**İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY**



# DESIGN OF A NEW DIGITAL RELAYING ALGORITHM FOR A GENERATOR PROTECTION AGAINST LOSS OF FIELD

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**Date of submission : 20 April 2001**

**Date of defence examination: 15 Fabruary 2002**

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**FEBRUARY 2002**

**ACKNOWLEDGEMENT**

I would like to acknowledge my supervisor Dr. Omer Usta for his valuable suggestions, continued encouragement, and understanding. Without his help and guidance this work wouldn't be done. Also I'm grateful to my friend Dr. Mehmet Bayrak for his assistance during my study.

I would like to express my deep thanks to the Electrical Engineering Department of Istanbul Technical University for all the facility they provide to me during my study.

Also I would like to tank my government [LIBYAN GOVERNMENT] for their financial support during my study.

February 2002 Mahmud Hasen **MUSA.**

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**LIST OF SYMBOLS**

$t$ : Time in sec.

$i_a, i_b, i_c,$ : Phase currents in Amp.

$i_a(n), i_b(n), i_c(n)$ : Sampled phase currents in Amp.

$i_a^*, i_b^*, i_c^*$ : Conjugate of phase currents in Amp.

$I_a, I_b, I_c$ : $RMS$ phase currents in Amp.

$\vec{I_a}, \vec{I_b}, \vec{I_c}$ : Phasors of phase currents in Amp.

$i_d, i_q, i_0$ : Park's transformed instantaneous currents in Amp.

$I_d, I_q, I_0$ : Park's transformed average currents in Amp.

$i_f$ : Instantaneous field current in Amp.

$I_f$ : Average field current in Amp.

$i_D, i_Q$ : Instantaneous current in damper windings Amp.

$[i]$ : Current vector (6 x 1)

$v_a, v_b, v_c$ : Phase voltages in volts.

$v_a(t), v_b(t), v_c(t)$ : Instantaneous phase voltages in volts.

$v_a(n), v_b(), v_c(n)$ : Sampled phase voltages in volts.

$V_a, V_b, V_c$ : $RMS$ phase voltages in volts.

$\vec{V_a}, \vec{V_b}, \vec{V_c}$ : Phasors of phase voltage in volts.

$v_d, v_q, v_0$ : Park's transformed instantaneous phase voltages.

$V_d, V_q, V_0$ : Park's transformed average phase voltages.

$v_f$ : Instantaneous field voltage.

$V_f$ : Average field voltage.

$[v]$ : Voltage vector (6 x 1).

$\lambda_a, \lambda_b, \lambda_c$ : Flux linkages of stator phases.

$\lambda_f$ : Flux linkages of field winding.

$\lambda_D$ : Flux linkages of d-axis damper winding.

$\lambda_Q$ : Flux linkages of q-axis damper winding.

$[\lambda]$ : Flux linkage vector (6 x 1).

$L_{aa}$ : Self-inductance of phase ($a$) in Henrys.

$L_{bb}$ : Self-inductance of phase ($b$) in Henneries.

$L_{cc}$ : Self-inductance of phase ($b$) in Henrys.

$L_{ff}$ : Self-inductance of field winding in Henrys.

$L_{DD}$ : Self-inductance of d-axis damper winding H.

$L_{QQ}$ : Self-inductance of q-axis damper winding H.

$L_{ab} = L_{ba}$ : Mutual inductance between phases ($a,b$).

$L_{ac} = L_{ca}$ : Mutual inductance between phases ($a,c$).

$L_{bc} = L_{cb}$ : Mutual inductance between phases ($b,c$).

$L_{fD} = L_{Df}$ : Mutual inductance between field wdg. & D-wdg.

$L_{af} = L_{fa}$ : Mutual inductance between field wdg. and phase *a*.

$L_{bf} = L_{fb}$ : Mutual inductance between field wdg. and phase *b*.

$L_{cf} = L_{fc}$ : Mutual inductance between field wdg. and phase *c*.

$L_{aD} = L_{Da}$ : Mutual inductance between D-wdg. and phase *a*.

$L_{bD} = L_{Db}$ : Mutual inductance between D-wdg. and phase *b*.

| | |
|---|---|
| $L_{cD} = L_{Dc}$ | : Mutual inductance between D-wdg. and phase *c*. |
| $L_{aQ} = L_{Qa}$ | : Mutual inductance between Q-wdg. and phase *a*. |
| $L_{bQ} = L_{Qb}$ | : Mutual inductance between Q-wdg. and phase *b*. |
| $L_{cQ} = L_{Qc}$ | : Mutual inductance between Q-wdg. and phase *c*. |
| $L_s$ | : Constant inductance H. |
| $L_m$ | : Constant inductance H. $L_m < L_s$. |
| $L_D$ | : Constant inductance H. |
| $L_Q$ | : Constant inductance H. |
| $M_R$ | : Constant inductance H. |
| $L_d$ | : d-axis inductance in H. |
| $X_d$ | : d-axis reactance in Ohms. |
| $L_q$ | : q-axis inductance in H. |
| $X_q$ | : q-axis reactance in Ohms. |
| $L_0$ | : Zero axis inductance in H. |
| $X_0$ | : Zero axis reactance in Ohms. |
| $L_n$ | : Inductance between neutral point and ground. |
| $[L]$ | : Inductance matrix (6 x 6). |
| $[L_{ss}]$ | : Stator's inductance matrix (6 x 6). |
| $[L_{rr}]$ | : Rotor's inductance matrix (3 x 3). |
| $[L_{sr}]$ | : Stator to rotor mutual inductance matrix (3 x 3). |
| $[L_{rs}]$ | : Rotor to stator mutual inductance matrix (3 x 3). |
| $r$ | : Resistance of armature windings/phase in Ohms. |
| $r_f$ | : Resistance of field winding in Ohms. |
| $r_D$ | : Resistance of d-axis damper winding in Ohms. |
| $r_Q$ | : Resistance of q-axis damper winding in Ohms. |
| $r_n$ | : Resistance between neutral point and ground . |
| $[R_s]$ | : Matrix of stator resistance. |
| $[R_r]$ | : Matrix of rotor resistance. |
| $P$ | : Active power in watts. |
| $P_a, P_b, P_c$ | : Active power in phases *a, b, c* respectively. |
| $P_t$ | : Total active power in watts. |
| $Q$ | : Reactive power in *VARS*. |
| $Q_t$ | : Total reactive power in *VARS*. |
| $Q_a, Q_b, Q_c$ | : Reactive power in phases *a, b, c* respectively. |
| $Q_g$ | : Internally generated reactive power in *VARS*. |
| $Q_s$ | : System supplied reactive power in *VARS*. |
| $Q_m$ | : Maximum allowed leading reactive power. |
| $S_t = Q_R$ | : Total apparent power in *VA*. |
| $S$ | : Trip value of the new relay in *VARS*. |
| $f$ | : Frequency in Hz. |
| $f_1$ | : Fundamental frequency in Hz. |
| $f_s$ | : Sampling frequency in Hz. |
| $N$ | : Number of samples per cycle. |
| $\omega$ | : Radian speed in rad/sec. |
| $\omega_1$ | : Fundamental radian speed in rad/sec. |
| $\delta$ | : Rotor load angle (torque angle) in degrees. |
| $\theta$ | : Angle between d-axis and axis of phase *a* in degree. |
| $\varphi$ | : Load angle in degrees. |

| | |
|---|---|
| $\chi_{0dq}$ | : Rotor referred variables of stator windings. |
| $\chi_{abc}$ | : Stator referred variables of Park's rotor variables. |
| $\boldsymbol{P}$ | : Park's transformation matrix. |
| $\boldsymbol{P}^{-1}$ | : Inverse of Park's transformation matrix. |
| $\boldsymbol{P}^{t}$ | : Transpose of Park's transformation matrix. |
| $\boldsymbol{U}$ | : Identity matrix. |

## SUMMARY

The object of this thesis is to develop a new digital-relaying algorithm for the protection of the generator in case of loss of its field current. In order to establish this goal the following steps are followed:

- Firstly a study of the main protection requirements of an electric generator was done in order to form a common understanding about the most essential protection devices used for this purpose. Loss of field protection of a synchronous generator was given more attention, with special concentration on the disadvantages of the conventional relaying method based on the application of a mho distance relay.

- Secondly a study of the operational characteristics of the generator during steady and transient states were done. These studies focus on the reactive power output from the generator, and its characteristics during loss of field.

- Thirdly attention is directed to the study of the traditional method used to protect generators in case of loss of field with concentration on its disadvantages in order to overcome them in the planned new relaying algorithm. The traditional method uses an offset mho distance relay, which measures the impedance of the generator seen at its terminals and compares it to the setting values of the relay.

- Then the new algorithm based on the direction of the reactive power flow through the generator was introduced. This algorithm measures the moving average of the total reactive power output of the generator over a complete cycle of the system frequency and compares it to its setting values.

- In the last section a computer simulation study was performed on a representative power system to test the response of this new algorithm for actual loss of field, and for other abnormal operating conditions.

- Finally a collection of conclusions and suggested recommendations were given at the end of this thesis.

**ÖZET**


Bu tezde, generatörleri uyarma alanı kaybına karşı korumak için yeni bir dijital koruma algoritması geliştirilmiştir. Bu amaç doğrultusunda aşağıdaki adımlar izlenmiştir:

- İlk olarak generatörlerin arızalara karşı başlıca koruma ihtiyaçları, bu amaçla kullanılan koruma araçları incelenmiştir. Ayrıca klasik alan kaybı algılama teknikleri ve bunların üstünlükleri ve eksiklikleri incelenmiştir.

- Daha sonra generatörlerin sürekli ve geçici hallerdeki çalışma karakteristikleri incelenmiştir. Bu çalışmalarda generatörlerin reaktif güç üretimleri ve alan kaybı sırasındaki karakteristikleri üzerinde yoğunlaşılmıştır.

- Generatörlerde alan kaybı sırasında kullanılagelen geleneksel empedans izleme yöntemi incelenmiş, bu yöntemin üstünlükleri ve zayıflıkları açıklanmıştır.

- Daha sonra generatörün ürettiği reaktif gücün değerini ve yönünü izleyerek, alan kaybını algılayan yeni bir dijital koruma algoritması geliştirilmiştir.

- Bu yeni algoritmanın uyarma alanı kaybı arızalarına ve güç sistemlerinde görülen diğer arızalara cevabının test edilmesi için örnek bir güç sisteminde simulasyon calışmaları yapılmıştır.

