DYNAMIC INTERACTIONS BETWEEN DVR DEVICES AND AC GENERATORS CONNECTED TO DISTRIBUTION SYSTEMS

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Abstract – **This paper presented a study about the influence of DVR (Dynamic Voltage Restorer) devices on the dynamic performance of induction and synchronous generators connected directly to distribution networks by using three-phase non-linear dynamic simulation. Considering that a DVR is employed to eliminate voltage sags during short-circuits, the impacts of this controller on the voltage and angle stability of ac generators as well as on the short-circuit currents supplied by them are analyzed. Computational simulation results have indicated that the presence of a DVR can improve considerably the stability performance of induction and synchronous generators. Furthermore, such device has considerable influence on the short-circuit currents provided by ac generators during faults.**

Keywords - **Custom power devices, distributed generation, DVR, induction generator, power system stability, synchronous generator.**

I. INTRODUCTION

Nowadays, the usage of power electronics-based devices and electric energy generation equipments connected directly to distribution systems has been induced by market deregulation and technological developments [1]-[5]. The connection of electrical generators to distribution system is known as embedded or distributed generation to distinguish it from traditional centralized generation [5]. Although much attention has been recently paid to new forms of power generation, such as photovoltaic arrays and fuel cells, at present, most sites of distributed generation employ ac rotating machines. Additionally, several power electronics devices especially designed to medium voltage networks have been recently proposed, which are generically called Custom Power devices [1]-[4]. Usually, Custom Power devices are adopted to improve power quality and reliability aspects, in particular those devices based on the voltage source converter technology. The DVR (Dynamic Voltage Restorer) is an important member of this family, which has been utilized in distribution networks.

Therefore, the consequences of the dynamical interactions among distributed generators and Custom Power devices on the distribution system operation should be understood. Thus, this paper investigates the main impacts of a DVR on the stability performance of induction and synchronous generators as well as on the short-circuit currents provided by them during faults in distribution networks. The stability studies were carried out using the phasor solution method for the network representation, whereas electromagnetic transient analysis was employed in the fault studies.

II. DVR CONTROL

A DVR consists of a voltage source converter connected in series to a distribution system through insertion transformers, as schematically shown in Fig. 1. Such configuration allows the device to absorb or supply reactive and active power in a controlled way if there is an energy storage element in the dc side. Usually, DVR devices have been utilized for elimination of voltage disturbances, such as sags, swells, unbalance and harmonic distortions [4]. In distribution voltage level, frequently, the switching elements employed in the converter are IGBTs (Integrated Gate Bipolar Transistor) due to its lower losses and reduced size. Moreover, the converter rating employed in Custom Power devices is relatively low. Consequently, the output voltage control may be executed through PWM (Pulse Width Modulation) switching pattern, decreasing the generation of low order harmonic components.

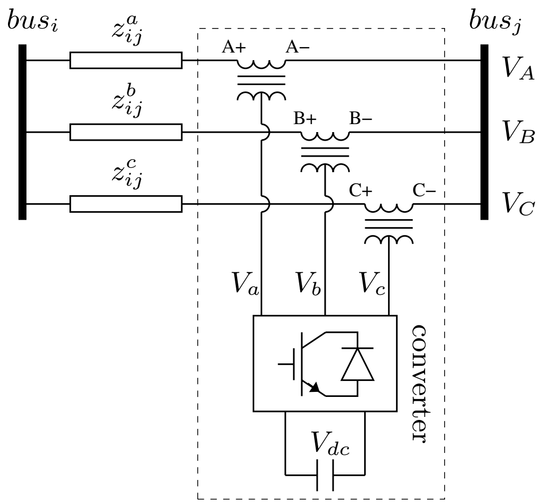


Fig. 1. DVR structure.

