A New Relaying Algorithm to Detect Loss of Excitation of Synchronous Generators

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Abstract

A new digital relaying algorithm is introduced for the protection of synchronous generators against loss of excitation conditions. The new algorithm is based on measuring of the 3-phase reactive power output of the machines, and monitors the direction and magnitude of leading reactive power at the generator terminal. The protection algorithm is designed such that it can provide reliable protection against loss of field conditions and remains stable during recoverable power system swing conditions. While the new relay produces a trip signal for partial loss of field conditions causing the machine to lose its stability, it remains stable for the partial loss of field conditions that can be corrected via machine excitation and AVR systems.

Key Words: *Digital relaying, generator protection, reactive power, loss of field, capability curve.*

1. Introduction

Following the loss of excitation of a generator operating in parallel with the utility network the machine speed will increase above the synchronous speed, and will start to operate as an induction generator taking its reactive power need from the power system. This may cause severe damage to the generator itself and to the power system to which the generator is connected [1-11], since loss of excitation results in:

- heavy over-loading of the armature windings of the generator,

- induced eddy current in the rotor surface and rotor windings at a slip frequency resulting in a heavy thermal heating in the rotor body.

- large voltage drop in the transmission lines with the possible drop-out of these lines, and loss of system stability.

- loss of the magnetic coupling between the rotor and the stator sides, immediately following the decrease in the magnetic coupling between them.

For these reasons, loss of excitation field of a generator should be detected as fast as possible, corrected if possible or tripping of the affected generator should be done fast enough to prevent any damage to that generator or to the power system as a whole. The primary indicator of possible loss of excitation is the large reactive flow into the generator, which could be detected by an impedance relay [1-3]. Traditionally loss of excitation protection is based on 1 or 2 impedance relays that have operating characteristics of 2 concentric circles. Following the loss of excitation the measured impedance at the generator's terminal falls within the relay's operating characteristics [1-8]. The operation of the relay with the outside operating characteristics is delayed for a second, whereas the tripping occurs more quickly with the inner characteristics.

In spite of excellent experiences of the impedance relay in loss of field detection, it shows a tendency towards recognizing some system disturbances as loss of excitation [6-9]. Therefore it is stated that a new relay is needed that can quickly and effectively distinguish the loss of field [12].

In this paper, a new power based algorithm is introduced to provide protection against loss of field conditions for synchronous machines. The primary objectives of the new algorithm are to detect loss of field conditions and remain stable during other power system faults and disturbances.

2. Generator Reactive Power Output

The reactive power output of a generator can be expressed as [10]:

$$Q_T = 3\left[\frac{E_q.V_t}{x_d}\cos\delta - \frac{V_t^2}{x_d}\right] = Q_F + Q_N \tag{1}$$

where E_q and V_t are generator internal and terminal voltage, respectively, and δ is the angle between them.

This equation shows that the reactive power output of a generator consists of 2 different components. While the first component Q_F is the internally generated reactive power, which is determined by the internal voltage (field current) and the load angle, the second component Q_N is supplied to the generator from the external network. If the above equation is re-arranged, the total reactive power output of the machine would be:

$$Q_T = \frac{3V_t}{x_d}(E_q\cos\delta - V_t) \tag{2}$$

There are 3 different operating conditions of a synchronous generator as the reactive power output of the machine is considered. This can be seen in Figure 1. These conditions are as follows:

- When $(E_q\cos\delta - V_t) > 0$, the reactive power is flowing from the generator to the external network. In this mode the generator is said to be over-excited and operating with a lagging power factor. Operation in this mode is limited by the allowed magnitude of the field current.

- When $(E_q\cos\delta - V_t) = 0$, the total reactive power measured at the machine terminal will be zero. The generator operates at the most convenient operation mode with a unity power factor, while delivering only the active power to the external system. Operation in this mode is limited by allowed armature current.

- When $(E_q\cos\delta - V_t) < 0$, the reactive power is flowing from the external network into the generator. The generator is said to be under-excited, and operating with a leading power factor. Operation in this mode is limited by armature winding heating. Operation of the generator with a leading power

factor is also accompanied by an increase in the load angle δ. This will bring the generator close to its steady-state stability limits as well.

