LVRT-Retardation-Device for Decentralized Power Plants

N. Essl, H. Renner

***Abstract*—During fault events in the electrical power grid nearby a synchronous generator, the rotor speed of the machine is increased, because dissipated power is below generated power. This may cause high rotor angle excursions and hence the machine to lose synchronism with the power grid. This paper presents a retardation device, which is able to curtail the acceleration of rotor speed during fault events. Besides, the backswing phenomenon, which decelerates the rotor speed in the first few milliseconds of the fault event is discussed. Different simulation methods are addressed within the scope of work. All simulations were performed with the power system analysis software DIgSILENT PowerFactory.**

***Index Terms*—backswing, distributed generation, dynamic simulation, grid codes, low voltage ride through, retardation device**

I. INTRODUCTION

In the past, most grid codes did not require decentralized power plants to support the power system during grid disturbances. They were allowed to disconnect from the grid when an abnormal grid voltage was detected. With the increased penetration of distributed generation based on regenerative energy resources, disconnection of those power plants during grid disturbances would lead to a sudden loss of a decent amount of generation and therefore could generate problems regarding frequency and voltage in the system, leading as a worst case to a system collapse. As a consequence, low-voltage-ride-through-(LVRT)-requirements were determined. They specify voltage limiting curves, within which the power plant isn't allowed to disconnect from the grid. Fig. 1 shows a selection of LVRT-profiles of several countries' grid codes.

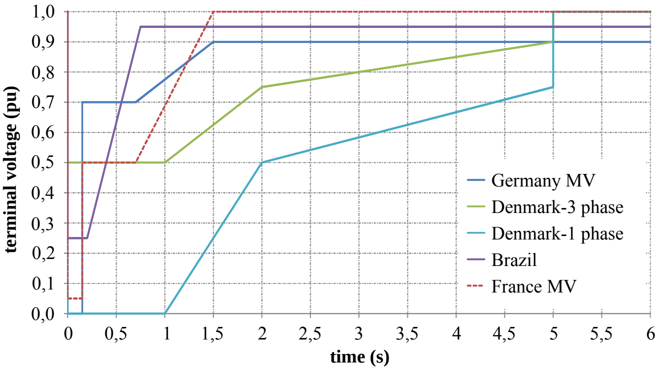

Fig. 1 Comparison of LVRT limiting curves from grid codes of several countries

Extensive research is being done on grid codes and LVRT-requirements. Reference [1], [2] and [3] investigate and compare different grid codes and their requirements and operating limits regarding frequency, voltage, power factor and active and reactive power control. Grid codes are mostly compiled by transmission system operators (TSOs) of countries or regions with high penetration of regenerative energy sources [2].

A lot of research work has been done for the improvement of LVRT-behavior of wind farms, especially for doubly-fed induction generators [4], [5].

In this paper the focus is put on gas engine driven generators. There have been approaches to face those requirements and help generators ride through a fault without losing synchronism. Different solutions are shown and investigated in [6].

Especially for engines with low inertia, the acceleration of the rotor during a fault event is very critical and can lead to loss of synchronism of the machine. This paper presents a retardation device, which is able to curtail the acceleration during fault events to keep synchronism of the generator with the external grid and thereby be grid code compliant. Several approaches were investigated during research. The examined retardation device is a switchable ohmic resistance, which is connected in series to the generator.

Introductory, basic simulation methods and the backswing phenomenon are discussed.

II. SIMULATION METHODS

In case of a nearby short circuit, which causes the most excessive voltage dip, the generator's fault current in each phase consists of two distinct components: A fundamental frequency component, which decays very rapidly and pursues relatively slowly to a steady-state value, and an unidirectional direct current (dc)-offset, which decays exponentially (similar to generator torque, shown in Fig. 5). The magnitude of the dc component depends on the rotor position related to the respective phase during an incidence.

In many power system analysis programs there are basically two dynamic simulation methods available: the instantaneous value simulation (EMT – Electro-Magnetic Transients) and the transient stability simulation (RMS – Root Mean Square). In EMT-simulations, the machine's flux and stator voltage equations are represented without simplifications. Therefore, dc components as well as harmonic components in short circuit currents and generator torque are represented in simulation results. In contrast, using the RMS simulation method, the machine's stator voltage equations get simplified (stator flux transients neglected).

The advantage of an RMS simulation is that the simulation time is significantly reduced compared to an

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This work was supported by the Austrian Research Promotion Agency (FFG), the national funding institution for applied research and development in Austria.