- Son olarak tez ile ilgili sonuçlar ve öneriler tartışılmıştır.

# 1.THESIS INTRODUCTION

## 1.1 INTRODUCTION

During its operation, the utility power system will be subjected to different abnormal operating conditions as well as different faults resulting from internal causes such as operational errors, accidental load rejections, accidental transmission line faults, wrong synchronisation, etc., and external causes such as lightening strokes on transmission lines, external accidents, etc. In order to keep the continuity of electric supply to all consumers, the safe operation of the power system components, and good economic investment in the system it will be necessary to provide a reliable protection devices to guard against these abnormal conditions.

A very important component of any electric power system is the electric generator, which is used to generate the electric energy by changing other energy forms such as heat energy into electrical one. Electric generators constitute a very important part in the over-all initial cost of the èlectric power system, as well as they usually operate continuously over a long period of time (may be for years) at their rated loads. For these reasons a fast, reliable, secure, and accurate protection devices must be provided to them to safe guard against any abnormal conditions.

## 1.2 AIM OF THE THESIS

The main object of this thesis is to develop a new digital relaying algorithm based on the direction of flow of the total reactive power output from the concerned generator for generator protection in case of loss of its field current. This new algorithm should reliably detect all actual loss of field cases at all loading conditions of the generator, fast enough before any damage can occur to the affected generator, or to the power system.

The excitation field current of a synchronous generator is a dc current supplied to the field winding of the generator, which is mounted on the rotor in two ways:

- Through carbon brushes sliding on copper slip rings mounted on the rotating shaft of the generator and insulated from it. In this case the excitation source is usually an external dc generator or a chargeable battery bank. This method of excitation is usually used with low rating generators, and has the disadvantage of possible carbon brush wear, and the need to replace these carbon brushes from time to time, which will result in removing the concerned generator from service.

- Through rotating rectifiers mounted on the shaft of the generator. In this case the excitation source is an alternating current generator with its armature winding mounted on the shaft of the generator, and connected to the rectifier. This method is used with most of the modern synchronous generators specially those with high ratings. This method overcomes the use of sliding carbon brushes, and their operational problems.

To complete this study a collection of the most important protection requirements of a generator are studied in chapter one. A study of the operational characteristics of the generator was done in chapters three with focus on its steady state reactive power flow. A study of the traditional method used for the protection of the synchronous generator against loss of excitation field current was given in chapter four. The traditional method was based on the application of an offset mho distance relay placed at the generator terminals, and measures the impedance seen at these terminals [1,2,3,4,5]. When the measured impedance falls within the operating characteristics of the relay a trip signal is produced. The main disadvantage of this relay is its possible operation during recoverable power swings [5], which will result in an unnecessary removal of the generator.

The new relaying algorithm is introduced in chapter five. This algorithm is based on measurement of the three-phase reactive power output at the generator terminals.

In chapter six, computer simulation studies were performed on this new relaying algorithm. In this study the concerned generator was connected to a power system, and a number of different abnormal operating conditions were applied to it including external faults, and actual loss of field current.

In chapter seven a collective conclusion, and recommendation for possible future work was given.

# 2. GENERATOR PROTECTION REQUIREMENTS

## 2.1 INTRODUCTION

During operation of the power system, sometimes we have to compromise between continuity of supply to the consumer, and the risk of damage allowed to the components of the power system. This means that either we have to remove the faulty component in the power system (such as the generator) from service for any abnormal operating condition, (so that no damage to these components is allowed) or we can keep the continuity of supply even if severe damage to these components (the generator) took place.

Protection devices are used in power systems to remove the faulty equipment from service as fast as possible in order to limit damage to that equipment, hazards to personal, and interruption to the continuity of supply. These protection devices should be able to detect the fault or the abnormal operating condition fast enough before any damage of operating equipment took place, yet slow enough to allow external transients to be by-passed.

In this chapter a brief description of the most important relaying devices used to protect electric generators are described, while in the following chapters attention will be directed to specific relaying devices used to protect the generator in case of losing its field current.

## 2.2 PROTECTION REQUIREMENT OF A GENERATOR

During normal operation of the electric generator, it may operate under abnormal operating conditions such as over-loading, faults (internal or external to the generator), over/under voltage, over/ under frequency, etc. [1,2,3,6,7,8]. Some of the most important protection requirements are given below

### 2.2.1 Protection Against Over-loading Conditions

When currents flowing in both the stator and the rotor windings are more than normal rated currents as a result of heavy over-loading of the generator or due to faults inside or outside of the generator, the heat generated by this over-loading condition could be extremely dangerous, and could destroy the winding insulations, or subject them to severe deterioration. This over-loading operation shouldn't be allowed for a long period of time, and the heat generated by it should be removed as fast as possible. This over-loading condition could be detected by over-current relays, or by over-heat sensors placed at different places in the generator stator and rotor bodies [8,9,10,81].

### 2.2.2 Protection Against Unbalanced Conditions

Operation of the generator under unbalanced loading of its phases will generate negative sequence currents in the stator windings. These currents will induce large alternating eddy currents at double the generator fundamental frequency in the rotor surface and rotor windings. These currents when exceed the allowable magnitude of the negative sequence current that could flow through the generator, and/or when they were left to flow for a long period of time could destroy the rotor as a result of the large heat generated in it, and the mechanical vibrations produced in the rotor and stator bodies. Protection against unbalanced operation could be provided by over-current relays operated by the negative sequence current flowing through the generator [11,12] or by the application of the power based digital relay used to protect against unbalanced conditions [81].

### 2.2.3 Protection Against Over/Under Voltage Condition

Operation of the generator at higher than normal voltage levels (over its rated voltage) will result in increased core losses due to the increased flux density at this high voltage. Also this operating condition requires large excitation current, and so excessive thermal loading of the field winding. For this reason operation of the generator at more than its normal voltage shouldn't be allowed for long period of time. Also operation of the generator at lower voltage levels are not allowed since they decrease the output power delivered by the generator as well as they require an increase in the generator speed in order to keep the generated voltage constant.

This operating condition of under/over voltage could be detected by voltage relays used to respond to any increase in the generator's voltage more than normal value, or by over-current relays used to respond to any increase in the field current of the generator more than its normal value [13,14].

### 2.2.4 Protection Against Over/Under Frequency Condition

Any decrease in the generator's frequency will require an increase in the generator's flux, in order to maintain its voltage constant at its rated value. This increase in generator's flux will result in increased iron core losses, increased field current and possible saturation of the magnetic material of the generator. For these effects operation of the generator at under normal frequency shouldn't be allowed. Over/under frequency relays are used for this purpose to provide protection against any increase or decrease in generator frequency [1,2,3,4].

### 2.2.5 Protection Against Motoring Operation

Operation of the generator in motoring mode specially when operating at no-load, will result in severe damage to the mechanical side of the generator (turbine blades, and ducts) due to the large heat produced in them. So motoring operation should be avoided under all conditions.

Motoring operation could be detected by a reverse power relays placed at the generator's terminals, and set to operate for any reversed power above the setting values flowing back to the generator [59].

### 2.2.6 Generator Winding Protection

Transients and faults that will result in heavy armature currents, which could lead to possible damage of the generator windings and their insulation could be due to

- Error in synchronisation of the generator to the power system.
- Lightning strokes on the transmission lines.
- Short circuits on transmission lines.
- Short-circuits and faults within the generator itself.

These faults will produce sudden drastic increase in armature currents, and mechanical shock to the mechanical part of the generator. For these reasons these faults should be early detected, cleared as fast as possible to limit damage to equipment, and interruption of power supply.

Differential relays are used for this purpose [8,10,15]. Differential relays are the most effective and sensitive devices used in detecting multi-phase internal faults. Their operation depend upon comparison of the current entering in and current leaving out of the generator windings. In normal operation these two currents will be nearly equal, and no tripping signal is produced by the differential relay. While in case of internal faults, the difference between in and out currents is very large, and tripping signal proportional to the difference between these two currents is produced. However they have the following disadvantages:

- For heavy external faults (as near-by faults); some of the current transformers used with differential relays may get saturated, such that they produce no output signal. This condition will be recognized by the differential relay as an internal fault, and will result in an unnecessary removal of the generator from service.

- When generators are grounded through high resistance to limit the magnitude of ground fault currents, and to provide safety for operating personal, the ground fault current in this case could be limited to very small magnitude specially when the fault is close to the neutral point of the generator. The differential relay will not detect this fault, and will see it as a normal load current. This will result in a decrease in the percentage of the winding protected by the differential relay [16,17,18].

### 2.2.7 Protection Against Pole Slipping Conditions

Pole slipping can be caused by external disturbances on the power system such as prolonged faults, large load shedding, line switching, and faulty excitation system. Pole slipping results in an increase in the rotor speed as compared to the speed of the stator rotating magnetic field.

Pole slipping results in large changes in the generator currents. These currents can over-load both the stator and rotor windings. Since the generator now operating as an induction generator, a large induced rotor currents will flow resulting in possible damage of the rotor body due to the heat generated in it. Pole slipping also results in mechanical pulsation torque, which may excite resonance in the shaft, and possible shaft failure. Also the large current flowing in the generator may cause voltage drop in the power system. This voltage drop could result in induction motor starter contactors to drop out, which will further depress the system voltage and may result in cascading loss of synchronism.

For these consequences, pole slipping should be early detected, and the affected generator should be fast removed. Traditional method of pole slipping protection is to use an impedance relay to monitor the variations in apparent impedance at the generator terminals. This relay is designed to remove the generator when the impedance measured by the relay enters its operating characteristics. In order to prevent operation of the relay during normal recoverable swings, blinders are added, which will permit relay operation only when its impedance enter its operating zone in a specific direction [5,96].

A new digital power based relay based on the application of the equal area criterion has also been developed [19,20]. This relay measures the instantaneous power output of the generator and its rate of change and compares it to its setting values. This relay proves to be more effective since it detects pole slipping early enough before it actually occurs, and also appear to be stable during recoverable power swings.

### 2.2.8 Protection Against Loss of Excitation

Removal of excitation current from the generator while it is carrying load will produce severe damage to the generator itself and to the power system to which the generator is connected [5,21,22,23,24,25]. These effects are the result of:

- Excessive heat developed in the rotor due to operation of the generator as an induction generator.
- Loss of magnetic coupling between the rotor and the stator sides, as a result of immediate decrease in magnetic coupling between them.