Limitations on the operation of a synchronous generator with a leading power factor can also be analyzed using the machine capability curve. The equation representing the steady-state stability limits or pull-out curve of a synchronous machine [10,11] can be expressed as follows:

$$P_T^2 + \left[Q_T - \frac{V_t^2}{2}\left(\frac{1}{x_s} - \frac{1}{x_d}\right)\right]^2 = \left[\frac{V_t^2}{2}\left(\frac{1}{x_s} + \frac{1}{x_d}\right)\right]^2 \tag{3}$$

where P_T and Q_T are the generator real and reactive power output, respectively, and x_s is the impedance over which the machine is connected to utility supply.
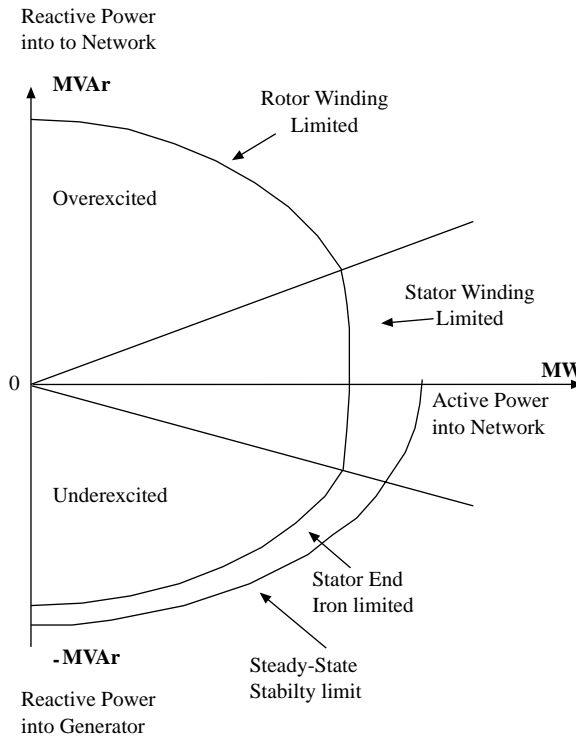

Figure 1. Synchronous generator loading capability curve.

It is well known that this equation represents a circle drawn on the P-Q plane, and crosses the Q–axis twice as seen in Figure 1. These 2 points define the theoretical maximum lagging reactive power and leading reactive power limits. The maximum theoretical reactive power taken from the external network following a loss of excitation condition can be calculated using the above equation:

$$Q_{\max} = -\frac{3V_t^2}{x_d} \tag{4}$$

This can also be seen from Eq. (1). In real life, this condition would not be allowed, since the machine has already lost its excitation and will also lose its stability as seen in Figure 1. The machine should be separated from the system before this condition occurs. The amount of leading reactive power Q_m allowed to operate continuously without being subjected to damage is usually determined from the manufacture's data. As a general practice it is taken as that corresponding to 0.95 leading power factor based on the generator's rating [10,11].

3.   A New Algorithm to Detect Loss of Excitation

When the generator loses its excitation as a result of short-circuited or open-circuited field winding, the field current will ultimately decay exponentially to zero with a decaying time constant of field circuit. The internally generated reactive power Q_F will also decay to zero with the same time constant, since it is dependent only on the field current of the generator. Whenever this power decreases to a level that is equal to Q_N in magnitude, the reactive power Q_T measured at the machine terminal starts to reverse its direction. This can be used to detect loss of excitation of a synchronous generator.

Measurement of Generator Reactive Power Output: The new protection algorithm firstly measures the 3-phase instantaneous reactive power at the generator terminal as follows [13,16]:

$$Q(n) = \frac{1}{\sqrt{3}} \left[v_a(n)(i_b(n) - i_c(n)) + v_b(n)(i_c(n) - i_a(n)) + v_c(n)(i_a(n) - i_b(n)) \right] \tag{5}$$

Eq. (5) is valid under any power system operating condition that is either in 3- or 4-wire systems, in transient or steady-state, in balanced or unbalanced conditions, or considering sinusoidal or non-sinusoidal conditions. More discussion about Eq. (5) can be found in reference [16].

The algorithm then computes the moving average of the instantaneous reactive power over a defined time period using:

$$Q_{ta} = \frac{1}{N} \sum_{n=0}^{N-1} Q(n) \tag{6}$$

where N is the sampling number, n is the sampling instant, and v_a, v_b, v_c, i_a, i_b, and i_c are the sampled values of instantaneous voltages and currents, respectively.