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EMT simulation. The increased simulation speed makes it possible to simulate much longer events and much more complex systems. Fig. 2 and Fig. 3 show simulation results of active power during and after facing a fault event (highlighted in red) lasting for 150 ms, using the RMS- and EMT-simulation method, respectively. Results shown are from the same simulation setup as described later (see section Simulation Setup) [7], [8].

As can be seen, high-frequency power oscillations are not represented using the RMS-simulation-method, whereas using the EMT-simulation method, high-frequency components are represented properly.

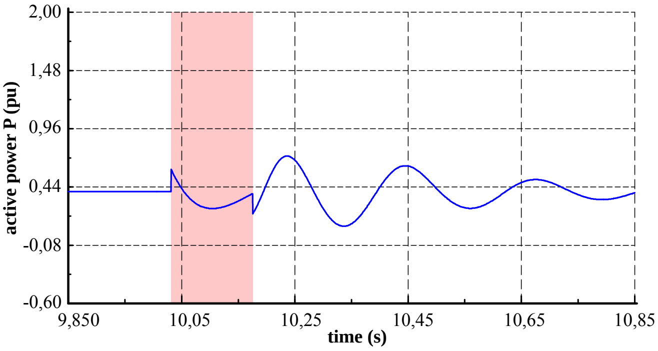

Fig. 2 Simulated generator active power P during a fault using RMS-simulation-method

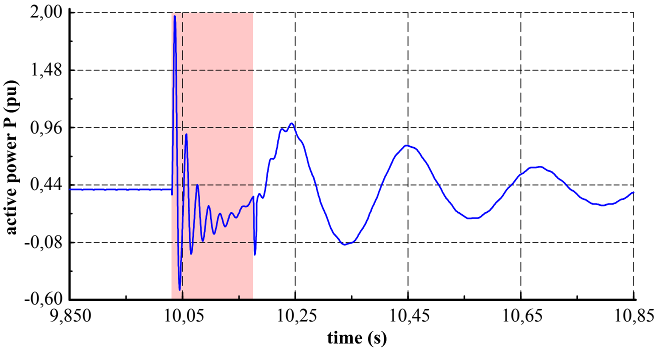

Fig. 3 Simulated generator active power P during a fault using EMT-simulation-method

III. BACKSWING PHENOMENON

Considering a generator during fault, typically an imbalance between mechanical power from the engine and electrical power fed to the grid emerges, leading to acceleration or deceleration of the rotor and possible loss of synchronism. Two basic effects can occur: The first and obvious one is the acceleration of the rotor due to reduced electrical torque during the voltage drop. However, in some cases a deceleration in the first few cycles of the fault can be observed – the backswing.

The backswing phenomenon describes the behavior of a synchronous generator in the first few milliseconds of the fault, where dissipated power is slightly increased, compared to the operating point prior to the fault. Therefore, the rotor is decelerated before being accelerated. This behavior is shown in Fig. 4 (highlighted in green), where simulation results for generated active power P are shown. The machine used for simulation was a 5.46 MVA synchronous generator running at full load and pf=0.95 ind. The simulated fault was a voltage dip to u=0.3 pu at the point of common connection (PCC) for 150 ms (highlighted red area).

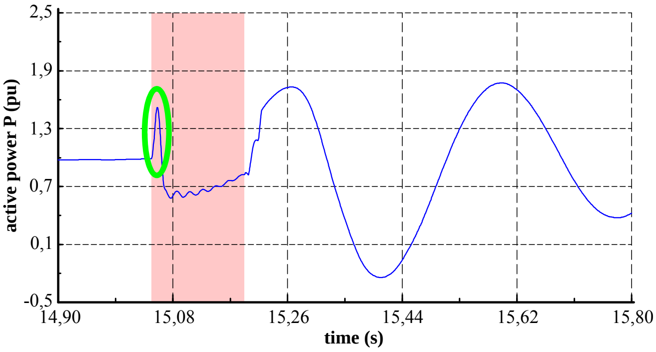

Fig. 4 Backswing of a 5.46 MVA machine during fault event (u=0.3 pu for 150 ms)

This behavior can be explained as follows: After a short circuit, the flux wave represented by flux linkages of d- and q-axis, Ψd and Ψq, respectively, remains as flux wave stationary referred to the armature. Therefore, voltages are induced in the rotor circuits and the consequent currents cause power losses in the ohmic resistances of the rotor. These losses, combined with armature short circuit power losses, produce an unidirectional breaking torque, which is counteracting the engine's torque. Hence, the backswing is decelerating the rotor and therefore, helping the machine ride through the fault. Nevertheless, in some cases this effect might be too strong and therefore, contribute to instability. Besides the unidirectional torque, the oscillatory torque, which is of fundamental frequency, influences the backswing as well. Both components add up to the total post-fault torque, which is shown in Fig. 5. Part a of the trace represents the initial load torque, b the component of torque due to losses and c the total transient torque.