In this work, the DVR is utilized to eliminate voltage sags during short-circuits. Moreover, the converter is indirectly controlled, *i.e.* only the output voltage angle is controlled and the magnitude remains proportional to the dc voltage [4], [6]. Consequently, active and reactive power compensations occur simultaneously. Although, directly controlled converters may present a better dynamical performance, they are more complex and costly to be implemented [6]. The controller utilized here is shown in Fig. 2, which is the same presented in [3] and [4]. The three-phase rms value of the terminal voltage (V_{rms}) at bus_j is measured and compared with the desired reference value (V_{rms}^*). The difference is processed by a PI controller, providing the reference angle δ for the voltage generated by the converter. More information about this controller and the DVR computational model can be obtained in [3] and [4]. Additionally, it was considered that the DVR is in operation only for the duration of the short-circuit. During normal operation of the network, the DVR is bypassed, as discussed in [3] and [4].

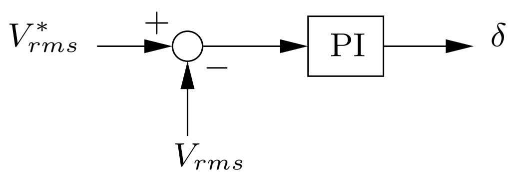


Fig. 2. Terminal voltage controller (indirectly controlled converter).

III. NETWORK COMPONENT MODELS

Distribution systems are inherently unbalanced due to factors such as occurrence of asymmetrical line spacing, combination of single, double and three-phase line sections and imbalance of customer loads. In consequence, single-phase models should not be used. Thus, in this work, all the network components were represented by three-phase models. The active components of loads were represented by constant current models and the reactive components by constant impedance models as recommended in [7]. The distribution feeders were modeled as series *RL* impedances, because they can be considered short lines. On the other hand, the three-phase transformers were simulated taking into account the core losses, but the saturation effects were neglected. The single-line diagram of the test network is shown in Fig. 3. Such network comprises a 133 kV, 60 Hz, subtransmission system with short-circuit level of 1500 MVA, represented by a Thevenin equivalent (Sub), which feeds a 33 kV distribution system through two 132/33 kV, Δ/Yg, transformers. In this system there is one ac generator with capacity of 30 MVA connected at bus 7, which is connected to the system through a 33/0.69 kV, Δ/Yg, transformer. This machine can represent either a generator in a thermal generation plant or an equivalent of various generators in a wind or small-hydro generation plant. In some cases, such machine was simulated as an induction generator and in other ones as a synchronous generator. Moreover, there is a DVR connected in series with branch 5-6, whose capacity of the dc voltage source was adopted equal to 5 kV.

A. AC Generator Models

The dynamic behavior of the induction generator was represented by a sixth order three-phase model in the *dq* rotor reference frame [8]. Additionally, in all cases simulated, a three-phase capacitor bank was connected to the terminals of the induction generator, which was adjusted to keep the terminal voltage equal to 1 pu during steady state. The synchronous generator was represented by an eighth-order three-phase model in the dq rotor reference frame [8]. Furthermore, such generator was considered equipped with an Automatic Voltage Regulator (AVR), which was represented by the IEEE - Type 1 model. In both cases, the mechanical power was considered constant, *i.e.* the primer mover and governor effects were neglected.

