APPLYING SERIES BRAKING RESISTORS TO IMPROVE THE TRANSIENT STABILITY OF LOW INERTIA SYNCHRONOUS DISTRIBUTED GENERATORS

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ABSTRACT

Widely held concerns over the environmental impact of emissions from large fossil fuelled generating plants are serving to promote the connection of renewable or sustainable generation onto distribution networks. Many such generators are synchronous machines with low values of inertia, and thus possess short critical clearance times to avoid the onset of transient instability. With fault clearance times of up to 1s occurring in distribution networks, there is the potential for a growing problem as distributed generation makes up a larger proportion of installed capacity. This paper proposes the use of series braking resistors that are switched into circuit at the generator terminals as a means of improving transient stability, and thus avoid, or at least defer major upgrades to distribution system protection.

INTRODUCTION

Concerns about emissions from large fossil fuelled generating plants, together with a general desire to reduce generation and transmission costs, have encouraged the installation of distributed generation. The anticipated widespread installation of renewable or sustainable generation within distribution networks creates not only commercial opportunities, but also a range of technical challenges to be overcome.

Many distributed generators are synchronous machines with low values of inertia, and thus have correspondingly short critical clearance times (CCT) for ensuring transient stability during network faults. As distributed generation is highly likely to make up a growing proportion of installed generating capacity, unnecessary tripping will increasingly cause system disturbances, thereby threatening revenue from generation and even system stability. Transmission systems mitigate these risks by using fast-acting protection; however, the cost of this is rarely justified on distribution systems. Instead, typical distribution system protection clearing times can be over 300 ms and, in some cases, may approach 1s [1]. Many distributed generators would have to be tripped in order to avoid transient instability and the resultant damage. Therefore, there is a pressing need to ensure transient stability in order to improve the performance of distributed generation such that ambitious government targets can be satisfactorily met. Series braking resistors (SBR) that are switched in following a fault are proposed as a practical and economic solution that avoids, or at least defers major upgrades to distribution system protection.

This paper presents simulation results that demonstrate that a combination of SBR, conventional switchgear, and control strategies can greatly improve transient stability at an acceptable cost. Not only may the technology be applied to new installations, it may also be retro-fitted to existing generators. An overview of a potential control scheme will also be given and areas for future work highlighted.

GENERATOR TRANSIENT STABILITY

The transient stability of synchronous machines is dependent upon a wide range of both construction characteristics and operational conditions [2], including: inertia (combined prime mover and generator), excitation system, pre-disturbance loading and the duration/nature of the disturbance.

The Swing Equation

The transient stability of a synchronous generator connected to an infinite busbar approximation can be explained by considering the well known 'swing' equation (1).

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = P_M - P_E \qquad \textbf{(1)}$$

The electrical angle (δ) between the internal (E) and the grid equivalent (V) voltages will change as rotor speed deviates from synchronous as dictated by the balance or otherwise of the electrical output (P_E) and mechanical input (P_M) powers. The term H represents the inertia constant and ω_0 is the synchronous speed.

The mechanical input power to the generator is determined by the governing of the prime mover, and the electrical power output by (2). $X_{d'}$ represents the transient reactance of the generator and is widely used within stability studies.

$$P_E = \frac{EV}{X_{d'}} \sin \delta \qquad \textbf{(2)}$$

If a disturbance occurs on the network that reduces the P_E that can be delivered, the imbalance between P_M and P_E will cause the machine to increase speed to store the excess energy, and will consequently increase the electrical angle (this being equal to the mechanical angle multiplied by the number of field poles). Should a disturbance (such as a fault) persist long enough, the electrical angle will increase until loss of synchronism occurs. The result is that the internal and grid voltages will sweep past each other at a rate equal to the difference between the grid and generator frequencies producing a pulsating current. The magnitude of this current will depend upon the location of the electrical centre of the system and could be potentially greater than a three-phase fault at the terminals of the generator.

The CCT of a generator refers to the time that the unit can feed into a fault (typically based on the assumption of a worst case three-phase fault) that, when cleared, will mark the boundary of stable damped rotor angle oscillations.

Factors Influencing Stability

For a given value of inertia, transient stability can be improved by quickly minimising the difference between P_M and P_E during the disturbance.

Although the governed response of the prime mover may not aid stability on the first swing due to its longer time constants, it may have a beneficial impact on the back and subsequent swings. The performance of the generator automatic voltage regulator (AVR) and excitation system (ES) are critical factors, as fast action and high field voltage ceilings can greatly increase the P_E delivered by the machine.

In addition to the actions of the AVR and ES, increasing the P_E delivered by the machine during disturbances can be achieved by the insertion of an additional resistance within the mainly inductive fault circuit.

SERIES BRAKING RESISTORS

The basic primary system configuration for a SBR is shown in Figure 1 below where the device is effectively switched into circuit between the generator terminals and the network by opening the circuit breaker indicated [3-5].