The moving average process is used to remove the high frequency terms and smooth the reactive power output of the generator to produce a more reliable output of the algorithm. This process also provides immunity against unbalanced operation of power systems [14], since the unbalance operation will produce sinusoidal oscillations in reactive power output of the generator at twice the power system frequency. This filtering process removes these oscillations as well [15]. The length of moving windows, i.e. the number of samples used in the moving windows, determines the trip time of the relay together with the magnitude of the leading reactive power and generator initial condition.

Trip Criteria for Loss of Field Protection: Following the measurement of reactive power output, the proposed algorithm checks the direction of reactive power flow at the machine terminal. As long as the reactive power output $Q_{ta} > 0$, the machine is delivering reactive power to the external system, whereas $Q_{ta} = 0$ shows that the machine is operating with a unity power factor. The algorithm does not response to these conditions.

Whenever Q_{ta} becomes negative, this means that the generator is taking some of its reactive demand from the external network. Then, the new algorithm responses according to the magnitude of leading reactive power Q_{ta}.

- If the imported reactive power is within the allowed leading operation limit Q_m, the algorithm may produce an alarm signal only to inform the operator. The maximum allowable reactive power corresponding to 0.95 leading power factor can be calculated as:

$$Q_m = (\sqrt{1 - (0.95)^2}) MVAr \tag{7}$$

- If the magnitude of this imported reactive power is greater than a pre-defined value, the algorithm will immediately produce a trip signal for the generator tie-breaker and field breaker. From the machine steady-state stability (pull-out) curve the magnitude of the leading reactive power at which the machine should be tripped [17] before losing its stability is usually taken in the range of

$$Q_t = (0.6 - 0.75)^{Q_{\max}} \tag{8}$$

- If the imported reactive power is somewhere between the trip value Q_t and the maximum allowable leading power Q_m, then a time delay is introduced allowing enough time for a correcting action to be taken. If no action is taken within a certain specified time, the relay will initiate a trip signal to remove the generator from service. This time delay could be inversely proportional to the reactive power being imported.

Under no loss of field conditions, as the load angle increases for some reasons, the load angle dependent term of reactive power decreases as seen in Eq. (1). This term will be zero, when the load angle reaches to the steady-state stability limits of $90°$. If the machine does not recover, it is expected that the algorithm will produce trip signal before the machine loses its stability. During the recoverable power swings, the generator load angle δ excites 90 electrical degrees and returns, and the reactive power output oscillates by changing its direction. It is also expected that the moving average process and time delay of the algorithm will prevent the tripping for stable power swings.

Although the proposed algorithm is designed to detect full loss of field conditions, it is expected that it will also detect partial loss of field conditions as long as a partial loss of field condition, i.e. a short-circuit in the field windings, causes the machine to import reactive power more than the trip value. The response of the algorithm to a partial loss of field condition depends on the amount of the short-circuited field windings and the AVR response.

4.   Computer Simulation Studies

Extensive computer simulation studies have been undertaken to examine the performance of the new algorithm for different loss of excitation conditions. The system simulated has a 991 MVA generator with a terminal voltage of 24 kV and is connected to the utility power system over a step-up transformer as seen in Figure 2. The simulated system parameters including the excitation system and the automatic voltage regulator are given in the Appendix. A test period of 3 s was chosen, starting 100 ms before loss of excitation. Required signals, 3-phase currents and voltages to represent the loss of field conditions, are produced at the generator terminal using the EMTP simulation program.

Figure 3 shows the system response to a loss of field condition. Before the loss of field, the machine is operating at full load with a 0.8 lagging power factor. The machine field current and the rotor angle are illustrated in Figures 3a and 3b, respectively. The algorithm output based on generator reactive power output is seen in Figure 3c. Following the loss of field generator, reactive power output starts to decrease according to the machine field winding constant; then it changes direction and reaches the trip level Q_t after 1.12 s before the machine loses its stability.