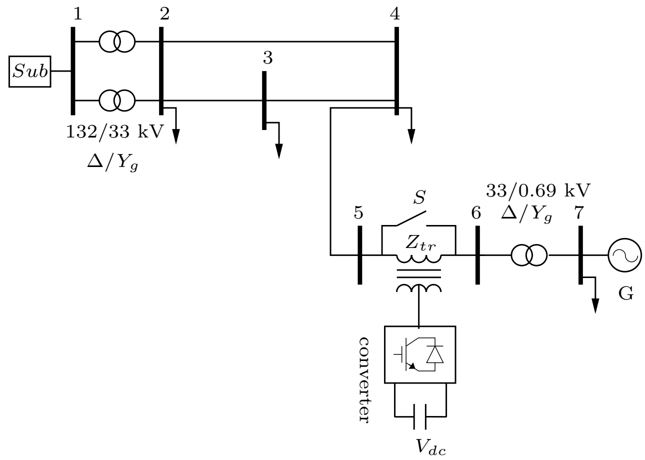


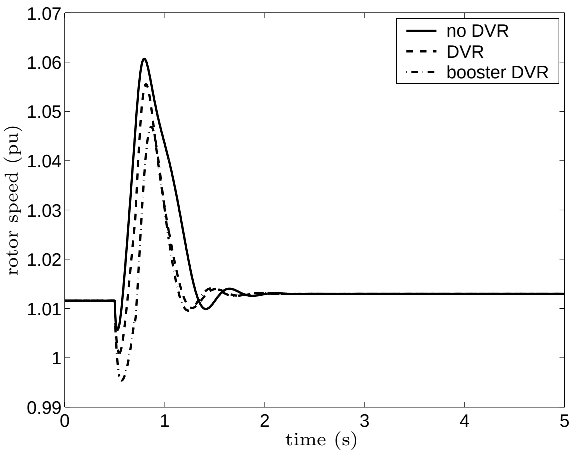
Fig. 3. Single-line test system.

IV. STABILITY ANALYSIS

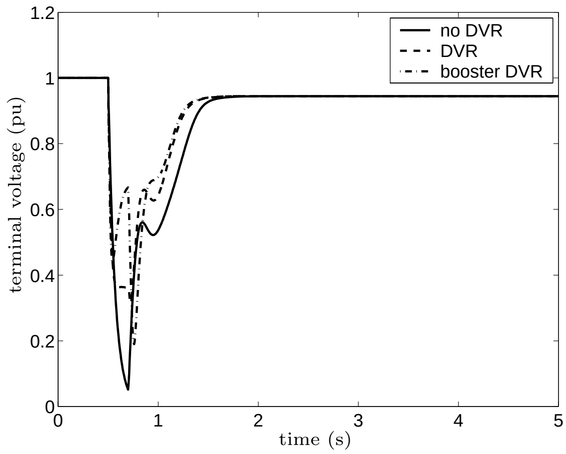
All simulations presented in this section were obtained using the phasor solution method for computing the network variables, as usual in transient stability studies. Two configurations for the DVR insertion transformers were tested: turn ratio equal to 1:1, *i.e.* without booster capability, and turn ratio equal to 1:2, *i.e.* with booster capability, this denomination is used in [3]. In this work, the cases using a DVR without booster capability are called simply DVR cases. Otherwise, the cases using a DVR with booster capability are called booster DVR cases.

A. Induction Generator

Case (a): a three-phase-ground short-circuit was applied at bus 4 at t = 0.50 second and eliminated at t = 0.70 second (12 cycles), by tripping branch 2-4, when the induction generator was injecting 25 MW into the network. The rotor speed responses for the three situations, *i.e.* without DVR, with DVR and with booster DVR, are presented in Fig. 4(a). It is possible to verify that all cases are stable. Moreover, it can be confirmed that the transients of this kind of generator are very fast. The behavior of the terminal voltage for each case is shown in Fig. 4(b). Note that, during the fault, the voltage depression is lower in the presence of the DVR. However, such depression is still significant, because the capacity of the DVR is not sufficient to mitigate it totally. Furthermore, the pos-fault terminal voltage for all cases is equal to 0.945 pu, not recovering to 1 pu even in the cases with DVR, because the DVR acts only during the fault interval. In this case, it can be noted that, although the maximum peak of the rotor speed is lower in the case with a booster DVR, the initial back-swing is larger than the other ones. Additionally, such back-swing is sufficiently large to provoke a momentary reversal of power flux (rotor speed smaller than 1 pu).

