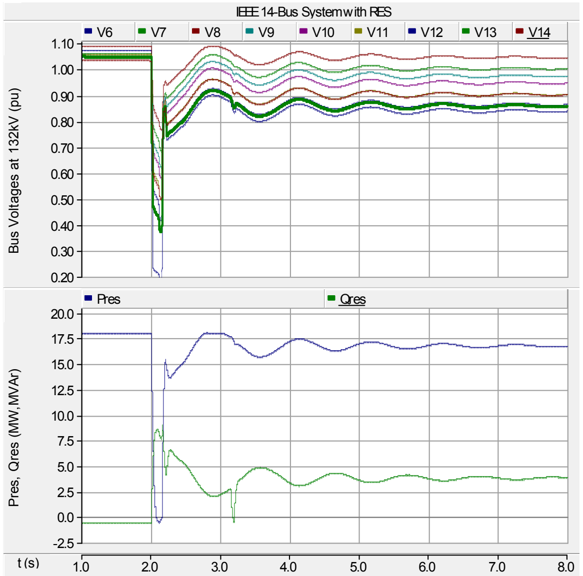

Figure 4. IEEE 14 bus system response when the RES operates according to the current grid regulations with k=2.

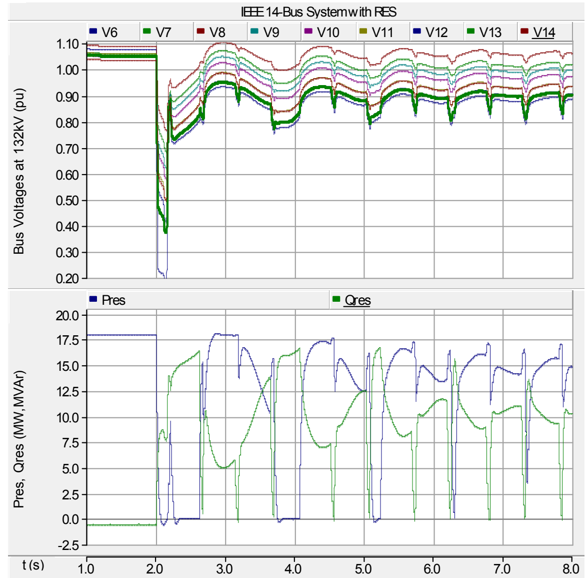

Figure 5. IEEE 14 bus system response when the RES operates according to the current grid regulations with k=8.

the fact that the reactive power support continues only for 500 ms after the voltage return within the DB zone 1. After 500 ms, the reactive power support by the FRT is stopped, imposing a discontinuity that causes intense reactive power fluctuation. The above-mentioned phenomena are observed in this case study when k is set to 5, 8, and 10. Power system operation according to Fig. 5, where RES operates according to the current FRT regulation (with k=8), indicates repeated voltage sags (3-10%) every 500 ms due to this discontinuity effect of the FRT. Hence, at the moment when the reactive power support stops (500 ms within DB zone 1) the voltage drops below the limits, forcing the RES to operate again according to the FRT regulations. This phenomenon is repeated as long as the voltage stability at the PCC is depended on the reactive support by the RES. As k is increased, the discontinuity impact of the DB zone is more intense (higher P and Q fluctuation of RES). In some occasions (as the one presented in Fig 6), such intense power fluctuations of RES can cause undamped oscillations on the synchronous machines operation, and as a result, the stability of the whole power system is also affected.

B. Modifications

The investigation of Section III.A, highlights two issues; the undesired power fluctuations due to the discontinuity of DB zone 1, and the trade-off between voltage and frequency support of the FRT according to parameter k. This section proposes two modifications on the FRT regulations for improving the power system operation.

The discontinuity of DB zone 1 can cause undesired repeated power fluctuation of the RES when the voltage recovery is achieved only with the contribution of RES. To overcome this undesired repetitive phenomena, a slight modification of current FRT regulations is proposed as shown in Fig. 7. The modification adds a new critical DB zone 2 (defined as 95<V_N <105%), which is only activated after a