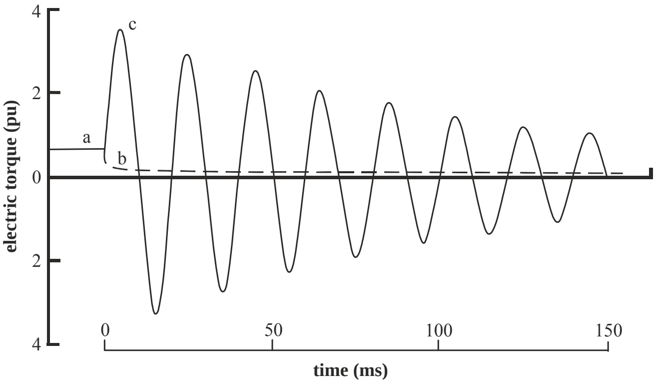

Fig. 5 Generator electrical torque following a nearby short circuit [9]

Although the backswing very often is neglected in transient performance studies, taking it into account can be quite important. Depending on the test setup and operating point of the machine, the backswing effect can have a quite significant impact on active power output and accordingly on rotor speed and rotor angle. The lower the pre-fault power level, the more severe the backswing. The larger the reactances of the grid near the machine, the higher the excitation level needs to be and with that, terminal voltage is higher. As a result, air-gap flux is higher and therefore, if a short circuit occurs, the initial transient losses and the initial unidirectional torque are increased. In addition to the factors pre-fault load and excitation level, the backswing is more severe if inertia is decreased or when the fault is closer to the machine, which causes a higher short circuit current and losses. The duration is also affected by armature resistance and field- and damper-winding time constants [9], [10].

IV. RETARDATION DEVICE

Although the backswing effect decelerates the rotor (more or less, depending on the test setup), in most cases acceleration of the rotor due to lack of dissipated power during a fault event is dominating, which can cause the machine to lose synchronism. To prevent the machine from falling out of step, a retardation device must be introduced. One way to do so is to increase the dissipated power during a fault by introducing an impedance in series to the generator. To increase dissipated real power, the series impedance has to be basically ohmic. As the problem of lacking power dissipation only persists during fault, the series resistor is activated upon detection of a fault event only and bypassed otherwise.

A. *Series Resistor Design*

The engaging of a series resistance inserted between generator and grid will lead to increased I^2R-losses during fault. Since the short circuit current depends on the remaining voltage during the dip, the series resistor solution shows an inherent self-stabilizing behavior. A lower remaining voltage leads to a higher power imbalance for the synchronous machine (as mentioned above). However, it also causes a larger short circuit current and a larger power dissipated in the resistor, compensating the power imbalance. Besides the series resistor, the ohmic parts of the components in the power supply of the generator must be taken into account. This is especially important in low-voltage installations with a low X/R-ratio.

Basically, for a given remaining voltage and a requested power dissipated in the resistor, two solutions for the value of the series resistor can exist. The generator's short circuit current can be expressed in terms of sub-transient values in a good approximation with

$$I'' = \frac{E''}{\sqrt{X''^2 + R^2}} . \tag{1}$$

With that, the dissipated power is

$$P'' = I''^2 \cdot R = \frac{E''^2 \cdot R}{X''^2 + R^2} . \tag{2}$$

To obtain transient and steady-state values, generator reactances included in the calculation need to be changed accordingly. Fig. 6 shows the dissipated power as a function of total line resistance for a specific test case (see section *Simulation Setup*). The dashed curves are obtained by varying the generator reactances with a tolerance of ±30 %.