System response to a loss of field condition is shown in Figure 4. Before the loss of field, the machine is operating at full load with a unity power factor. Following loss of field the machine field current and the rotor angle are seen in Figures 4a and 4b, respectively. The new algorithm detects this event and initiates a trip signal after 0.460 s as seen in Figure 4c.
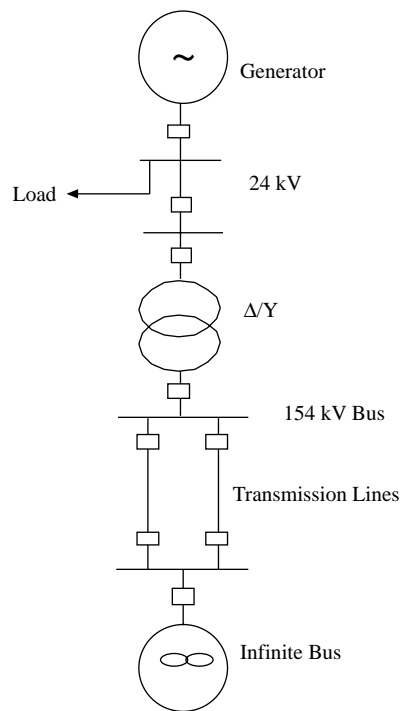
Figure 2. Power network used for loss of excitation studies.
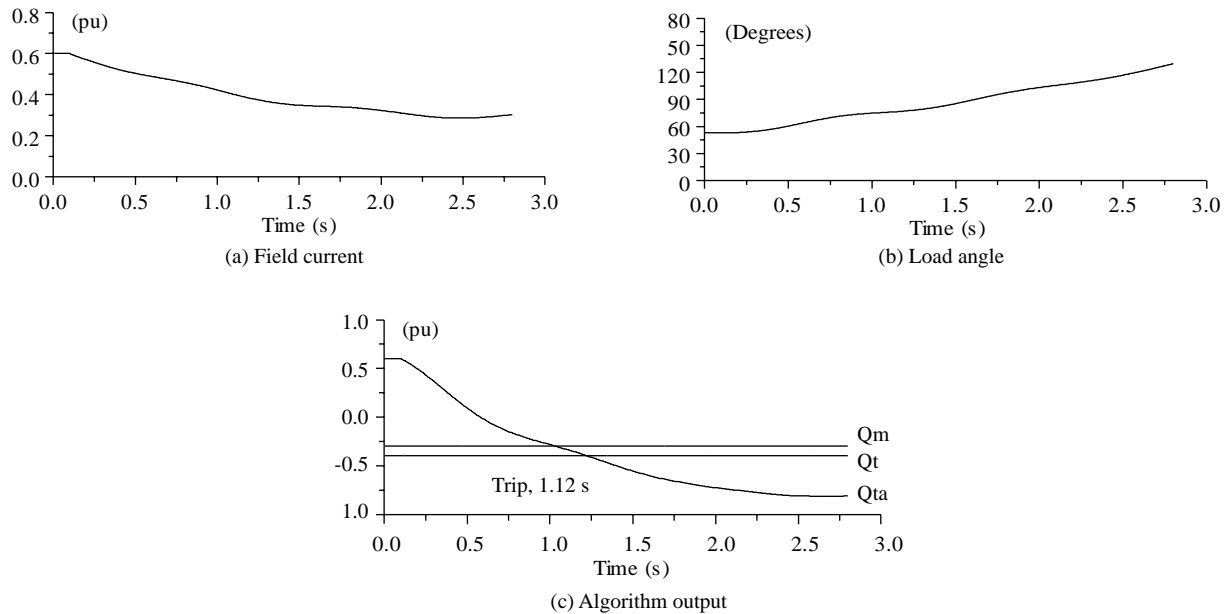

Figure 3. Loss of field at full load with 0.8 lagging power factor.

The response to another loss of field condition is seen in Figure 5. While the generator is operating at 50% loading with a 0.8 lagging power factor, the machine loses its excitation. The proposed algorithm detects this condition and produces a trip signal after 0.816 s.