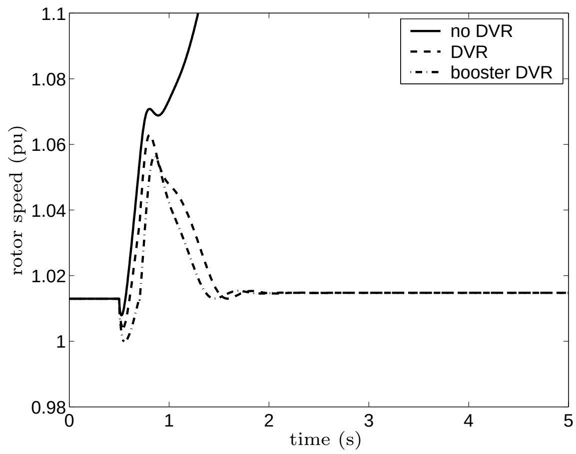


(a) rotor speed.

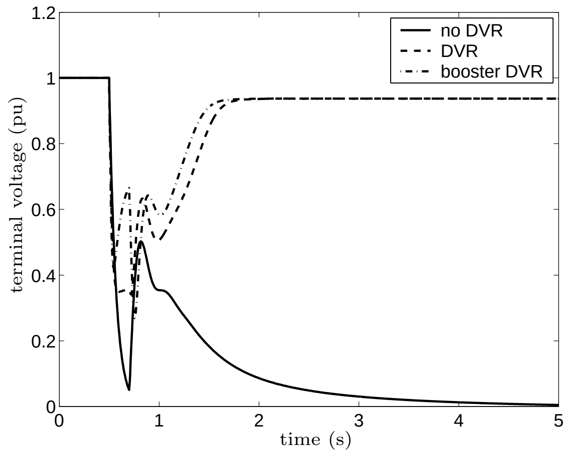


(b) terminal voltage.

Fig. 4. Rotor speed and terminal voltage responses of the induction generator (Case (a)).



(a) rotor speed.



(b) terminal voltage.

Fig. 5. Rotor speed and terminal voltage responses of the induction generator (Case (b)).

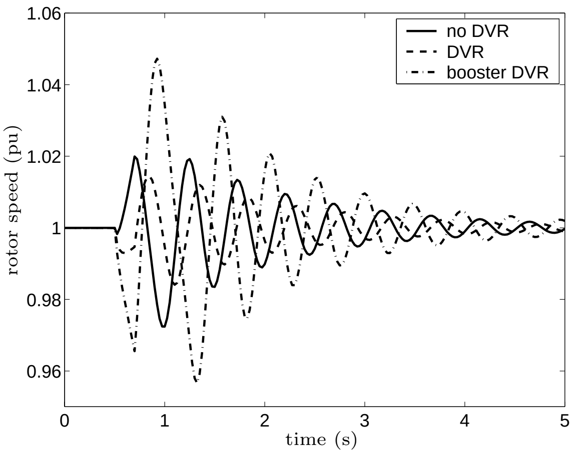
Case (b): the same previous contingency was simulated, however, the induction generator was injecting 28 MW into the network at the short-circuit moment. The rotor speed responses are presented in Fig. 5(a). As it can be verified, only if there is a DVR the behavior of the induction generator is stable. The behavior of the terminal voltage for all cases are exhibited in Fig. 5(b), showing that the depression voltage during the fault is smaller in the presence of a DVR. Additionally, the pos-fault terminal voltage is equal to 0.937 pu for the stable cases. Even though the instability phenomenon of an induction generator occurs mainly due to the lack of reactive power, it can be stabilized by limiting the rotor acceleration.

It is important to mention that, for this contingency, the maximum active power that the induction generator can inject into the network remaining stable is 26.8 MW. On the other hand, with a DVR without booster capability, this limit is increased to 29.1 MW, and for the case with a booster DVR is possible to increase the injected active power up to 30 MW, which is the nominal capacity of the generator.