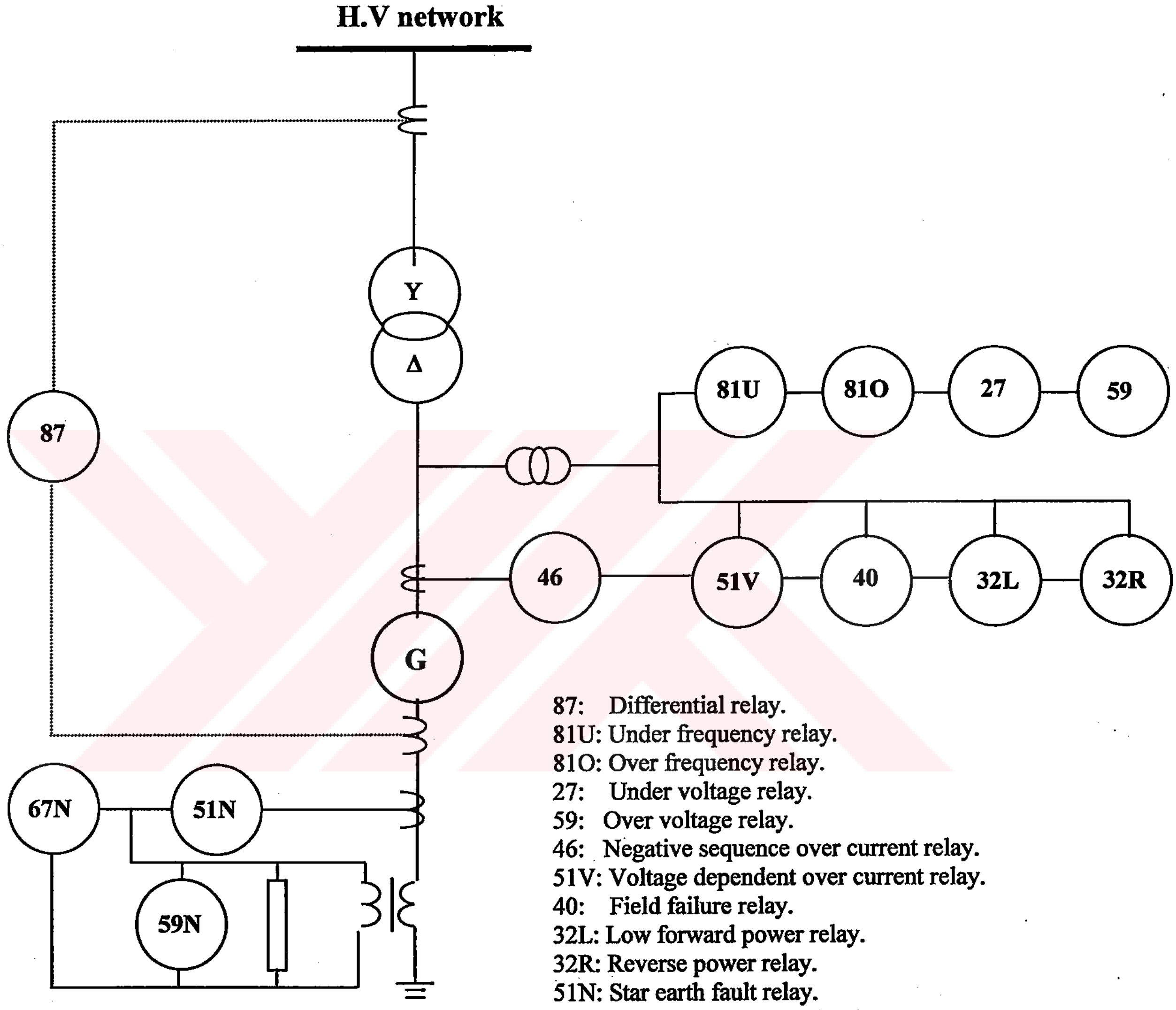
- Loss of the stability of the power system due to the large drop in the power system voltage resulting from the large reactive power absorbed by the affected generator.

- Excessive over-loading of the armature windings of the generator as a result of the large reactive power absorbed from the power system to supplement the decrease in the excitation current of the generator.

Loss of excitation current of the generator could be detected by an offset mho relay, which measures the impedance at the generator's terminals. When the impedance measured by this relay falls within its operating characteristics an appropriate action will be taken.

## 2.3 SUMMARY

In this chapter a brief description of the protection requirements of a generator was given. These requirements are collected in a representative drawing shown in figure 2.1. The references listed at the end of this thesis could be referred to for more information on any of these protection requirements. In the following chapter the steady state as well as the transient state of the round rotor generator are going to be introduced to give a general understanding of the main characteristics of that generator. These characteristics will be used in introducing the new relaying algorithm.




87: Differential relay.
81U: Under frequency relay.
81O: Over frequency relay.
27: Under voltage relay.
59: Over voltage relay.
46: Negative sequence over current relay.
51V: Voltage dependent over current relay.
40: Field failure relay.
32L: Low forward power relay.
32R: Reverse power relay.
51N: Star earth fault relay.
67N: Directional earth fault relay.
59N: Neutral displacement relay.

Figure 2.1 Generator protection circuit diagram

## 3. GENERATOR OPERATION CHARACTERISTICS

### 3.1 INTRODUCTION

To provide a reliable protection system to an electric generator, an extensive study of the transient and steady state operating characteristics of that generator are required. In Appendix A the mathematical model of the synchronous generator was studied, with special attention being given to its steady state equivalent circuits. These circuits will be used in this chapter to obtain some of its important operating characteristics such active and reactive power output, steady state stability limits, and the operating capability curves. This study is needed to form a background for the next chapters, in which loss of excitation current of a generator will be studied, and a digital relaying algorithm will be introduced to perform the necessary protection.

### 3.2 GENERATOR ACTIVE POWER OUTPUT

From appendix A, the average active power output $P$ per phase of the generator is:

$$P = \frac{E_q . V_t}{X_d} \sin \delta \qquad \text{Watts/phase} \tag{3.1}$$

For salient pole generators, the active power output contains another component resulting from the saliency of the air-gap. The resultant power output per phase in this case is:

$$P = \frac{E_q V_t}{X_d} \sin \delta + V_t^2 \left( \frac{X_d - X_q}{2 X_d X_q} \right) \sin 2\delta \tag{3.2}$$

Note that the second part of equation (3.2) decreases as $X_q$ becomes closer to $X_d$.

From these equations it can be seen that for constant terminal voltage, the active power output could be controlled by:

- Controlling the internally generated voltage $E_q$ by controlling the field current $I_f$ of the generator. This method is not usually applied in real life application, since control of field current is usually used to control the generator's internal voltage only.

- Controlling the load angle $\delta$ by adjusting the input mechanical power (adjusting the turbine's steam valves). This is the usual way of power control used with electrical generators.

When a synchronous generator operates under normal balanced loading conditions, the total three- phase power is three times the power produced by one phase. The above equations are written for single-phase power, for three-phase power just multiplied them by 3.

### 3.3 GENERATOR REACTIVE POWER OUTPUT

The per phase reactive power output of the generator is defined as the multiplication of the terminal *rms* phase voltage by the imaginary component of the conjugate of armature *rms* phase current. Then the reactive power output for one phase is:

$$Q = \frac{E_q . V_t}{X_d} \cos\delta - \frac{V_t^2}{X_d} \quad VARS/phase \tag{3.3}$$

It can be seen from this equation that the total reactive power output could be divided into two components:

- The internally generated reactive power, which depends only on the field current of the generator. This component is given by the first part of equation (3.3).

– The reactive power supplied to the generator by the external power system. It depends only on the terminal voltage $V_t$, and is given by the second part of equation (3.3).

Now writing these components for the total three-phase reactive power (for a round rotor generator), we get:

$$Q_g = \frac{3E_q.V_t}{X_d}\cos.\delta \quad \text{and} \quad Q_s = -\frac{3V_t^2}{X_d}$$

Then the total output reactive power of the generator is:

$$Q_t = Q_g + Q_s \qquad (3.4)$$

## 3.4 GENERATOR CAPABILITY CURVES

When a synchronous generator is connected to a power system, its frequency, and terminal voltage are held constant as determined by that of the power system. The only controllable parameters of the generator are the field current, and the input mechanical power. Field current controls the flow of reactive power, and so the power factor of the generator, while control of mechanical power input controls the active power output of the generator. The operating states of the generator are:

i. Constant excitation state.

ii. Constant load current or constant *MVA* state.

iii. Constant active power output state.

iv. Constant reactive power output state.

v. Constant power factor state.

These operating states could be easily explained with the aide of the phase diagram shown in figure 3.1. At the operating point *m*, the above operating states could be defined as:

- The operating state with constant excitation is represented by the circular arc of radius *ob*, with its center at *o*. The radius of this circular arc is determined by the magnitude of the field current of the generator.

- Constant armature current or constant *MVA* state is represented by the locus of circular arc of radius *ab*, with its center at *a*. The radius of this circular arc is determined by the generator total *MVA* output.

- Constant active power state is represented by the constant line *bc*.

- Constant reactive power output state is represented by the constant line *ac*.

- Constant power factor state is represented by extension of the line *ab*, where the angle $\theta$ is kept constant.

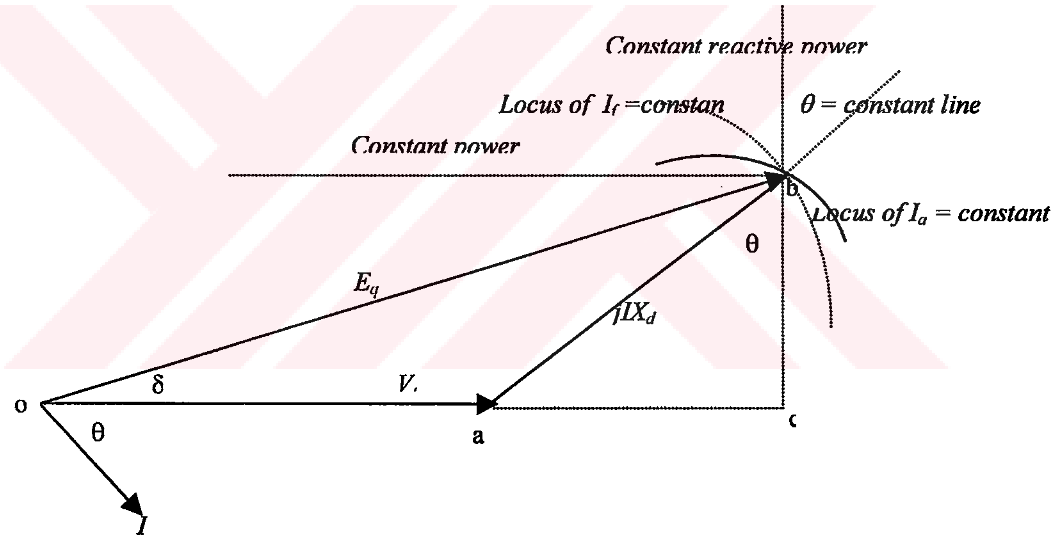



Figure 3.1 Phase diagram of round rotor generator.