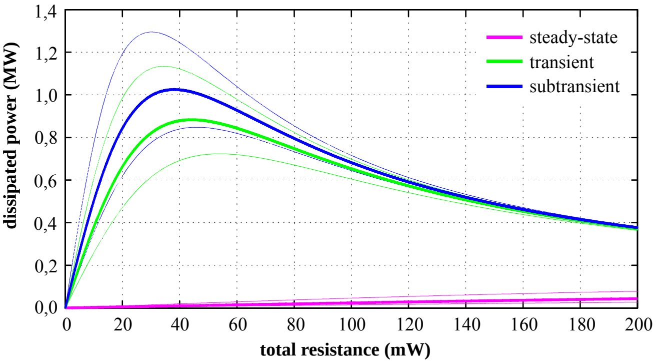

Fig. 6 Dissipated power between generated voltage and PCC [8]

To maximize dissipated power during fault, the total ohmic resistance (series resistor, cables, transformer, generator) can be obtained from Fig. 6, where the curves have their peak value. It is assumed that the timeframe, where the system is active, lies within the area where the generator behavior can be described by the transient characteristics. Usually it's not a single resistor value but a certain range, which meets the desired stability criteria, such as no loss of synchronism or keeping the rotor angle or rotor speed in a certain range around their nominal operating point.

In the following the procedure to determine the resistor value is described. The operating point is set to maximum power, the remaining voltage at the PCC is set to 5 %, the dip duration according to ENTSO-E requirements to 250 ms [11] and the circuit breaker activation delay to 25 ms (see section *Control Strategy*). In an iterative process the value of the series resistor at a certain remaining voltage level is increased from zero until the stability criteria (no loss of synchronism, limited rotor angle deviation or limited speed deviation) is reached. This resistor value is the lower limit of the possible range. Then the resistor value is further increased until the range of stable LVRT is left again, marking the upper value of the possible resistor range.

In a next step the remaining voltage is increased and the process repeated. Again the result is a range for the resistor value. Due to the self-stabilizing effect described above, the determined resistor ranges will clearly overlap. So it is possible to determine a single value which covers different remaining voltages, respectively identify the voltage limit where stability is kept without series resistor. After that, the simulation is extended to operation points below maximum power, using the predetermined resistor value. In some scenarios it will happen, that the power dissipation of the resistor is too high. In those cases, the on-time of the resistor will be reduced. Simulation has shown that the on-time of the resistor can be easily controlled according to the loading of the machine. For simulation results regarding resistor dimensioning see TABLE III.

B. *Control Strategy*

The series resistor should be activated after the backswing effect has decayed, because otherwise the activation of the braking system would intensify the backswing effect. By then, the conventional problem of low generator power can be approached with engaging the series resistance. However, when the backswing has decayed, the braking system should get activated as soon as possible to maximize the braking effect. The activation delay of the system is an essential parameter to define its effectiveness.

Anyway, from a practical point of view, an instantaneous activation of the series resistance is not possible. Referring to realistic activation times, including fault detection (≈15 ms) and commutation delay (≈5 ms), thyristor-controlled elements should be able to activate the series resistor within ≈25 ms. This value is used for the simulations. The thyristor has to be in parallel to the series resistor to build a bypass for the operational current during normal operation. Thyristor controlled switches are chosen over common LV circuit breakers, since the response time of the latter is in the range of ≈60 ms.

The system loses its effectiveness by further delaying the activation. Depending on the delay, the rotor acceleration may be too progressed to stop over-speeding. Consequently, a fast reaction ensures efficiency and operational ranges of the braking system in the same way as an optimal designed resistor does.

The relation between activation time and resistance design variations is shown in Fig. 7. Activation time is outlined on the x-axis, presuming a 15 ms delay from fault detection. The y-axis shows design deviations related to an 'optimum resistor' – the theoretical optimum suited for a specific case. Exact design of the resistor – that corresponds to the theoretical optimum – is practically not feasible, because tolerances are always present (e. g. in generator parameters).

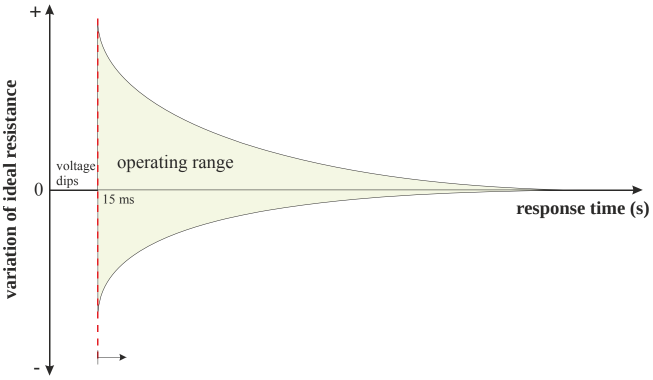

Fig. 7 Schematic connection of activation time and design variation of series resistance

The series resistance is deactivated when the fault is cleared (respecting detection and commutation delays), or earlier if necessary (see section *Series Resistor Design*). Therefore, depending on the loading of the machine and the remaining voltage during fault, the series resistor is activated or not.