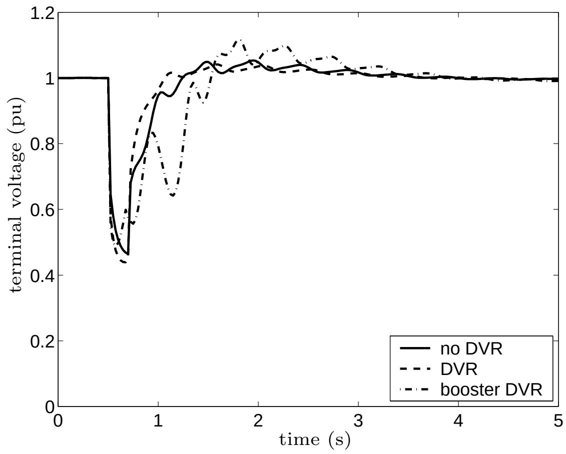
B. Synchronous Generator

Case (c): the simulated fault is the same of the previous cases. In this case, the synchronous generator was injecting 25 MW at the fault instant. The rotor speed responses for all situations are presented in Fig. 6(a). It can be verified that the damping is better if there is a DVR without booster capability in the network. On the other hand, if the DVR has booster capability the damping is worse due to the large initial back-swing of the generator during the DVR actuation. Analyzing the dynamic behavior of the terminal voltage, which is shown in Fig. 6(b), it can be seen that the system is intensively disturbed after the fault clearance in the presence of a booster DVR.

Case (d): the simulated fault is the same of the previous cases. In this case, the synchronous generator was injecting 30 MW into the network at the fault moment. In Fig. 7(a), the rotor speed responses are presented, showing that only if there is a DVR into the network the system is stable. Additionally, when the DVR has no booster capability, the system damping is better than with booster capability. The dynamical behavior of the terminal voltage for the stable cases is shown in Fig. 7(b), where it can be observed that the responses are similar in both cases.

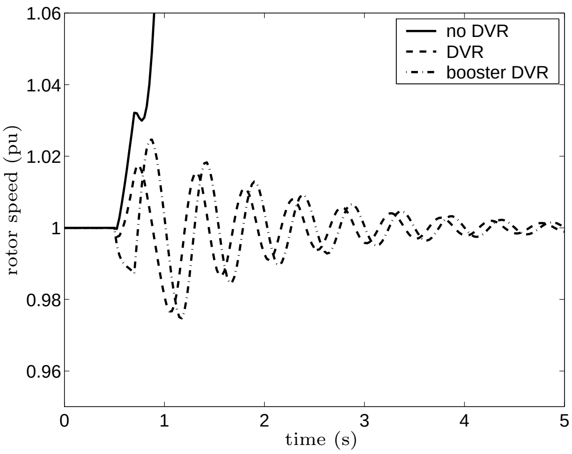


(a) rotor speed.

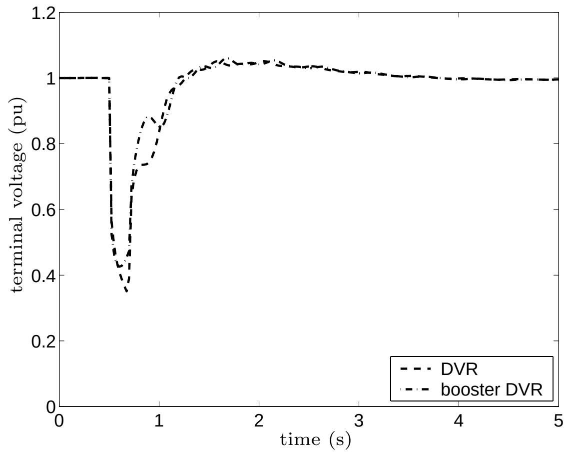


(b) terminal voltage.

Fig. 6. Rotor speed and terminal voltage responses of the synchronous generator (Case (c)).



(a) rotor speed.