The above operating states can be re-drawn in a more suitable form as shown in figure 3.2.

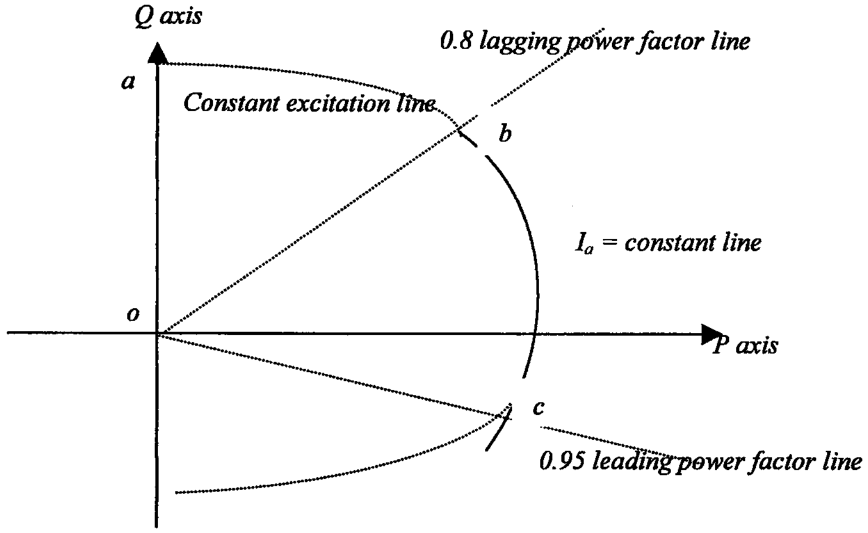



Figure 3.2 Capability curves of a synchronous generator.
*ab*: constant excitation current line.
*bc*: constant MVA line.
*oc*: leading power factor limit line.
*ob*: lagging power factor limit line.

## 4.5 STEADY STATE STABILITY LIMITS (PULL-OUT CURVES)

To study this characteristic, a synchronous generator with negligible armature resistance is connected to a power system with impedance of ($jX_s$). The terminal voltage of the generator $V_t$ is kept constant, while the apparent power flows from the generator to the external power system as shown in figure 3.3.

where:

$$\vec{E_s} = E_s \angle -\partial_{ts}$$
$$\vec{V_t} = V_t \angle 0$$
$$\vec{E_q} = E_q \angle \partial it$$

By using exponential form in representing the above phases, we get

$$E_s = E_s e^{-j\partial_{ts}}$$
$$E_q = E_q e^{+j\partial_{it}}$$

The apparent power flowing from the generator to the external power system is:

$$S_1 = V_t.I^{\bullet} = V_t.\frac{(V_t - E_s)^{\bullet}}{(jX_s)^{\bullet}} = j\frac{V_t}{X_s}\left[V_t - E_s e^{j\partial_{ts}}\right] \tag{3.5}$$

Apparent power flowing from the generator to its terminal $S_2$

$$S_2 = V_t.I_2^{\bullet} = j\frac{V_t}{X_d}\left[E_q e^{-j\partial_{it}} - V_t\right] \tag{3.6}$$

The over-all apparent power flowing from the inside of the generator to the power system $S_t$ is:

$$S_t = E_s.I_t^{\bullet} = j.\frac{E_s}{(X_d + X_s)}\left[E_q e^{-j\partial_{is}} - E_s\right] \tag{3.7}$$

In equation (3.7), $E_s$ were assumed as a reference, and also the angle $\delta_{is}$ is

$$\delta_{is} = \delta_{it} + \delta_{ts} \tag{3.8}$$

The maximum power transfer from the generator to the system, is found by substituting in equation (3.8) by:

$$\delta_{ism} = \pi/2 = \delta_{itm} + \delta_{tsm}$$

then

$$P_{\max} = \frac{E_s E_q}{(X_d + X_s)} \tag{3.9}$$

Also from equation (3.1), the maximum power $P_{max}$ is:

$$P_{\max} = \frac{V_t E_q}{X_d}.\sin\delta_{itm} \tag{3.10}$$

By equating these last two equations, $E_s$ as function of terminal voltage $V_t$ can be found as:

$$E_s = \left(\frac{X_d + X_s}{X_d}\right)V_t \sin\partial_{itm}, \text{and} E_s = V_t.\frac{(X_d + X_s)}{X_d}\left[\frac{e^{j\partial_{itm}} - e^{-j\partial_{itm}}}{2j}\right] \tag{3.11}$$

Now from equation (3.8), the resultant output apparent power $S_2$ is found by substituting for $E_s$ from (3.11), and remembering that for maximum power transfer ($\delta_{itm} + \delta_{tsm} = \pi/2$). Then:

$$S_2 = j\frac{V_t^2}{X_s}\left[1 - \frac{(X_d + X_s)}{2X_d}\left(1 - e^{-j2\partial_{itm}}\right)\right] \tag{3.12}$$

This equation can be expanded in the following form:

$$S_2 = P + jQ$$
$$P = \frac{V_t^2}{2}\left[\left(\frac{1}{X_s} + \frac{1}{X_d}\right)\sin.2\partial_{itm}\right]$$
$$Q = \frac{V_t^2}{2}\left[\left(\frac{1}{X_s} - \frac{1}{X_d}\right) + \left(\frac{1}{X_s} + \frac{1}{X_d}\right).\cos.2\partial_{itm}\right]$$

Now by taking the trigonometric terms in one side, the above two equations can be written as:

$$\frac{V_t^2}{2}\left[\frac{1}{X_s} + \frac{1}{X_d}\right]\sin 2\partial_{itm} = P$$
$$\frac{V_t^2}{2}\left[\frac{1}{X_s} + \frac{1}{X_d}\right]\cos.2\partial_{itm} = \left[Q - \frac{V_t^2}{2}\left(\frac{1}{X_s} - \frac{1}{X_d}\right)\right]$$

These last two equations can be combined together as follows:

$$\left[\frac{V_t^2}{2}\left(\frac{1}{X_s} + \frac{1}{X_d}\right)\right]^2 = P^2 + \left[Q - \frac{V_t^2}{2}\left(\frac{1}{X_s} - \frac{1}{X_d}\right)\right]^2 \tag{3.13}$$

Equation (3.13) is the equation of a circle, which has a center *c*, and radius *r* as:

$$c = \left(0, \frac{V_t^2}{2}\left(\frac{1}{X_s} - \frac{1}{X_d}\right)\right) \tag{3.14}$$

$$r = \frac{V_t^2}{2}\left(\frac{1}{X_s} + \frac{1}{X_d}\right) \tag{3.15}$$

Equation (3.13) is known as the pullout equation of the generator or its steady state stability limit. It can be seen from this equation that:

- Stability limit of the system can be increased by increasing the radius of the circle, which is usually done by decreasing (either or both) $X_s$ and $X_d$. The usual way of increasing the stability limit is by decreasing $X_s$ such as by using double circuit transmission lines or adding series capacitors.

- The maximum power transfer capability of the system is increased by increasing the voltage $V_t$.

- The pullout curve crosses the $Q$-axis at two points *a, b* as shown in figure 3.4, which are:

  At point *a*, which is located at $(0, V_t^2/X_s)$. This point represents the case of maximum over-excitation operation of the generator at which it delivers only reactive power of $V_t^2/X_s$ *VARS* per phase to the power system.

  At point *b*, which is located at $(0, - V_t^2/X_d)$, the reactive power output from the generator is now negative, since it operates at a leading power factor. At this point the generator imports its reactive power, which is equal to $(- V_t^2/X_d)$, from the external power system. In real life this amount of reactive power could not be allowed to flow to the generator since the generator has already lost its field excitation.

- Operation of the generator at any of these two points mentioned above is not allowed since at both points the generator will lose its stability with the power system.

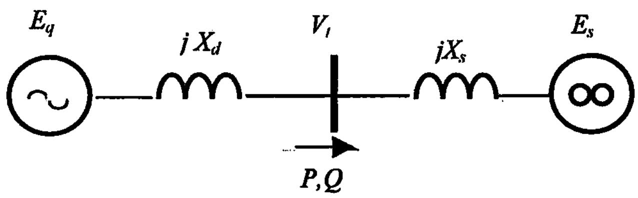



Figure 3.3 Synchronous generator connected to an infinite bus.

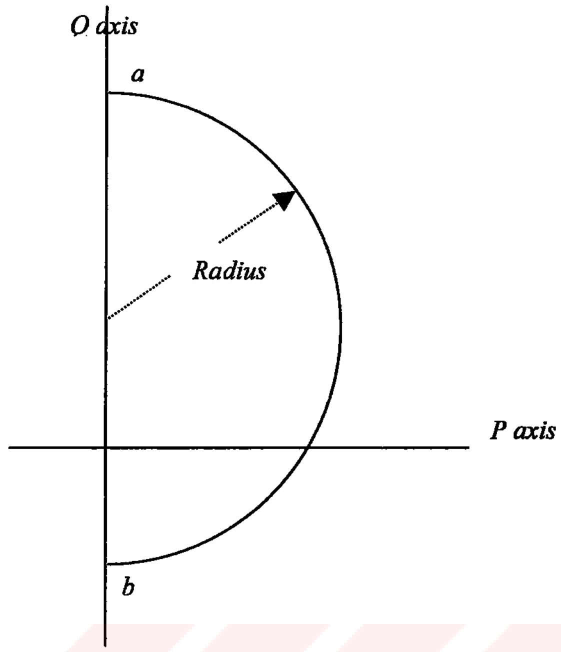



Figure 3.4 Pull-out curve with limiting points *a* and *b*.

### 3.6 SUMMARY

In this chapter extensive analysis of generator operating characteristics such as active and reactive power output, capability curves and maximum power transfer has been done. These results will be used in chapter five to introduce a new relaying algorithm for the protection of generators against loss of field excitation. This algorithm is mainly based on the measurement of the total reactive power output at the terminals of the concerned generator.