V. SIMULATION

The simulations were performed in power system analysis software DIgSILENT PowerFactory, using the EMT simulation method.

The simulation model of the synchronous machine including a voltage regulator and limiters has been verified through measurements.

A. *Simulation Setup*

The setup used for simulation was a small low voltage grid as shown in Fig. 8. It basically consists of a gas engine driven generator (data see TABLE I.), connected via cables and the series resistor to the low voltage side of the transformer (data see TABLE II.) and finally via another cable to the external power grid. The breaker element represents the thyristor controlled switch. The red flash depicts the location, where the fault event is set – in this case the PCC. P1 and P2 are active power measurement points used for illustration of series resistor action in the simulation results (see Fig. 13).

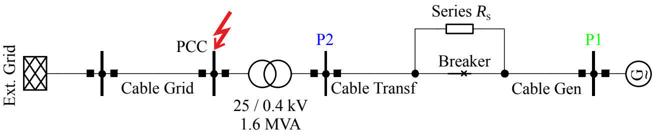

Fig. 8 Grid setup for simulations

To achieve a worst case scenario for rotor angle excursions, the operating point of the generator is set to *pf*=0.95 under-excited. Loading of the machine is varied from no load to full load. Short circuit power S_k" of the external grid was set to 20 MVA. Following, generator and transformer data are shown in TABLE I. and TABLE II. , respectively.

TABLE I. GENERATOR DATA

Parameter	Value	Unit
U_n	0.4	kV
S_n	792	kVA
H	0.32	s
xd	2.173	pu
xq	1.628	pu
xd‘	0.161	pu
xd‘‘	0.128	pu
xq‘‘	0.14	pu
Td’	0.156	s
Td’’	0.010	s
Tq’’	0.012	s

TABLE II. TRANSFORMER DATA

Parameter	Value	Unit
U_1	25	kV
U_2	0.4	kV
S_n	1.6	MVA
u_k	5.5	%
P_{fe}	3	kW
I_0	1.3	%

B. *Simulation Results*

In TABLE III. the results of the series resistor dimensioning process (described in section *Series Resistor Design*) are given. Green shaded areas indicate ranges where no activation of the series resistor is necessary, orange shaded areas indicate a limited on-time (here: 55 ms) of the resistor and yellow shaded areas indicate operation of the series resistor during the whole duration of the voltage dip. As can be seen in TABLE III. , it is possible to use the same ohmic resistance for all investigated cases for the given setup. Ohmic resistances of cables, transformer and generator between the fault location and the generator total 6.34 mΩ.

TABLE III. SERIES RESISTOR DIMENSIONING

R_S	U_{PCC}				
load	***0%***	***5%***	***10%***	***20%***	***30%***
0%	🟩	🟩	🟩	🟩	🟩
10%	🟩	🟩	🟩	🟩	🟩
20%	🟩	🟩	🟩	🟩	🟩
30%	🟩	🟩	🟩	🟩	🟩
40%	🟩	🟩	🟩	🟩	🟩
50%	🟩	🟩	🟩	🟩	🟩
60%	🟩	🟩	🟩	🟩	🟩
70%	30 mΩ 55ms	30 mΩ 55ms	30 mΩ 55ms	🟩	🟩
80%	30 mΩ 55ms	30 mΩ 55ms	30 mΩ 55ms	30 mΩ 55ms	🟩
90%	30 mΩ	30 mΩ	30 mΩ	30 mΩ	30 mΩ
100%	30 mΩ	30 mΩ	30 mΩ	30 mΩ	30 mΩ

Following, simulation results performing a voltage dip are shown for two specific simulation setups selected from TABLE III. Results for rotor angle, rotor speed and active power at terminals P1 and P2 are shown. The difference between active power at P1 and P2 during fault illustrates the action of the series resistance. Data for the first simulation setup is shown in TABLE IV.