(b) terminal voltage.

Fig. 7. Rotor speed and terminal voltage responses of the synchronous generator (Case (d)).

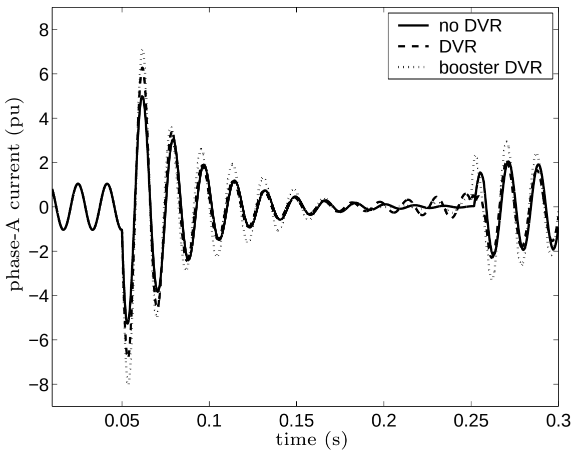
For this contingency, the maximum active power that the synchronous generator can inject into the network, keeping a stable response, without a DVR is 27.3 MW. Therefore, it can be concluded that for this case a DVR with or without booster capability can increase such limit at least to 30 MW, which is the generator nominal capacity.

V. SHORT-CIRCUIT CURRENTS

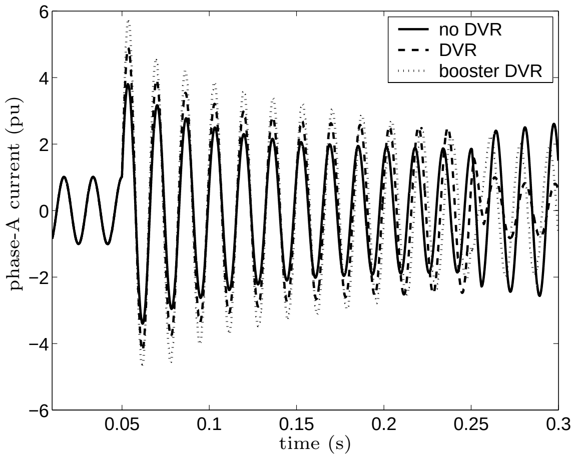
All simulations presented in this section were obtained using electromagnetic transient analysis and the DVR simplified model. Although different faults were simulated, all short-circuits were applied during 200 ms (12 cycles), from t = 0.05 second to t = 0.25 second, and cleared without disconnection of lines. The objective here was to determine the influence of the presence of a DVR on the short-circuit currents provided by ac generators during unbalanced and balanced faults.

A. Three-Phase Short-Circuit

In this section, the simulation results considering a three-phase-ground short-circuit applied at the middle of branch 4-5 are analyzed. The phase-A stator currents of the induction and synchronous generators for this fault are presented in Fig. 8(a) and 8(a), respectively. It can be noted that the presence of a DVR has significant influence on the short-circuit currents provided by the ac generators, increasing them. Additionally, if the DVR has booster capability, such currents are even higher. Furthermore, comparing 8(a) and 8(b), it can be seen that, although the initial value of the short-circuit current provided by the induction generator is higher than the current of the synchronous generator, the former decays very quickly. In Table I, the rms value of the phase-A stator short-circuit currents provided by the induction and synchronous generators, for all cases, are presented considering different instants after fault occurrence.

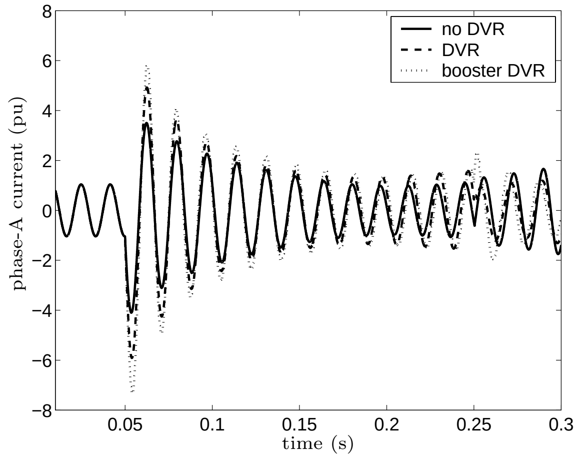


(a) induction generator.