The response to a different loss of field condition is seen in Figure 6. Immediately before the loss of excitation, the machine was lightly loaded with about 10% of the rated capacity. The proposed algorithm detects this condition and produces a trip signal after 0.624 s as seen in Figure 6c.
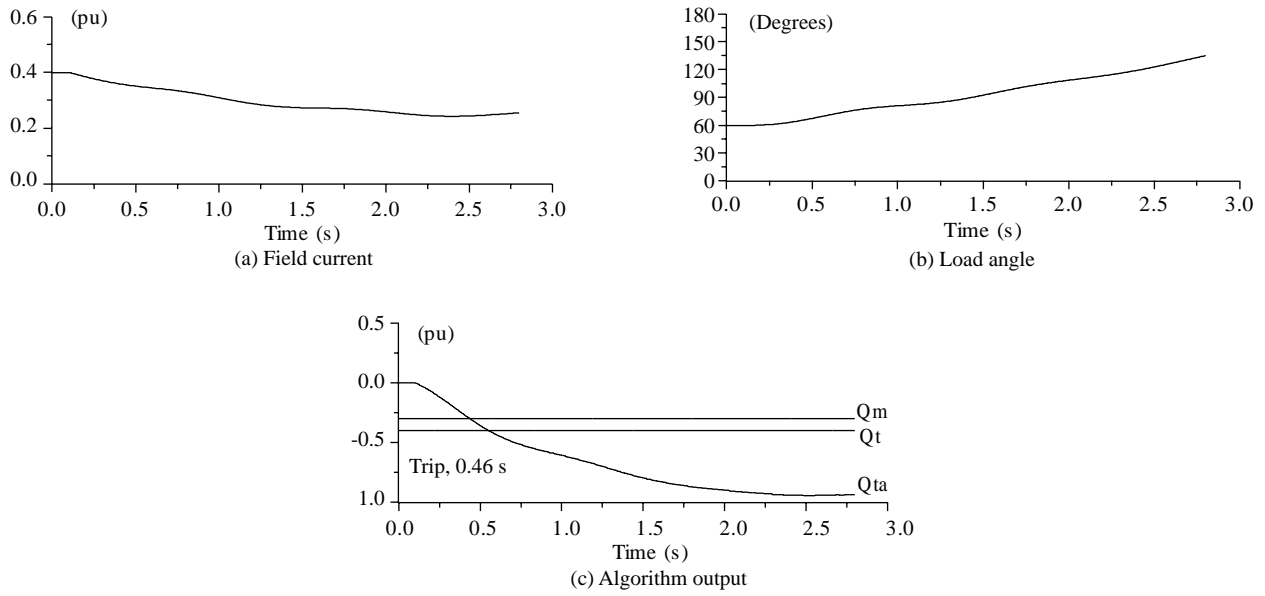
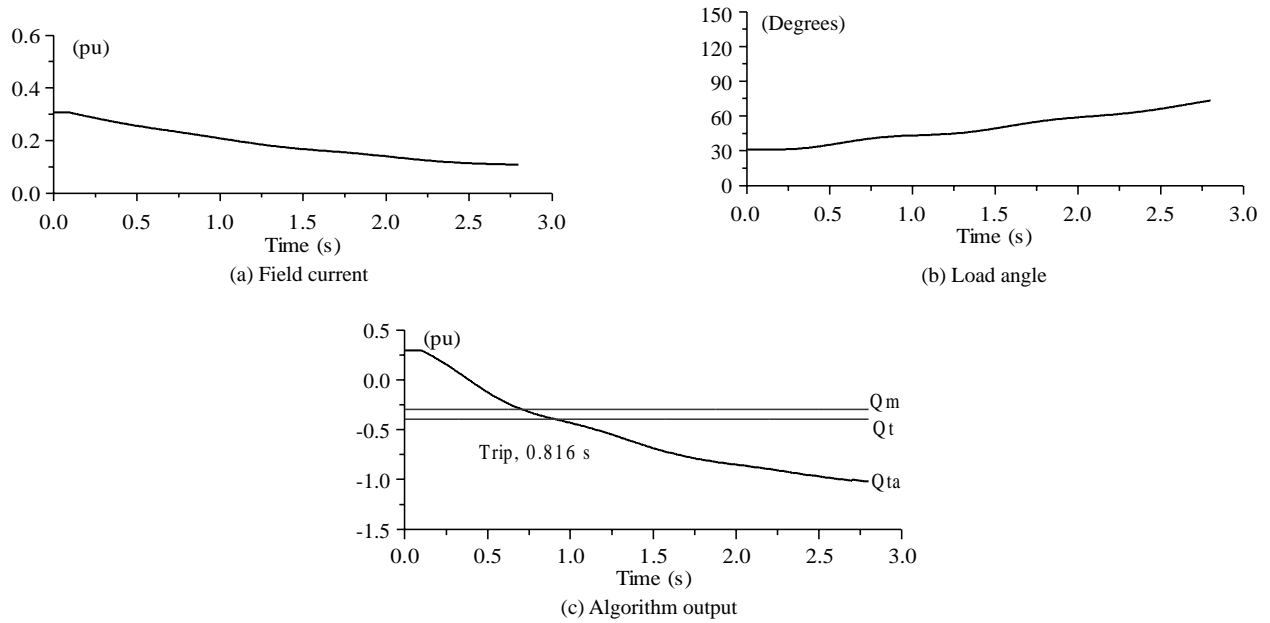**Figure 4.** Loss of field at full load with unity power factor.