TABLE IV. SIMULATION SETUP I

Parameter	Value	Unit
Residual voltage U_{PCC}	0.05	pu
Machine loading P_{Load}	0.9	pu
Series resistance R_S	30	mΩ
Time of fault	2	s
Fault duration	0.25	s
Activation delay of R_S	0.025	s
Activation time of R_S	2.025	s
Deactivation time of R_S	2.275	s
Maximum rotor angle	±120	°

Fig. 9 shows the generator rotor angle without activation of series resistance R_S. It can be seen that the generator falls shortly out of step at about t=2.2 s. The red area highlights the fault event. Fortunately, in this case the generator is able to gain synchronism with the grid again. Nevertheless, such a behavior is undesired under any circumstances.

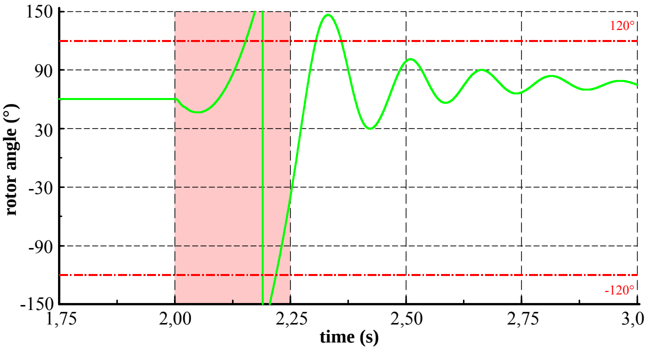

Fig. 9 Generator rotor angle without activation of R_S (Setup I)

Following, generator rotor speed without activation of series resistor R_S is shown in Fig. 10. In this specific case, the rotor speed is able to get back to its pre-fault level after the pole-slip as well.

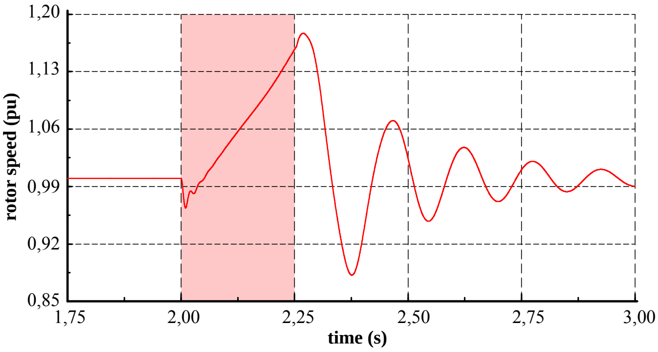

Fig. 10 Generator rotor speed without activation of R_S (Setup I)

Fig. 11, Fig. 12 and Fig. 13 show the rotor angle, rotor speed and active power measurements, respectively, with operation of the series resistor. Timestamps (pink) for activation and deactivation of the series resistance are shown in Fig. 13.

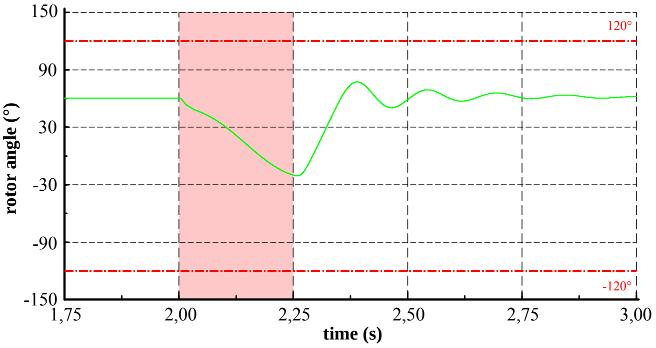

Fig. 11 Generator rotor angle with activation of R_S (Setup I)

It can be seen that rotor angle excursions are limited to an acceptable level and can be kept within the set boundaries.

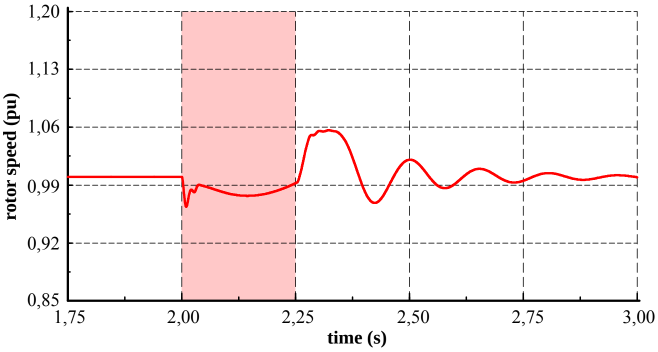

Fig. 12 Generator rotor speed with activation of R_S (Setup I)

From Fig. 12 one can see how the series resistance R_S is not only preventing the acceleration of the rotor, but also stabilizing it on a certain level during activation time of the resistor.