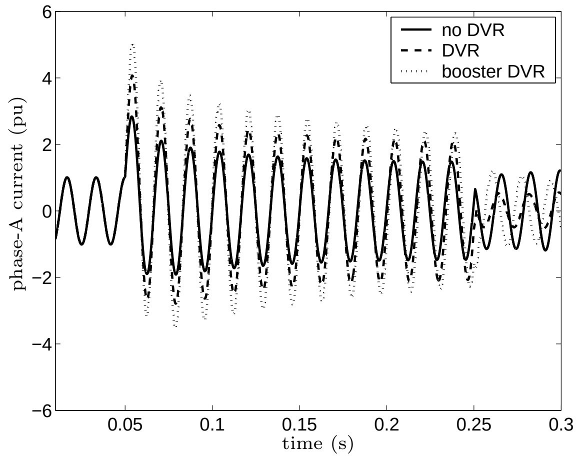


(b) synchronous generator.

Fig. 8. Phase-A stator current of the ac generators (three-phase-to-ground fault).



(a) induction generator.



(b) synchronous generator.

Fig. 9. Phase-A stator current of the ac generators (phase-A-to-ground fault).

TABLE I
Phase-A short-circuit currents provided by ac generators.

	Phase-A stator current (pu)			
time (cycles)	3	6	9	12
synchronous generator	2.70	2.13	1.94	1.89
synchronous generator + DVR	3.44	2.79	2.57	2.49
synchronous generator + booster DVR	4.11	3.35	2.86	2.19
induction generator	2.21	0.56	0.15	0.04
induction generator + DVR	2.22	0.51	0.21	0.55
induction generator + booster DVR	2.84	0.98	0.07	0.33

B. Phase-Ground Short-Circuit

An unbalanced fault is analyzed in this section. The simulated contingency was a phase-A-ground short-circuit at bus 5. The phase-A stator current responses for an induction generator and a synchronous generator, without and with DVR, are presented in Fig. 9(a) and 9(b). It can be observed that the currents are higher in the presence of a DVR and the highest current occurs for the cases in which the DVR has booster capability, as happened in the previous case too.

VI. CONCLUSIONS

As opposed to that has occurred in transmission systems, where the impacts of FACTS devices on synchronous generators have been intensively investigated, in distribution systems, the influences of Custom Power devices on the performance of ac generators have been less studied. However, such equipments have been increasingly installed in medium voltage networks simultaneously. Therefore, in this work, the main impacts of a DVR with and without booster capability on the dynamical performance of ac generators were analyzed. It was verified that a DVR can considerably improve the stability performance of inductions and synchronous generators if they are conveniently dimensioned. Additionally, it was observed that short-circuit currents provided by ac generators during faults tend to be higher in the presence of DVRs. It could also be noted, analyzing the cases where the DVR has booster capability, that the synchronous generators become more perturbed as the capacity of the DVR increases due to a larger initial back-swing. This actually is expected because the terminal currents during faults increase in the presence of a DVR. Thus, if the terminal voltage is kept constant in the pre-fault value, the electric power at the machine terminal will also increase. Consequently, the generator will decelerate during the short-circuit. In an extreme case, it may become unstable due to a large initial back-swing. Additionally, induction generators may motorize momentarily due to the initial back-swing if the capacity of the DVR is sufficiently large, as it was verified in this work for the case with a booster DVR. However, this would occur during a very brief period, because induction generators usually do not provide sustained short-circuit currents.

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