Figure 5. Loss of field at 50% load with 0.8 lagging power factor.

The algorithm performance following a partial loss of field condition is illustrated in Figure 7. Immediately before the loss of field resulting from the short-circuit of 50% of the field windings, the machine is operating at full load with a 0.8 lagging power factor. Following the short-circuit in the field windings, the machine tries to recover by increasing its excitation current using the AVR. The algorithm output just produces a trip signal around 1.65 s following the partial loss of field.

This indicates that the new algorithm detects the partial loss of field conditions provided that 50% or more of the field windings are short-circuited. As stated before, the algorithm response to partial loss of excitation conditions is determined by the excitation circuit, AVR system parameter, and the magnitude of the imported reactive power due to the short-circuit in the field winding.
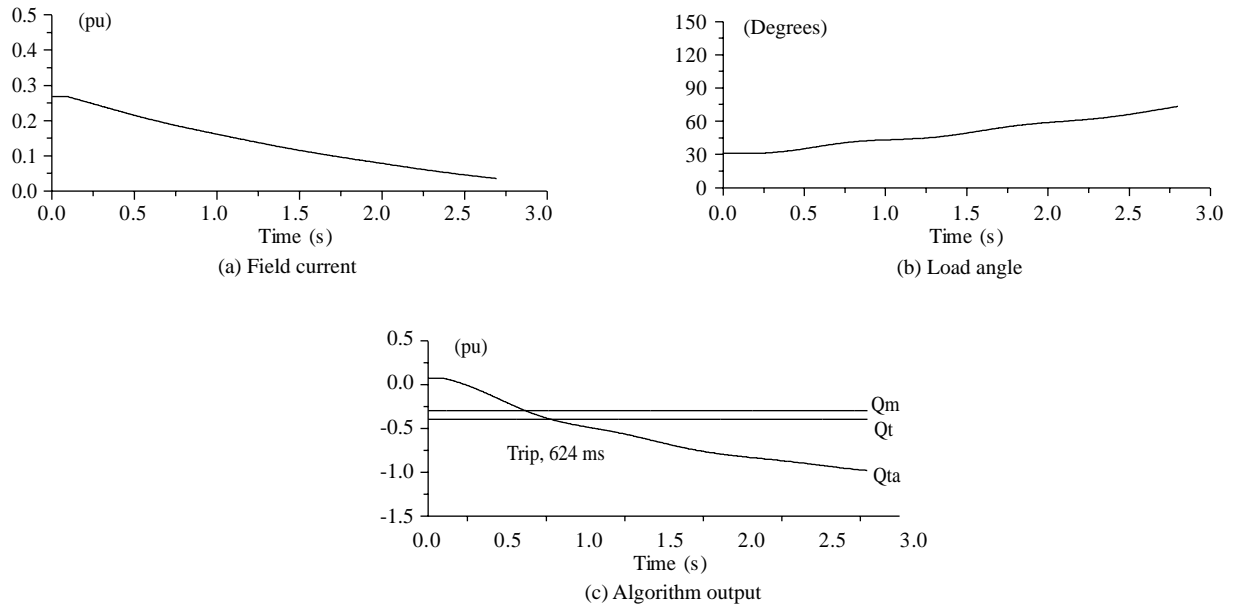

(a) Field current

(b) Load angle

(c) Algorithm output

Figure 6. Loss of field at 10% load with 0.8 lagging power factor.