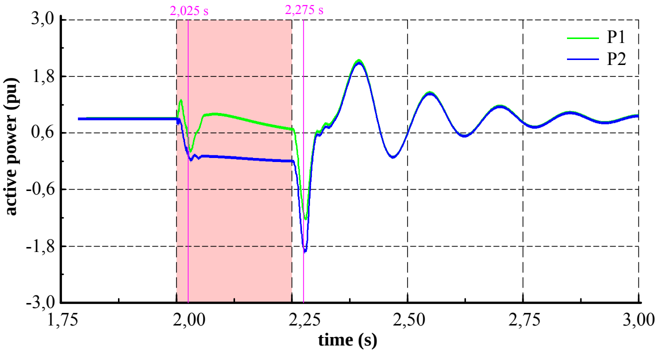

Fig. 13 Active power measurements at terminals P1 and P2 with activation of R_S (Setup I)

Drawing attention to the difference between active power signals at P1 and P2, one can clearly see the action of the series resistor. The area between both signals during fault mainly corresponds to the series resistors dissipated energy. A considerable difference between active power at P1 and P2 within the period of fault start and activation of R_S can be seen, because the initial short circuit current (sub-transient part) is very high and therefore, the active power dissipated in the cables between the two measurement points P1 and P2 is noticeable.

The second simulation setup is shown in TABLE V. In this case, the series resistor is not active the whole time during fault, but only for 55 ms.

TABLE V. SIMULATION SETUP II

Parameter	Value	Unit
Residual voltage U_{PCC}	0.05	pu
Machine loading P_{Load}	0.7	pu
Series resistance R_S	30	mΩ
Time of fault	2	s
Fault duration	0.25	s
Activation delay of R_S	0.025	s
Activation time of R_S	2.025	s
Deactivation time of R_S	2.080	s
Maximum rotor angle	±120	°

Following, plots for generator rotor angle and rotor speed without activation of R_S are shown in Fig. 14 and Fig. 15, respectively.

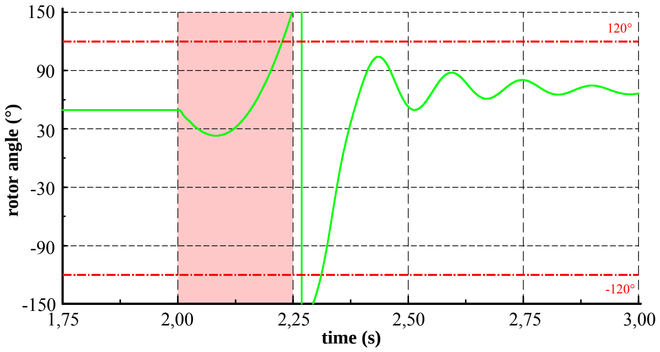

Fig. 14 Generator rotor angle without activation of R_S (Setup II)

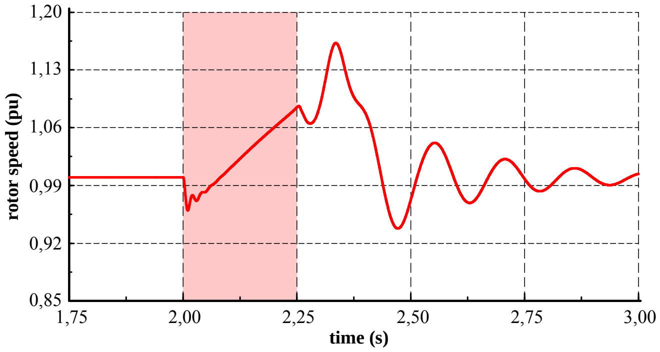

Fig. 15 Generator rotor speed without activation of R_S (Setup II)

Results for rotor angle, rotor speed and active power are shown in Fig. 16, Fig. 17 and Fig. 18, respectively.