# 4. TRADITIONAL LOSS OF FIELD RELAY

## 4.1 INTRODUCTION

The normal operation of generators is always subjected to abnormal operating conditions, such as faults, over-loadings, etc. One of these abnormal operating conditions is the loss of excitation current (field current) of the generator.

The primary indicator of possible loss of field excitation in a generator is the large reactive flow into the machine, which could be detected by an impedance relay connected at the terminals of the generator. This relay will be studied in this chapter.

## 4.2 OFFSET MHO RELAY

Mho relays are single-phase, single element units in which the relationship between operating and restraining torque is an offset circle [1,2,7]. The amount of offset and the angle of maximum torque are a design parameters. This relay monitors the impedance seen at its terminals, and a trip signal is produced when this impedance falls inside the relay characteristic. When this relay is used for loss of excitation protection, the amount of offset is set equal to one-half of the transient synchronous reactance, and the angle of maximum torque is 90° along the $-jx$ axis. The diameter of this circle is set equal to the reach of the relay. Two relay types are used for this protection requirement, with each relay connected such that its polarizing voltage is the line-to-line voltage, while its current is the difference between the phase currents to which the relay is connected:

The first type has a characteristic as shown in figure 4.1. In this type the operating characteristic of the relay has a diameter equal to direct axis synchronous reactance $X_d$, and an offset equal to one half of the direct axis sub-transient reactance $X_d'$. The upper part of the relay's characteristic follow the operating capability curve of the generator during normal leading operation, such that the relay is prevented from operation during recoverable swings.

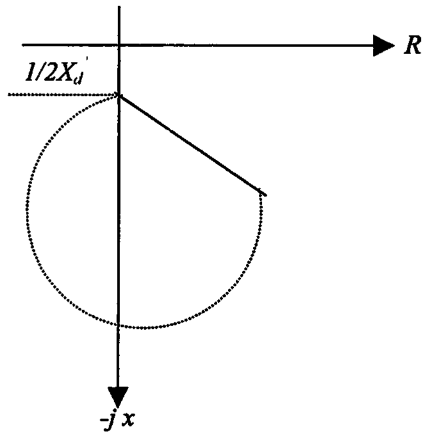



Figure 4.1 Operating characteristics offset an impedance relay.

The second type has the characteristic shown in figure 4.2, where it consists of two circles both with an offset equal to $X_d'/2$.

- The inner circle has a diameter of $Z_1$ equal to1.pu based on the machine ratings. Here the relay is set to operate very fast within 0.1 to 0.3 sec. after the impedance measured by the relay falls inside this circle.
- The outer circle with a diameter of $Z_2$ equal to $X_d$. Here a time delay for about 1.5 to 2 sec. is introduced after the impedance falls inside the relay characteristic to prevent operation of the relay during recoverable swings.

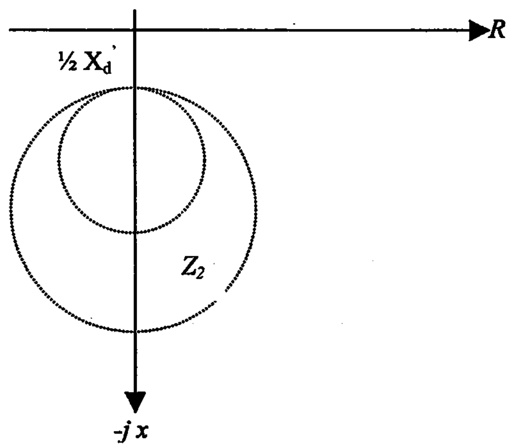



Figure 4.2 Offset mho distance relay with two zones of protection.

### 4.2.1 Sources Of Relay Error

During system transients, both frequency and voltage are subjected to a change in magnitude. These changes affect the relay's characteristics as:

- Voltage changes have little effect on relay characteristics, since a small change in voltage doesn't considerably affect the impedance [5].
- While frequency changes have appreciable effect on relay characteristics as shown in fig 4.3. From these curves we see that frequency changes affect both the relay's reach, and the angle of maximum torque. As frequency increases the effective diameter of the relay increases too [27,28], resulting in possible operation of the relay during recoverable system swings. While a decrease in the system frequency results in a decrease in the effective diameter of the relay, which will result in a reduced detection capability for actual loss of field current.

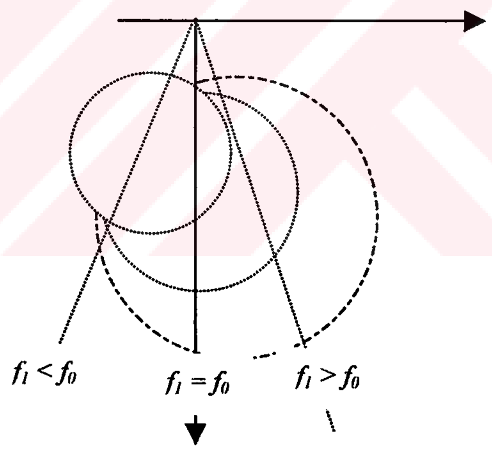



Figure 4.3 Frequency effect on relay characteristics.

### 4.2.2 Other Effects on Relay Operation

The generator characteristic when it losses its field current is defined as the locus of the apparent impedance seen by the affected generator at its terminals. This characteristic is affected by:

- The initial loading state of the generator.

- Impedance of the system to which the generator is connected.
- Presence of a voltage regulator on the faulted generator.
- Recoverable swings occurring in the power system.

The last point concerning effect of recoverable swings is also affected by

- Fault clearing time.
- System impedance.
- Presence of automatic voltage regulator [AVR] on the generator.

The worst swings occur when

- The system impedance is low.
- No voltage regulator is present in service during loss of excitation.
- Fault clearing time was equal to critical switching time.
- The generator was initially operating at a leading power factor.

In cases when it is possible for stable swings to enter the relay characteristics in the outer zone for a short period of time, then this could be solved by introducing a time delay in the relay settings.

### 4.3 SUMMARY

From the study of the traditional loss of excitation relay it can be conclude that:

- Loss of excitation can be a damaging one to the faulted generator as well as to the power system. So loss of excitation protection relays should be installed on all generators.
- For proper detection of loss of excitation cases, from any generator loading, the relay characteristic should be set with a diameter equal to $X_d$.

- Proper time delay should be introduced to the relay to prevent relay operation during stable swings

- The main disadvantages of this relay are the increased capability of possible relay operation during recoverable swings, and the need to introduce longer time delay to over-come this problem. This time delay may result in losing the stability of the generator. Also this relay is affected by changes in system frequency and voltage.

# 5. A NEW DIGITAL ALGORITHM FOR PROTECTION AGAINST LOSS OF FIELD OF A GENERATOR

## 5.1 INTRODUCTION

Synchronous generators are used mainly to produce active power at the most economic operating state to properly serve the demand on electric energy. Electric generators require reactive power to establish their magnetic flux such that electromagnetic energy conversion process can take place. This reactive power is produced by the field current supplied to the field winding, which is mounted on the rotor side of the generator. When a deficiency occurs in the field current, the generator imports part of its reactive power need from the utility power system. On the other hand, power systems need reactive power to maintain the voltage throughout the system within the allowable range. In this case we could have:

- When the power system is lightly loaded, and when there are long transmission lines and cables connected to it, there will be an excess in reactive power in the system. This excess reactive power, which is of a capacitive type will result in a rise in the power system voltage above the allowable ranges. In this case in order to limit the voltage magnitude, this extra reactive power should be absorbed, which is usually done by:

  - Connecting shunt reactors at specified points in the power system.
  - Operating the generators at a leading power factor mode, such that they absorb part of their reactive need from the power system.

- While when there is a deficiency in reactive power in the power system, as when it is heavily loaded, then the system voltage will decrease below the allowable ranges due to the large inductive load current flowing into the power system. To maintain this voltage within allowable ranges, reactive power should be injected to the power system [29]. This is usually done by:

- Connecting shunt capacitors at specified points such that reactive power required by the load is provided to it near to its location in order to limit reactive power flow within the power system.

- Operating the generators at lagging power factors (in over excited mode) to produce reactive power too. This kind of operation will result in over-loading of the generators, and a decrease in their efficiency. But the most appropriate operating condition of a generator is that at unity power factor, where all the current is an active one, and the generator has the highest efficiency.

In this chapter the active and reactive power output of the generator as functions of the above operating conditions are going to be investigated. Then the effect of variation of the field current on the reactive power output of the generator will be studied. The results obtained from these studies will be used in introducing a new loss of field relaying algorithm based on the measurement of reactive power output of the generator.

## 5.2 POWER IN SINGLE PHASE SYSTEMS

### 5.2.1 Instantaneous Power

The instantaneous power in single phase system $p_{ph}(t)$ is defined as the multiplication of the instantaneous phase voltage $v_{ph}(t)$, and the instantaneous phase current $i_{ph}(t)$.

$$P_{ph}(t) = v_{ph}(t).i_{ph}(t) = VI\cos\varphi + (VI\cos\varphi\cos 2\omega t + VI\sin\varphi\sin 2\omega t) \quad (5.1)$$

Equation (5.1) is variable with time, and consist of two components:

- Constant component represented by the first part and is equal to the average active power.

- A variable component with a frequency equal to double the system frequency given by the second part. This component has a zero average value.

### 5.2.2 Average Power

The average active power is defined as:

$$P = \frac{1}{T}\int_0^T p(t)dt \tag{5.2}$$

$T$ is the fundamental period of the system frequency in sec.

By using the *rms* values of phase voltage and phase current, the active power can be calculated by:

$$P = V.I.\cos\varphi \tag{5.3}$$

Where;

$\varphi$ is the angle between phase voltage and phase current.

The factor $cos\varphi$ is known as the power factor *pf*, and it measures how effectively the apparent power is transferred to active power. Maximum power transfer occurs when the power factor is unity, which occurs when both current and voltage are in phase. For any other operating conditions the power factor will be less than one, and part of the apparent power is not transferred to useful active power.

When dealing with digital signal processing, phase voltages, and phase currents consist of sampled signals obtained at a specific sampling frequency $f_s$. In this case the instantaneous active power is defined in terms of the sampling instant $n$ as:

$$p(n) = v(n).i(n) \tag{5.4}$$

Where; $n$ is the sampling instant.