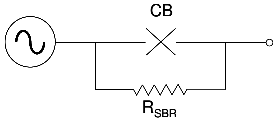

Figure 1: *Series braking resistor configuration.*

The circuit breaker shown above will be rated based on the generator sub-transient reactance to ensure that it can successfully interrupt the current from the machine quickly after fault inception. It is clear that the operation of this device will have to be inhibited for internal faults within the generator owing to the larger current to interrupt in this direction.

The rating of the SBR can be intuitively specified based on the maximum fault clearance time on the network (approximately 1s) and the rating of the machine. A reasonable estimate for the ohmic size of the SBR can be arrived at by assuming initially that a transient reactance of 0.25pu will be used and that rated power of the machine will be dissipated. The fault current from the machine based on a typical 0.25pu transient reactance will limit the fault current to 4pu. Thus based on this fault current, the breaking resistor size would have to be 0.0625pu on the machine base as dictated by (3). Clearly, the presence of the SBR in circuit will reduce the fault current contribution from the generator (in addition to armature reaction) and thus its value can, in fact, be increased from this estimate to more closely match the required power dissipation. Generator protection settings may also have to be reviewed for retrofit applications.

$$P_E = I^2 R_{SBR} \qquad \textbf{(3)}$$

Should the generator not be operating at rated power, it would theoretically be advantageous to match the power dissipated in the SBR to the pre-fault output of the generator such that the stresses on the prime mover shaft can be minimised. This could be achieved by partitioning the SBR and switching it into circuit in stages. A fuller discussion of a potential control scheme for the series breaking resistor is provided in a later section.

SYSTEM MODELS

All models created for this set of studies were built and simulated using PSS/E version 30 [6].

Network Model

The studies reported in this paper are based on the radial suburban network model (EHV3) from the United Kingdom Generic Distribution System (UKGDS) library [7].

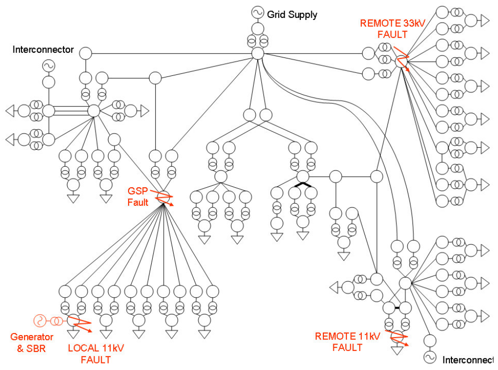

Figure 2: *UKGDS EHV3 – radial suburban network.*

The network is shown in Figure 2 and consists of a mixture of overhead line and cable circuits. Distribution voltages include 11, 33 and 132kV and interconnections can be provided to adjacent 33kV networks.

Generator, Controller & Prime Mover Models

The GENSAL salient pole model is used to represent the synchronous generator (2MVA, H=1.5s) and it is connected to an 11kV busbar using a 0.4/11kV transformer. A gas turbine and governing system is provided by the GAST model. The ESAC5 brushless excitation model has been used and thus field voltage is not directly dependent upon terminal voltage that will be reduced during fault conditions. It has been assumed that this generator will be regulating the voltage at its terminals to meet the requirements of local load.

CASE STUDIES

Three case studies are presented in the following sections that demonstrate potential benefits of a SBR and include typical relaying and circuit breaker opening times. All graphs in the following sections assume a grid reference angle of zero degrees.

Case Study A: 11kV Local & Remote Faults

For this study the generator is operating at close to its maximum output prior to the disturbance, and faults are applied in separate simulations at the local and an electrically distant 11kV busbar for a period of 0.6s. The faults occur at 0.2s and the SBR is switched into circuit at 0.3s to allow for relaying and the operation of the SBR circuit breaker. The SBR is switched out of circuit at 0.86s (to allow for relaying and circuit breaker opening) and the electrical angle response is shown in Figure 3.

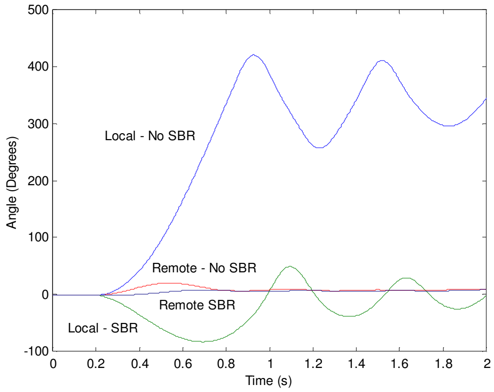

Figure 3: *Case Study A – 11kV Local & Remote Faults – Electrical Angle Response*

The results in Figure 3 above show that the presence of the SBR avoids the pole slipping event for the local case and improves the response during the remote fault by reducing the angle oscillations.

Case Study B: 33kV GSP Fault

For this study the generator is operating at close to its maximum output prior to the disturbance and a fault is applied at the upstream grid supply point (GSP) for a period of 300ms. The fault occurs at 0.2s and the SBR is switched into circuit at 0.3s. The SBR is switched out of circuit at 0.56s and the electrical angle response is shown in Figure 4.