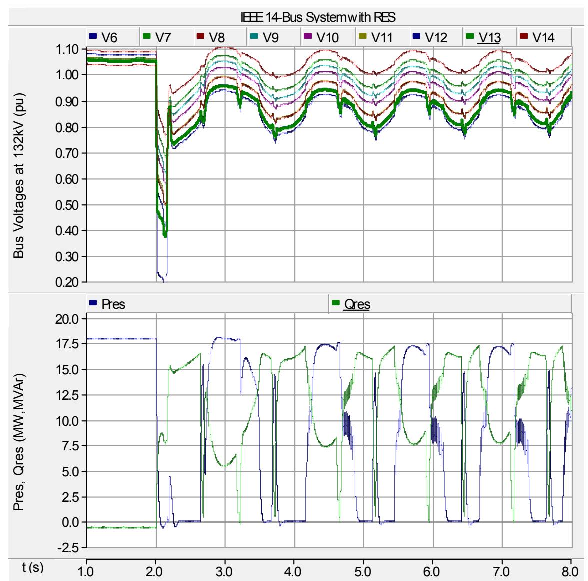

Figure 6. IEEE 14 bus system response when the RES operates according to the current grid regulations with k=10.

voltage sag event. The new voltage control as presented in Fig. 7 avoids the discontinuities effect on the fault recovery, since the termination of the voltage control is only achieved after the voltage returns smoothly (without discontinuities) into the critical DB zone 2 for more than 1 s. The results for this modification are presented in the third case study of Table II. The results show that the FRT properly supports the system for various values of k without imposing repetitive voltage sags (and power fluctuations). The proposed modification causes a 1% lower voltage compared to the second case study, but it eliminates undesired phenomena. The improved operation of power system (avoiding undesired repetitive voltage sags) is demonstrated in Fig. 8, where the RES operates according to the proposed FRT modification (with the additional critical DB zone 2) with k=8.

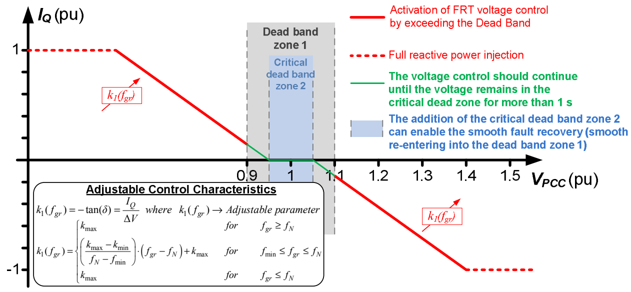

Figure 7. Proposed modifications on the FRT voltage control strategy.

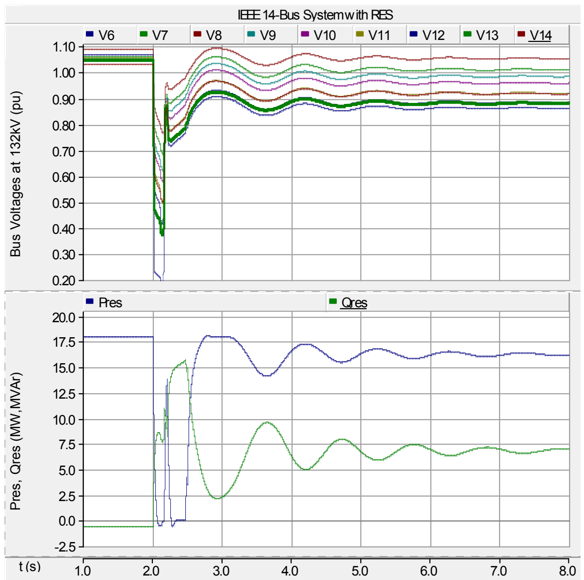

Figure 8. IEEE 14 bus system response when the RES operates according to the suggested FRT strategy with the additional DB zone 2 and constant k=8.

The second modification tries to compromise the FRT between voltage and frequency support. Higher values of k enhance the voltage but can inversely affect the frequency support. When a grid fault occurs, it usually affects both voltage and frequency of the system. Especially during under-frequency operation, a high value of k can cause cascading events in the system. Hence, a modification in FRT regulations is proposed for balancing the trade-off between voltage and frequency support. In this modification, parameter $k_1(f_{gr})$ of (3) is adjusted during an event according to the grid operating frequency (f_{gr}). Therefore, the new I_Q and I_P will be real-time adjusted providing a more properly FRT operation (better compromise between V and f support).

$$k_1(f_{gr}) = \begin{cases} k_{\max} & , f_{gr} \geq f_N \\ \left(\dfrac{k_{\max} - k_{\min}}{f_N - f_{\min}}\right) \cdot \left(f_{gr} - f_N\right) + k_{\max} & , f_{\min} \leq f_{gr} \leq f_N \\ k_{\min} & , f_{gr} \leq f_N \end{cases} \quad (3)$$

Fig. 9 presents the power system operation with the adjustable $k_1(f_{gr})$ modification. The last case study of Table II summarizes the evaluation of the above modification for k_{max}=10, k_{min}=2, f_N=50 Hz, and f_{min}=49 Hz. Additionally, Fig. 10 presents EMT simulation for the RES response according to the adjustable $k_1(f_{gr})$. It is clear that a properly voltage support is still provided during low-voltage event. In the meantime, when the RES also senses an under-frequency operation, it adjusts its support (by adapting $k_1(f_{gr})$) to fairly mitigate both voltage and frequency disturbances.