The average power $P$ is found as:

$$P = \frac{1}{N}\sum_{n=1}^{n=N} p(n) = \frac{1}{N}\sum_{n=1}^{n=N} v(n).i(n) \tag{5.5}$$

### 5.2.3 Reactive Power

Reactive power $Q_{ph}$ is defined as the cross product of phase voltage and phase current, which is defined as the product of the voltage with the normal (perpendicular) component of current, and is measured in units known as *VARS*. In single-phase systems, the reactive power $Q_{ph}$ is defined as:

$$Q_{ph} = V_{ph}.I_{ph}.\sin.\varphi \tag{5.6}$$

The components of this equation are as previously defined. The sign of the reactive power is determined by the sign of the phase angle $\varphi$ as:

- For lagging power factor, when the current lags behind the voltage as in inductive circuits, $\varphi$ is assumed positive, and so the reactive power.
- For unity power factor where both voltage and current are in phase the reactive power is zero.
- For leading power factor, when the current leads the voltage, as for capacitive circuits, $\varphi$ is negative, and so the reactive power. Here negative reactive power means that it flows in a direction opposite to that of the active power.

## 5.3 POWER IN THREE PHASE SYSTEMS

### 5.3.1 Instantaneous Power

For balanced three-phase systems, the instantaneous total power $p$(t) is three times the instantaneous power delivered by one phase.

$$p(t) = 3.v_{ph}(t).i_{ph}(t) \tag{5.7}$$

For unbalanced phases the instantaneous total power is equal to the sum of the instantaneous powers of all the three phases. That is:

$$p(t) = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t) \tag{5.8}$$

The instantaneous power can be calculated using sampled voltages and currents as used previously for single-phase system as:

$$p(n) = v_a(n)i_a(n) + v_b(n)i_b(n) + v_c(n)i_c(n) \qquad (5.9)$$

### 5.3.2 Real (Active) Power

In a balanced three-phase system, the three phases share equal amount of the total average active power produced by that system. The total average active power is

$$P = 3V_{ph}.I_{ph}.\cos.\varphi \qquad (5.10)$$

When the three phases are under unbalanced conditions, as when the load is not balanced, or as in cases of unbalanced faults, the phase voltages and phase currents are unbalanced, and each phase will deliver different amount of the total active power. The average power delivered by each phase is given by equation (5.5). The total average power is:

$$P = P_a + P_b + P_c = V_a I_a.\cos\varphi_a + V_b I_b.\cos.\varphi_b + V_c I_c.\cos.\varphi_c \qquad (5.11)$$

For sampled signals the total average power is found from equation (5.9) as:

$$P_a = \frac{1}{N}\sum_{n=1}^{n=N} p(n) = \frac{1}{N}\sum_{n=1}^{n=N}[v_a(n)i_a(n) + v_b(n)i_b(n) + v_c(n)i_c(n)] \qquad (5.12)$$

The relationship between sampling frequency and the sampling number in a period of system frequency is:

$$f_s = N.f_0 \qquad (5.13)$$

### 5.3.3 Three Phase Reactive Power

For balanced three-phase system, the total average reactive power is three times that produced by one of the phases. That is:

$$Q_t = 3.V_{ph}.I_{ph}.\sin.\varphi \qquad VARS \qquad (5.14)$$

For unbalanced three-phase system, the total reactive power is found as the sum of the reactive power produced by each phase.

$$Q_t = Q_a + Q_b + Q_c = V_a.I_a.\sin.\varphi_a + V_b.I_b.sn.\varphi_b + V_c.I_c.\sin.\varphi_c \qquad (5.15)$$

For sampled three phase systems, the total instantaneous reactive power is [19,20,30]:

$$Q(n) = \frac{1}{\sqrt{3}}\left[v_a(n)(i_b(n) - i_c(n)) + v_b(n)(i_c(n) - i_a(n)) + v_c(n)(i_a(n) - i_b(n))\right] \qquad (5.16)$$

From this equation, we calculate the moving average reactive power as:

$$Q_t = \frac{1}{N}\sum_{n=1}^{n=N} Q(n) \qquad (5.17)$$

This averaging process is carried out here to smooth the relaying signal used by the algorithm.

## 5.4 GENERATOR OPERATING MODES

By rearranging equation (3.4), the total reactive power will be in the following form:

$$Q_t = \frac{3V_t}{X_d}\left[E_q.\cos\partial - V_t\right] \qquad (5.18)$$

From this equation it can see that the direction of reactive power flow is determined by the sign of the term between parentheses. This shows that there are three cases of reactive power flow as:

- When ($E_q.\cos.\delta \succ V_t$), then the reactive power output from the generator is positive, flowing out from the generator to the external power system. This situation results when the generator is over-excited (has excess field current), and operates with a lagging power factor as shown in Figure 5.1a. This operation of the generator in over-excited state is limited by the limitation on excitation field current and the thermal heat generated by it. Economically it will be better to provide the needed reactive power by some other means as by shunt capacitors, and over-excited synchronous motors other than by the generator.

- When ($E_q.\cos.\delta = V_t$), then the total output reactive power is zero. The generator delivers only active power to the external power system, and operates at the most convenient operating mode, with a unity power factor as shown in Figure 5.1b. In this case the internally generated reactive power $Q_g$ equals in magnitude and opposite in direction to that supplied by the external power system $Q_s$, and the generator is said to operate at the normal excitation level.

- When ($E_q.\cos.\delta \prec V_t$), then the total reactive power output of the generator is negative, flowing from the power system back to the generator. This operating situation results when there is a deficiency in the field current of the generator. Then the generator imports its reactive need from the external power system, and the generator is said to be under-excited, and operate at a leading power factor as shown in Figure 5.1c. Note also that this leading power factor operation of the generator is accompanied by an increase in the load angle $\delta$, which case will bring the generator closer to its stability limit. Also operation of the generator in a leading power factor mode results in increased armature end-winding leakage losses, where a damaging heat could be generated. For these reasons it is recommended that generators be not allowed to operate in leading power factor mode for long period of time (better if not at all).

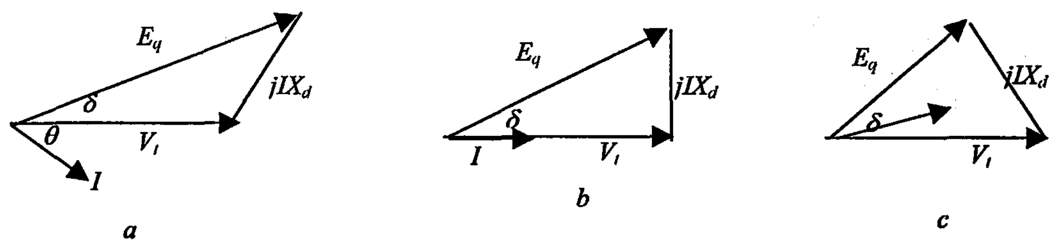



Figure 5.1 Phase diagrams of a synchronous generator:
a-Lagging power factor.
b-Unity power factor.
c- Leading power factor

- During power swings the load angle of the generator $\delta$ may undergoes some oscillations and may exceed 90° in which case the reactive power will reach a large negative value. This situation mainly occurs during recoverable power swing operation of the generator. Since this power swings lasts only for short period of time, then this can be handled in protection relays used in pole slipping and loss of excitation protection by introducing certain time delay in their operating characteristics.

## 5.5 LOSS OF EXCITATION

### 5.5.1 Field Current During Loss of Excitation

When the generator losses its excitation current as a result of short-circuited or open-circuited field winding, the field current will decay exponentially to zero with a decaying time constant $T_0$ as usually occur in inductive circuits, where $T_0$ is the time constant of the generator field circuit in sec. The field current in this case can be written as:

$$I_f(t) = I_{f0} e^{-t/T_0} \tag{5.19}$$

Then as a result of this decaying field current, the internally generated reactive power $Q_g$ will also decay to zero with the same time constant since it is dependent only on the field current of the generator. Then from appendix A, $Q_g(t)$ is:

$$Q_g(t) = \frac{3\omega M_f V_t I_{f0}}{\sqrt{2} X_d} e^{-t/T_0} = Q_{g0} e^{-t/T_0} \tag{5.20}$$

Where; $Q_{g0}$ is the internally generated reactive power prior to loss of excitation.

This decay in $Q_g$ will affect the total generator reactive power output, which in turn will decay to zero too (if it were initially working with a lagging or unity power factor). Then it will reverse its direction starting to flow from the power system back to the generator in an attempt to supply the deficiency in its reactive power. So at any time during the operation of the generator, if:

$$Q_t \prec 0.0 \tag{5.21}$$

Then this is the first indicator of a lack or a deficiency in the excitation current of the generator.

### 5.5.2 Allowable Reactive Power Being Import

During the operation of the generator with a leading power factor, the maximum allowable reactive power that could be absorbed from the system is determined by many factors as the end winding leakage losses, which usually increase to a damaging value when the generator carry large leading power factor load. For this reason it is usually recommended that during the leading power factor operation of the generator, the maximum leading power should not be lower than 0.95 [31,93,94].

For these reasons the maximum allowed reactive power $Q_m$ is taken as:

$$Q_m = \left(\sqrt{1-\left(0.95^2\right)}\right)MVA \qquad MVAR \tag{5.22}$$

Where; *MVA* is the rated load of the concerned generator.

Equation (5.22) represents the maximum allowable reactive power that can flow during the leading operation of the generator at full load without subjecting it to damage.

### 5.5.3 Extreme Reactive Power

When the generator has completely lost its excitation current, the extreme reactive power that can flow from the external power system back to the generator can be obtained by referring to the equivalent circuit of the generator given in Appendix A-1. From this circuit. the phase diagram can be drawn as shown in figure 5.2. In this diagram the armature resistance of the generator was neglected as compared to its synchronous reactance. The voltage equation of this diagram is given by

$$E_q^{\rightarrow} = V_t^{\rightarrow} + I^{\rightarrow}.jX_d \tag{5.23}$$

When a complete loss of field occurs, the internally generated voltage $E_q$ will decrease to zero, in which case the above equation reduces to

$$0 = \vec{V_t} + \vec{I}.jX_d \qquad (5.24)$$

Then the current flowing in the armature of the generator per phase is now leading the terminal voltage by 90°, and is given by

$$I = \frac{V_t}{X_d} \qquad (5.25)$$

In this case the synchronous generator delivers no active power output, and is not stable since the rotor load angle δ is equal to 90°. The reactive power imported by the generator from the power system is:

$$Q_t = -\frac{V_t^2}{X_d} \quad VAR/phase \qquad (5.26)$$

Generators are not allowed to operate under this condition or even close to it, since they will lose stability with the power system.