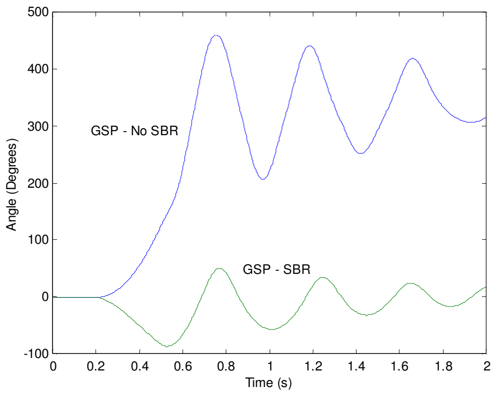

Figure 4: *Case Study B – 33kV GSP Fault – Electrical Angle Response*

The avoidance of transient instability can be observed in Figure 4 above.

Case Study C: 33kV Local Fault with Reduced Loading & Matched SBR

For this study the generator is operating 50% of its maximum output prior to the disturbance and a fault is applied on a remote 33kV circuit for a period of 0.3s. The fault occurs at 0.2s and the SBR is switched into circuit at 0.3s. The SBR is switched out of circuit at 0.56s and the electrical angle response is shown in Figure 5 for both half and full rated SBR (based on generator rating).

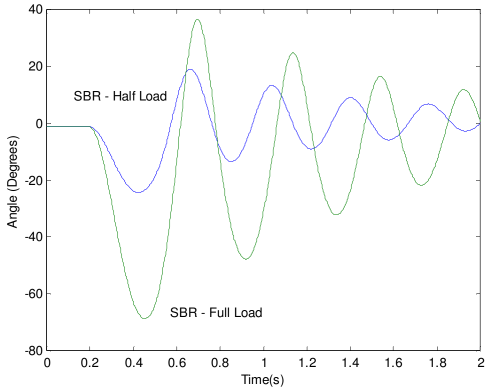

Figure 5: *Case Study C – 33kV Remote Fault with Reduced Loading & Varied SBR Resistance – Electrical Angle Response*

The reduction in angle oscillation is clearly illustrated in Figure 5 and demonstrates the potential of matching the SBR resistance to pre-disturbance loading.

CONTROL SCHEME

A potential control strategy for a SBR is outlined diagrammatically in Figure 6.

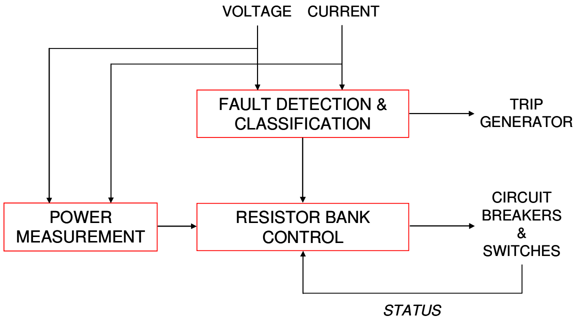

Figure 6: *High level control scheme for SBR.*

Fault Detection & Classification

Fault detection will be based on the actuation of a low-set undervoltage and instantaneous overcurrent elements in conjunction with a directional element to ensure that the SBR is only operated for network faults. A timing element will be triggered on detection of the fault and will be set such that a generator trip (main generator CB, not shown in Figure 1) will be initiated if the network fault is not cleared after a time that is selected to be less than the rating of the SBR. This is in addition to the conventional protection applied as standard to generators.

Resistor Bank Control

Case study C demonstrated that partitioning the resistor and switching sections into circuit according to the pre-fault power output of machine can minimise rotor angle swings and thus reduce shaft stress. A measurement of power from the machine can be used to continually provide the best match of resistance based on the resolution of SBR stages available. This function would be performed at regular intervals and, after fault detection, further switching of individual SBR elements is inhibited.

Removal of the SBR will be initiated by the presence of a healthy network voltage for a period of several cycles. This time has been estimated based on a combination of the need in provide resistive damping of extended rotor swings and to minimise the presence of the SBR in the post-fault period. In terms of the latter restriction, the SBR under normal network conditions will reduce the power that can be delivered from the machine and could potentially require extensive governor action to reduce the mechanical input power from the prime mover.

CONCLUSIONS

This paper has reported on the study of the applying SBR to improve the transient stability of low inertia synchronous distributed generators. The main outcomes of this work can be summarised as follows:

- The application of SBR has a demonstrable and tangible beneficial impact on the transient stability of low inertia synchronous distributed generators.
- The capabilities of modern switchgear and numerical relaying techniques do not present any obvious problems with regard to the construction or the successful application of SBR.
- A control scheme was presented and can be easily implemented on industry standard control platforms.

FURTHER WORK

Further work is currently underway to implement the control scheme outlined in this paper, and to investigate the optimal selection of settings to achieve the best balance between sensitivity and the avoidance of unnecessary operations.

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