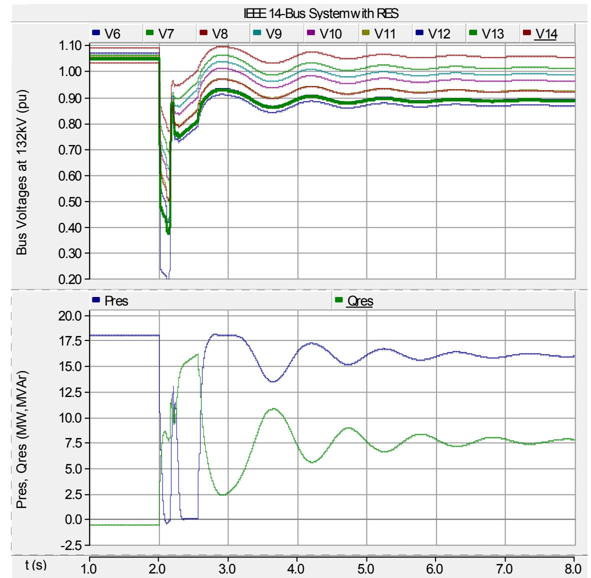

Figure 9. IEEE 14 bus system response when the RES operates according to the suggested FRT strategy with the additional DB zone 2 and the adjustable $k_1(f_{gr})$.

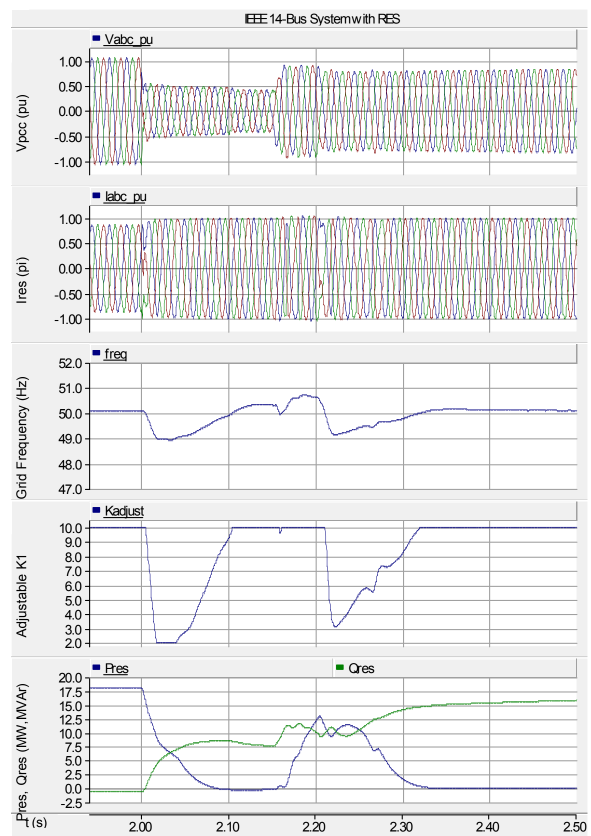

Figure 10. The RES response when operates according to the suggested FRT strategy with the additional DB zone 2 and the adjustable $k_1(f_{gr})$.

IV. CONCLUSIONS

This paper investigates the FRT operation of RES according to current grid regulations for providing support to the power system under grid faults. The investigation highlighted two issues of the current FRT regulations on the power system response that were not considered previously. Firstly, undesired power fluctuations imposed by the RES due to the discontinuity of DB zone may repeatedly cause small voltage sags and undamped machine oscillations. Secondly, the trade-off between voltage and frequency support of the FRT is required to be fairly balanced. Hence, a critical DB zone modification and an adjustable $k_1(f_{gr})$ modification are proposed to address these problems. EMT simulations on the IEEE 14-bus system with integrated RES are used to investigate both current and proposed FRT strategies. The simulation results demonstrate the beneficial effect of the proposed modifications in the operation of the power system.

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