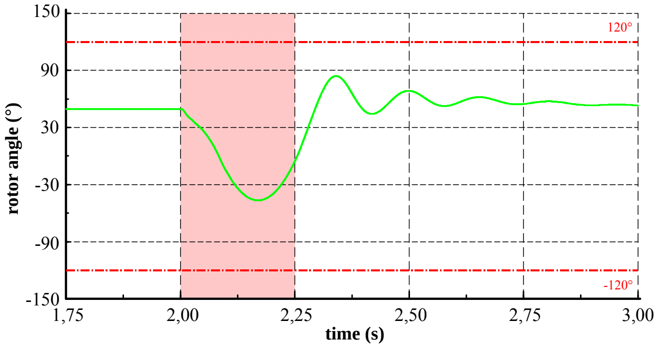

Fig. 16 Generator rotor angle with activation of R_S (Setup II)

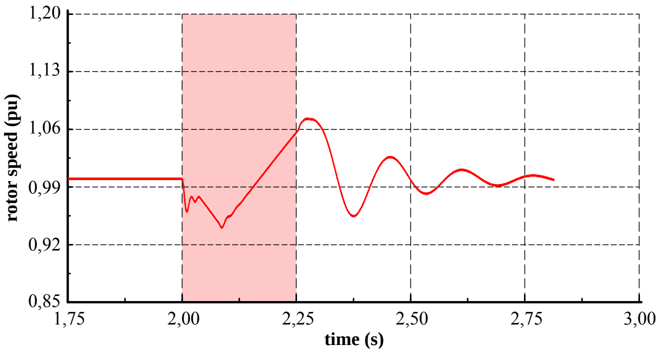

Fig. 17 Generator rotor speed with activation of R_S (Setup I)

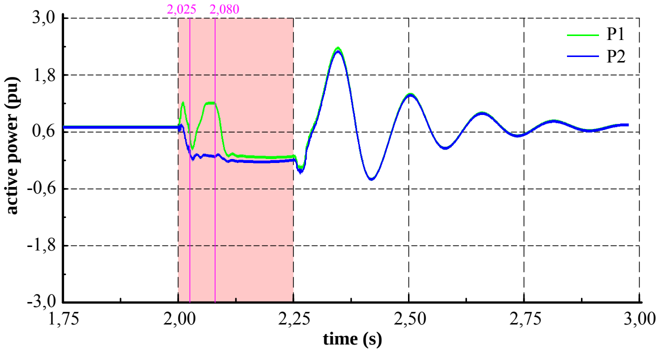

Fig. 18 Active power measurements at terminals P1 and P2 with activation of R_S (Setup II)

It can be clearly seen in Fig. 17, that if the series resistor would have been activated the whole time during fault, the generator would have decelerated too far. This is because dissipated power in the series resistor is almost the same as in the first simulation setup, but this time the pre-fault active power operation point is lower. Therefore, activation of R_S leads to a power output higher than the power input of the generator, which leads to deceleration and can be seen in Fig. 18.

VI. CONCLUSION

A retardation device was introduced into a low voltage grid setup to reduce rotor acceleration during fault and with it prevent losing synchronism of the generator with the grid. Different machine sets and grid topologies were simulated. The simulation results have shown that introducing a switchable series resistance to the grid setup is able to keep all selected values within its boundaries and therefore, prevent generator rotor slip. One of the big advantages of the series resistance as a retardation device is the simplicity of its control and the inherent self-stabilizing behavior. Besides that, no changes to the mechanical structure or the drive train are necessary. On the negative side are permanent losses in normal operation mode of the thyristor modules, because they have to carry the operational current in continuous duty. On-site tests and simulations have shown that not only rotor angle or rotor speed excursions can cause generators to disconnect from the grid during fault events, but also protection devices, such as stator current and excitation current limiters. Therefore, the ability to ride through a fault without disconnecting from the grid is not only a matter of keeping the rotor angle in check, but also minding the operation of protective devices.

VII. ACKNOWLEDGEMENT

The authors gratefully acknowledge the support and cooperation of Lukas Vogl and Uwe Liebscher from GE Jenbacher gas engines, TPSG department during research for this paper.

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BIOGRAPHIES

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The main focus of his research is the LVRT-behavior of decentralized power generation units facing fault events in the power grid.

Herwig Renner was born in Graz, Austria, in 1965. He completed his doctoral degree in 1995 and his habilitation in 2003 at Graz University of Technology, where he works as associate professor at the Department of Electrical Power Systems. His main research work is in the area of electrical power quality and power system dynamics. He holds a position as guest docent at Aalto University (Finland) and is chairman of CIRED TC session 2 and member of several CIGRE working groups.