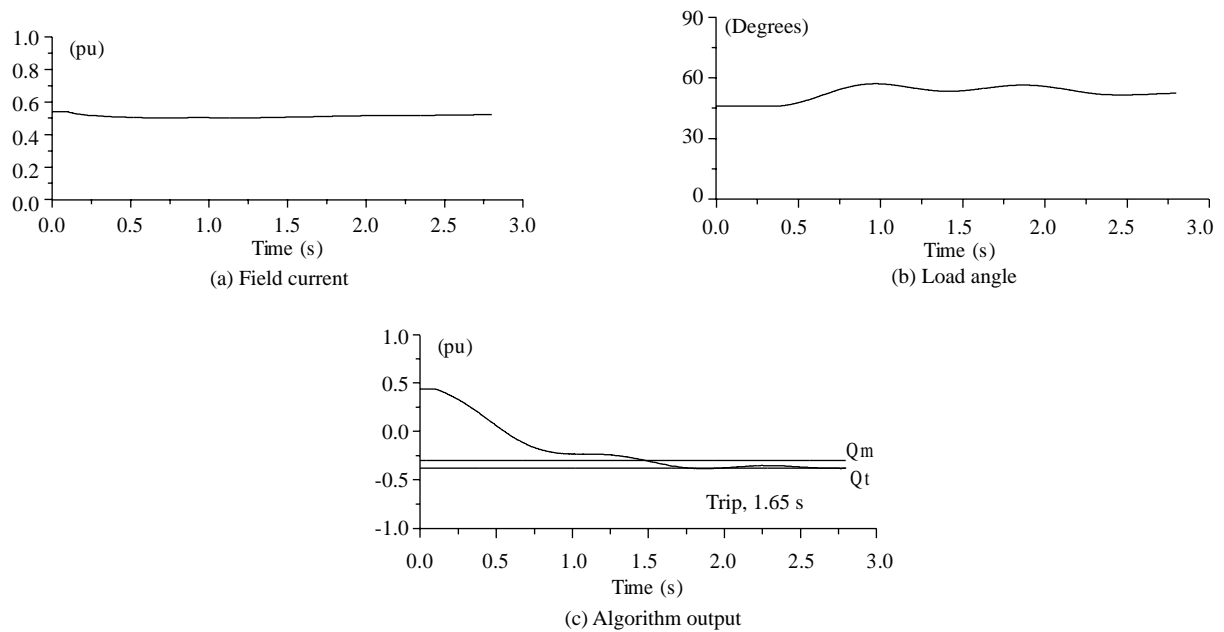(a) Field current

(b) Load angle

(c) Algorithm output

Figure 7. Partial loss of field with 50% of field windings short-circuit.

The response of the proposed algorithm to a severe power disturbance is illustrated in Figure 8. A 3-phase fault is created in the middle of one of the parallel transmission lines shown in Figure 1. The fault is