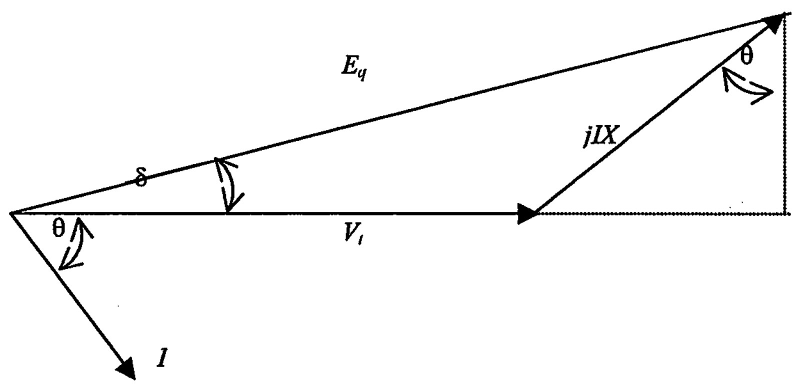



Figure 5.2 Phase diagram of round rotor generator.

## 5.6 THE NEW ALGORITHM

Equation (5.16) gives the instantaneous reactive power output from the generator, while equation (5.17) gives the total moving average reactive output over a complete cycle. These equations can be used to monitor the reactive power-state of the generator at any loading condition. Then by equation (5.21) the direction of the reactive power flow through the generator can be obtained. When this reactive power becomes negative, it gives the first indication of a deficiency in the excitation-state of the generator. Then by comparing this reactive power to the maximum allowable reactive power flow during leading operation a decision can be made about the possible loss of field of the generator. This idea will be used in the following sections to develop a relaying algorithm based on the calculation of the total three-phase moving average reactive power output of the generator to provide protection against loss of field.

### 5.6.1 Algorithm Objects

During the design of this relaying algorithm, the main objects will be:

- The algorithm should not detect or operate for any external or internal faults other than the actual loss of excitation current. This requirement will prove the selectivity of this algorithm.
- The algorithm should detect actual loss of field fast enough to allow for appropriate actions to be taken before any damage to the generator could take place. This requirement will prove the dependability of the algorithm in detecting actual loss of field.
- The algorithm must stay stable and operate properly during recoverable power swings resulting from abnormal operating conditions. This requirement will prove the security of the algorithm.

### 5.6.2 Algorithm Procedure

The steps followed by the suggested algorithm are:

- In the first step the algorithm reads the instantaneous phase currents and phase voltages in sampled form at the generator terminals
- In the second step the algorithm calculates the total three-phase reactive power of the generator using equation (5.16). Then by equation (5.17) the moving average reactive power output $Q_t$ is obtained over one complete cycle of the system frequency.
- In the third step the algorithm determine the direction of the reactive power flow from the sign of the reactive power calculated in step 2. If the sign is negative then this will indicate a lack or deficiency of the field excitation. If on the other hand the reactive power is positive or zero, the algorithm assumes it as a normal operation of the generator in the over-excited or normal modes respectively.
- In the fourth step the algorithm compares this negative reactive power to the maximum allowable reactive power flow into the generator during normal leading operation $Q_m$. If the total reactive power output in absolute value is found less than or equal to $Q_m$ the relay will consider it as a normal leading operation, and repeats the above steps again.
- If the calculated total reactive power output $Q_t$ has a lower negative value than $Q_m$ then the algorithm compares it to the extreme reactive power $Q_R$. If $Q_t$ has a lower negative value than $Q_R$ then this indicates a confirmed loss of field state and the algorithm issued a 100 msec time delayed trip signal to remove the generator from service as fast as possible.
- But if the calculated total reactive power $Q_t$ falls in the range between $Q_m$ and $Q_R$, then the algorithm considers this as an abnormal leading operation state and introduces an adaptive time delay function accompaned by an alarm signal to warn the operator about this abnormal leading operation. The time delay used in this algorithm has a linear inverse time proportion function.
- To overcome the possible tripping of the generator as a result of existence of a recoverable power swings, where the total three-phase moving average reactive

power may reach negative values lower than $Q_R$ for short period of time, then a 100 msec time delay is introduced in the instant tripping function after confirming the loss of field.

### 5.6.3 Setting Values of The Algorithm

Using the capability curves of the concerned generator shown in figure 5.3 the setting values of the suggested algorithm can be found as:

- The capability curve represents the permissible loading of the concerned generator under the operating modes mentioned earlier. The curve *bcd* in the figure represent the full load line of the generator. The allowable power factors at this loading are such that point *b* represents a lagging power factor of 0.8, while point *d* represents a leading power factor of 0.95. This point *d* determines the maximum allowable reactive power $Q_R$ used by the algorithm.
- To operate the generator at a leading power factor less than 0.95 requires the reduction of its percentage loading. For modern generators designed to operate at their highest efficiency it is not allowable to operate the generator in a leading power factor less than 0.95.
- Point *f* in the figure represent the case of complete loss of excitation at which $\dot{E}_q$ has fallen to zero. The generator should be tripped before this point to prevent the loss of stability with the power system and its back effects on the system as a whole. For these reasons the tripping value $Q_R$ is chosen to correspond to point *e* in the figure. Point *e* falls in the range between [(0.6 to 0.75)] of *of.*
- When the reactive power measured by the algorithm has a value between $Q_m$ and $Q_R$, an adaptive time delay function is introduced, with an alarm signal to warn the operator about this abnormal leading operation. This adaptive time delay is given by the following equation

$$t = T_d \cdot \frac{|Q_R - Q_m|}{|Q_t - Q_m|}$$

$T_d$ is a time controlled by the operator according to the severity of the leading conditions.

