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Research Article

A simple optimization logic based on the parameters of the angle between voltage and current and the size of the terminal voltage to protect loss of excitation of synchronous generator

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Extended Abstract:
The reliable and secure operation of synchronous generators, which represent the most critical and capital-intensive assets in a power system, is paramount to maintaining overall grid stability and integrity. Among the various threats to their safe operation, Loss of Excitation (LOE) stands out as a particularly insidious and dangerous fault condition. LOE can be triggered by a multitude of failures, including the inadvertent tripping of the field circuit breaker, malfunctions in the Automatic Voltage Regulator (AVR), or short circuits within the excitation winding itself. If left undetected and unmitigated, an LOE event forces the generator to operate as an induction machine, drawing a significant amount of reactive power (Q) from the grid to sustain its magnetic field. This behavior has severe cascading consequences: it can cause dangerous overheating in the stator windings due to excessive current, induce damaging slip-frequency currents in the rotor, and critically, precipitate a voltage collapse in weak areas of the power system as other generators struggle to meet the sudden, massive demand for reactive support. To prevent this scenario, protective relaying schemes are essential, and for decades, the industry-standard solution has been the impedance-based LOE relay with a negative offset characteristic on the R-X plane. While this method is widely deployed and capable of detecting all forms of LOE, it is plagued by significant operational drawbacks that compromise its effectiveness in modern, dynamic power systems. The primary weaknesses of the conventional impedance relay are its relatively long operating time, which is highly dependent on the generator's loading condition, and its susceptibility to maloperation during stable but transient system disturbances, such as a three-phase short-circuit fault. During such events, the relay's impedance trajectory can inadvertently cross its protective characteristic, leading to the unnecessary and costly tripping of a healthy generator—a scenario that can exacerbate the initial disturbance and lead to widespread outages.

In direct response to these critical limitations, the research by Fatolahi, Moradi, and Rostami proposes a novel, simple, yet highly effective protection logic for detecting LOE in synchronous generators. The core innovation of their approach lies in its elegant simplicity and its foundation on two directly measurable and physically intuitive electrical parameters at the generator terminals: the angle between the terminal voltage and current phasors (θsg) and the magnitude of the terminal voltage (Vsg). The method employs a precise, sequential combinational logic that leverages the distinct and predictable behavior of these two parameters during an actual LOE event versus other benign or transient operating conditions. The protection algorithm initiates its logic by continuously monitoring the power factor angle, θsg. In normal operation, particularly when the generator is operating in an over-excited mode (which is common to support system voltage), this angle is negative, indicating that the current lags the voltage. However, a fundamental shift occurs during an LOE event: as the generator starts absorbing reactive power from the grid, the current begins to lead the voltage, causing θsg to become positive. This sign change serves as the primary trigger for the protection logic. However, the authors astutely recognize that a positive θsg can also occur during normal under-excited operation or as a transient response to a system-side disturbance, such as the connection of a large capacitor bank. To ensure selectivity and prevent false tripping, the method does not rely on this trigger alone.

The second stage of the combinational logic is where the method's robustness is established. Once θsg is detected as positive, the algorithm then scrutinizes the terminal voltage magnitude, Vsg. In a benign

scenario, such as the generator operating stably in an under-excited mode or responding to a system voltage rise, the control system (AVR) will actively adjust the field current to maintain the terminal voltage within acceptable limits, typically keeping it above a threshold of 0.95 per unit (p.u.). The proposed logic interprets this stable or increasing Vsg as a sign of a controlled, healthy system response, and the generator is allowed to continue its operation without intervention. Conversely, during a genuine LOE event, the loss of field control means the AVR is unable to regulate the terminal voltage. As the generator sinks reactive power, the terminal voltage begins to decay. The algorithm is designed to detect this specific condition: a positive θsg coupled with a Vsg that falls below the 0.95 p.u. threshold. The concurrent occurrence of these two conditions is the definitive signature of an LOE fault, and upon its detection, the protection system issues an immediate trip command to isolate the generator, thereby preventing equipment damage and safeguarding system stability. The entire decision-making process is designed with a deliberate and sufficient observation window of 1.6 seconds to ensure stability against noise and transient spikes.

The performance and validity of the proposed protection scheme were rigorously evaluated through a comprehensive set of simulations in the MATLAB/Simulink (2017b) environment. The testbed for these simulations was the IEEE 39-bus standard test system, a well-established benchmark for power system studies that provides a realistic and sufficiently complex network for validation. The evaluation covered a wide spectrum of scenarios to test the method's sensitivity, selectivity, and speed. It was challenged with various types of LOE, including both complete loss of field (where excitation voltage drops to zero) and partial loss (where it is reduced to a fraction of its nominal value). Furthermore, these LOE events were simulated under diverse operating conditions, specifically heavy and light loading, and with the generator initially operating in both over-excited and under-excited states. This thorough testing demonstrated that the proposed logic successfully detected all LOE scenarios with high speed and accuracy, confirming its sensitivity.

Just as critically, the scheme was tested against numerous non-LOE events to verify its security. These scenarios included severe system transients such as three-phase short-circuit faults with both high and low fault impedance, as well as the stable operation of the generator in an under-excited mode. In all of these cases, the combinational logic correctly refrained from issuing a trip command. For instance, during a short-circuit fault, while θsg might become positive, the terminal voltage Vsg typically collapses well below 0.95 p.u. However, because the fault is a system-side event and not a machine excitation failure, the post-fault recovery dynamics are different. The proposed method, through its specific sequential logic and the 1.6-second observation window, was able to distinguish this transient collapse from the sustained voltage decay characteristic of an LOE, thereby maintaining its security.

A direct comparative analysis was also conducted between the proposed combinational logic and the conventional impedance relay. This comparison clearly highlighted the superiority of the new method across all key performance metrics. In terms of speed, the proposed logic was able to identify an LOE event significantly faster than the impedance relay, which often requires multiple cycles to definitively establish its trajectory on the R-X plane. Regarding accuracy and security, the proposed method demonstrated a complete immunity to maloperation during system transients, a weakness that the impedance relay could not overcome. Finally, from a practical standpoint, the proposed method offers a major advantage in simplicity and implementation cost. It requires only basic phasor measurements that are readily available from standard protective relays or Phasor Measurement Units (PMUs) and involves a straightforward logical decision process, unlike the more complex impedance calculation and trajectory monitoring required by the conventional relay.

In conclusion, this research presents a significant practical contribution to the field of power system protection. By introducing a novel, combinational logic that leverages the synergistic behavior of the voltage-current angle and terminal voltage magnitude, the authors have developed a protection scheme that effectively addresses the long-standing deficiencies of the standard impedance relay for LOE detection. The method is not only faster and more secure but is also remarkably simple and cost-effective to implement in existing generator protection systems. The extensive simulation results on a standard test system provide robust empirical evidence of its effectiveness, making it a highly promising and viable solution for enhancing the reliability and resilience of modern power grids against the critical threat of loss of excitation.

Keywords: synchronous generator, loss of excitation protection, impedance relay, power angle, terminal voltage.

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