cleared approximately 0.5 s after the fault. Then the circuit breaker close to the high voltage bus is re-closed after 1.5 s following the clearing process. The field current, load angle, and instantaneous reactive power output of the generator are seen in Figure 8a, 8b, and 8c, respectively. Although Figure 8c shows that the machine reactive power changes direction during power oscillations, the algorithm output does not produce a trip signal and remains stable due to the time delay and moving average process as seen in Figure 8d as expected.
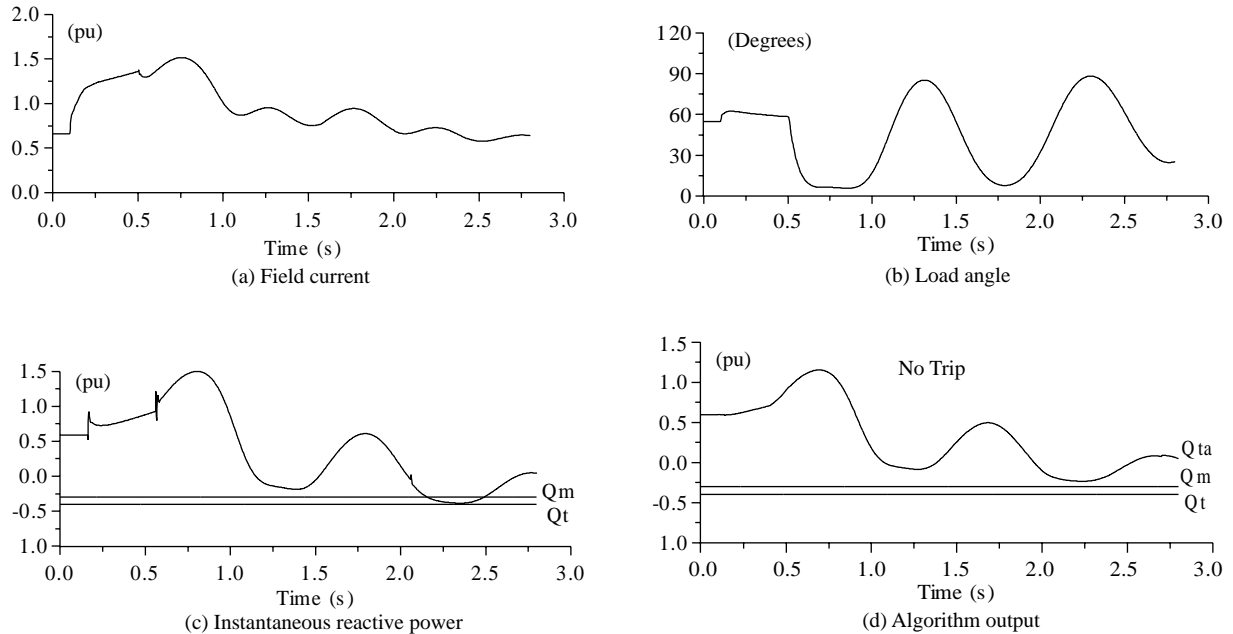

(a) Field current

(b) Load angle

(c) Instantaneous reactive power

(d) Algorithm output

Figure 8. Re-closing after fault clearing following a 3-phase fault.

5. Conclusion

This paper introduced a new loss of field protection algorithm using the generator reactive power output and its pull out curve. The work presented in this paper includes the theoretical background and design of the new protection algorithm and performance analysis of the algorithm using well known EMTP Power System Simulator. It is accepted that short term and long term real-time testing of the proposed algorithm requires more hardware work and it is not the subject of this paper.

Computer simulation studies presented show that the new relaying algorithm provides effective and reliable protection against loss of field conditions and remains stable for the recoverable power system swing conditions. The proposed algorithm detects loss of field events within 1.12 s. The algorithm also detects the partial loss of field conditions before the machine loses its stability. The algorithm does not response to partial loss of field conditions as long as the AVR can increase the field current enough to correct the situation. The trip time of the algorithm is determined by the magnitude of the leading reactive power, the length of the mowing window, and the operating point of the machine on the P-Q plane before the loss of excitation event.

Since the relay inputs, 3-phase current and voltage signals, are also required for the other protection algorithms for the generator, the proposed algorithm can easily be integrated into a multi-functional microprocessor-based relay without changing the relay hardware.

Acknowledgments

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APPENDIX

Generator parameters:

Rated voltage: 24 kV
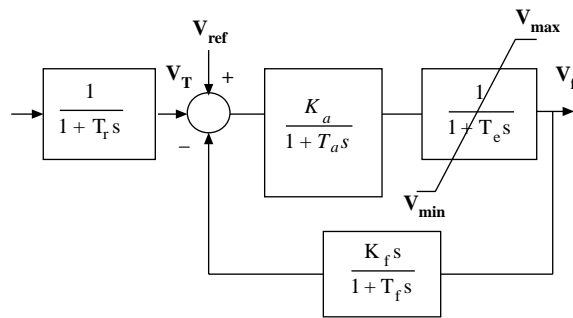
Rated power: 991 MVA at $\cos\varphi = 0.8$

Rated excitation current: 1640 A

$x_d = 1.15$ pu, $x_q = 0.685$ pu, $x_d\prime = 0.31$ pu, $x_q\prime = 0.68$ pu, $x_d = 0.21$ pu, $x_q = 0.182$ pu

Transformer rated power: 1300 MVA

For each transmission line: r = 4.74 ohm, x = 21.34 ohm.

Automatic Voltage Regulator:

$K_a = 250$	$T_a = 0.05$	$V_{min} = -9.6$
$K_f = 0.04$	$T_f = 0.8$	$V_{max} = 9.6$
$T_e = 0.04$	$T_r = 0.015$	