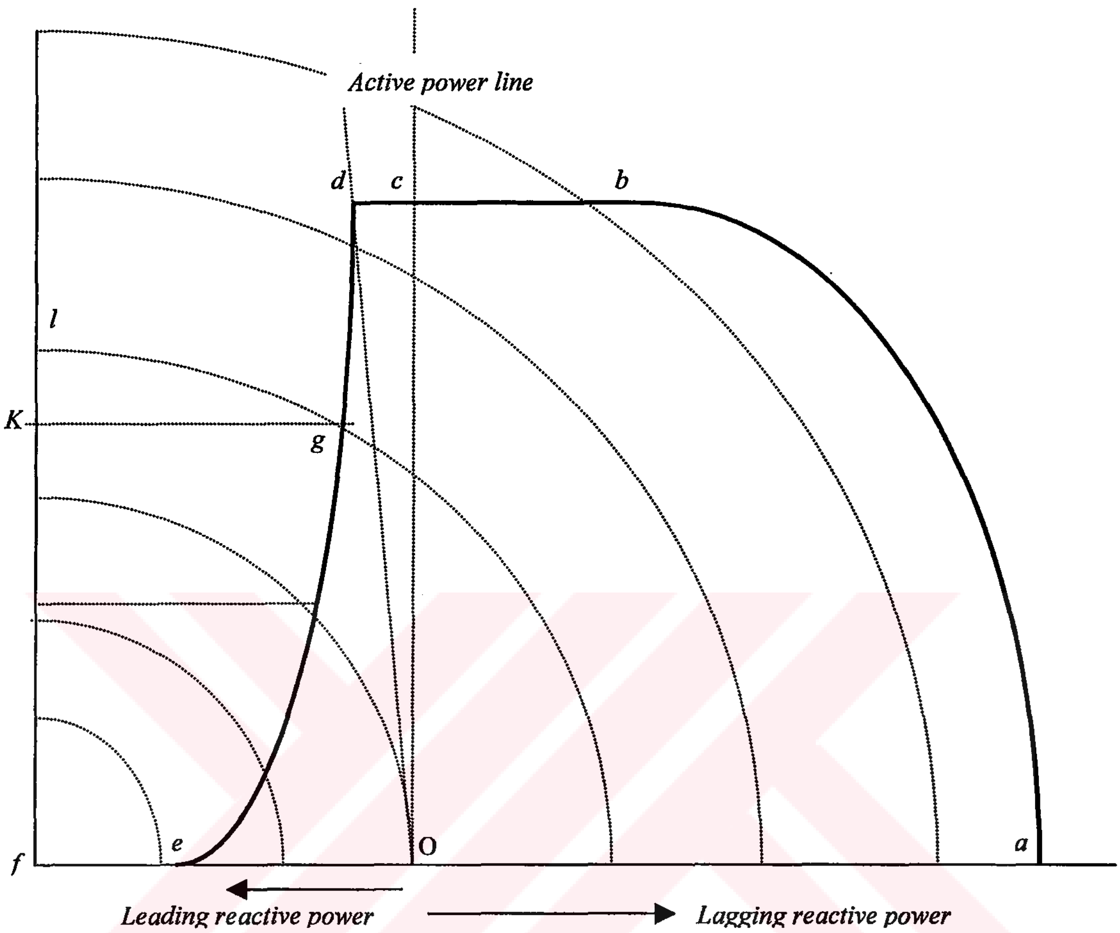



Figure 5.3 Capability curve of a synchronous generator

### 5.6.4 Flow Chart of The Algorithm

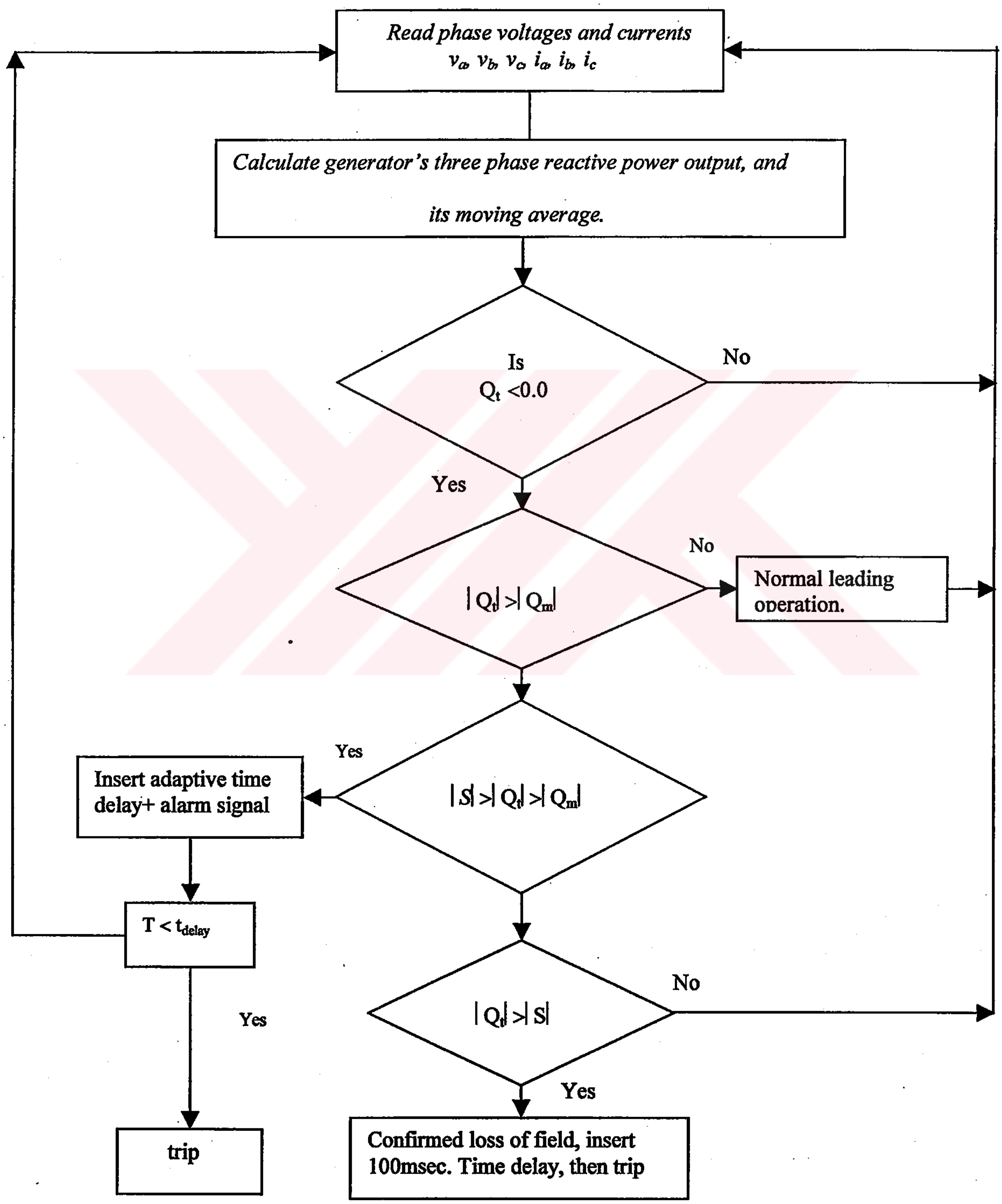



Figure 5.4 Flow chart of the new algorithm

## 5.7 SUMMARY

In this chapter a new digital relaying algorithm is introduced to provide protection against loss of field conditions. The algorithm is designed such that it will produce a trip signal after 100 msec for completely loss of field current, and produce adaptive time delayed trip signal for partial loss of field, and abnormal leading conditions. It is also expected that it will not produce trip signal for other abnormal and fault conditions.

Using the EMTP simulation program in the next chapter a representative power system is to be subjected to different abnormal operating conditions including complete and partial loss of excitation, and other fault conditions. The output of this simulation program is to be introduced to the new relaying algorithm to examine its response to these effects.

# 6.COMPUTER SIMULATION STUDIES

## 6.1 INTRODUCTION

The previously designed digital relaying algorithm used for the detection of loss of field of electric generators is now going to be tested using computer simulations. In these simulations a numerous abnormal operating conditions including actual loss of field under different loading conditions of the generator are to be performed to see how the algorithm will respond to them.

The steps to be followed are:

- Representation of the generator's connection to the external power system.
- Application of EMTP program in this study to perform the different abnormal operating conditions.
- Application of the output results of the EMTP program to the new relaying algorithm.

The generator under study is connected to the external power system as shown in single line diagram in figure 6.1. Faults are represented by switches, which are easily opened or closed at specific time to represent the application or removal of the fault. Circuit breakers are also represented by switches, which can be easily opened or closed to represent the opening or closing of a line or a load. The parameters of this system are given in appendix B.

External faults are applied at the starting point of one of the transmission lines. These faults are cleared after 0.1 sec of the application of the fault, just before the system losses its stability.

The loss of field cases are simulated by changing the output of the voltage regulator to pre-specified values (by setting the factor $K$ of the automatic voltage regulator to zero). The block diagram representing the automatic voltage regulator (AVR) is given in appendix C.

EMTP transient program is used in these simulations for the different abnormal conditions used in this study. The generator phase currents, phase voltages, field current, and load angle are obtained in sampled form at specific time intervals controlled by the simulator. The simulation period used in this study is 3.0 sec.

Simulation results are displayed as a set of curves of the generator field current, instantaneous reactive power output of the generator (components of the generator's reactive power), rotor load angle δ, and the output of the new relaying algorithm, as the functions of simulation time.

In each of the study cases the first graph *a* shows the field current of the generator in p.u based on generator ratings. The second graph *b* shows the instantaneous components of the reactive power output of the generator. These components are the total reactive power *Qt*, the reactive power supplied by the external system *Qs*, and the internally generated produced by the field current *Qg*. The third graph *c* shows the load angle δ, while the fourth graph *d* shows the response of the new relaying algorithm. The reactive power components shown on this curve are the maximum allowed reactive power *Qm*, and the tripping value for this algorithm $Q_R$. In case of a confirmed loss of field, the algorithm produces a tripping signal and ceases program operation.

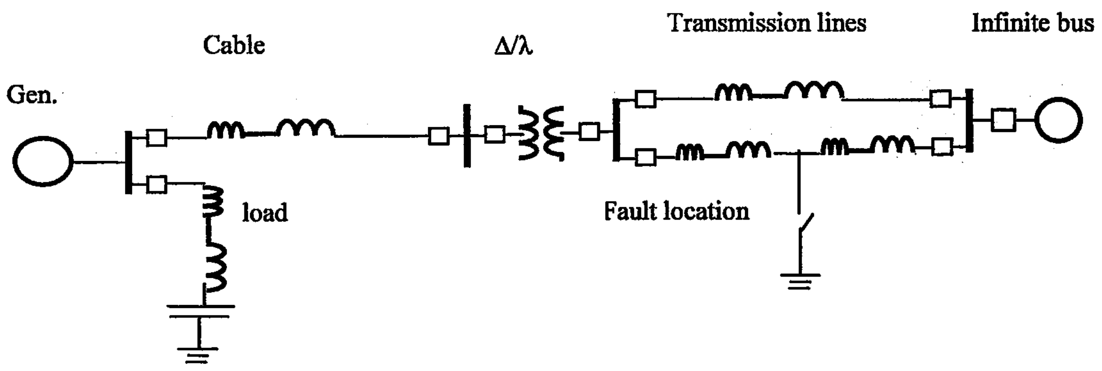



Figure 6.1 Representation of the power network used for computer simulation studies.

## 6.2 CASE STUDIES

### 6.2.1 Fault Studies

#### a. External Three Phase Fault

A solid three-phase fault is applied at the starting point (just after the circuit breaker) of one of the transmission lines, while the generator operating at no-load. This fault is cleared after 0.1 sec by opening the circuit breakers at both ends of the affected line.

The results of this study are shown in figure 6.2, where it can be seen that:

- The field current $I_f(t)$, shown in figure 6.2a first increases to about 10 pu during the sub-transient period, and then decreases to its normal value after opening of the affected line. There are some oscillations in the field current during the fault period due to the existence of a dc offset current in the armature windings, which appears as an alternating current in the field winding.

- Figure 6.2c represents the rotor load angle $\delta$ during the fault. From this curve it can be seen that, the rotor load angle $\delta$ oscillates about its steady state value during the transient period in a decaying form. It finally settles down to its steady state value after the clearance of the fault and the subsidence of the oscillations.

- The last figure 6.2d represents the response of the new relaying algorithm in the form of the total reactive power output of the generator as function of time. It can be seen that during the fault, the reactive power output of the generator always has a positive sign flowing out of the generator to the fault. The new relaying algorithm doesn't indicate any loss of field current in this case, and as it is designed it stays stable during this abnormal condition.

- While if a solid three-phase fault is applied at the same previous point with the generator fully loaded, the response of the new relaying algorithm is shown in figure 6.3, where also the new algorithm doesn't indicate any loss of field current, and stays stable.

**b. Lint to Ground Fault**

A single line to ground fault on phase *a* was applied at the starting point of the transmission line, while the generator was operating at no-load. The output of this study is shown in figure 6.4 as:

- The field current $I_f(t)$ shown in figure 6.4a appears similar to that in case of three phase fault except the existence of a third harmonic component super-imposed on it. This third harmonic component arises from the existence of zero sequence currents it the armature windings. The field current finally settles down to its normal value after clearing of the fault.

- The components of the reactive power output of the generator as shown in figure 6.4b, also have the same form as that of three phase fault except the existence of third harmonic oscillations due to the zero sequence currents flowing in the armature windings.

- Similarly the rotor load angle $\delta$ has third harmonic oscillations super-imposed on it as shown in figure 6.4c. Finally these oscillations die out and the rotor load angle settles to its steady state value.

- The response of the new relaying algorithm shown in figure 6.4d also has a third harmonic oscillations imposed on it. The total reactive power output stays always positive, and as it can be seen the new algorithm produces no tripping signal.

While when a line-ground fault applied at the same point as in the previous case with the generator fully loaded, the response of this new relaying algorithm is shown in figure 6.5. Where also it can be seen that the new algorithm does not indicate any loss of field, and stays stable.

**c. Line to Line Fault**

Using the same circuit connection as used in previous cases, and under the same loading conditions a solid line-line fault between phases *b* and *c* was applied at the starting-point of one of the transmission lines, and cleared after 0.1 sec.

While figure 6.6 shows the response of the system to a line to line fault with an unloaded generator, figure 6.7 shows the case where the generator was fully loaded. As expected the new algorithm doesn't indicate any loss of field, and stays stable during this abnormal condition.

**d. Line to Line to Ground Fault**

Using the same circuit connection as used in previous cases, a solid line-line-ground fault was applied between phases *b* and *c* at the starting-point of one of the transmission lines. The fault was cleared after 0.1 sec by opening the circuit breakers at both ends of the line. Case of unloaded generator is shown in figure 6.8, while the case of a fully loaded generator is shown in figure 6.9.

Also as expected the algorithm doesn't indicate any loss of field on the generator, and stays stable during this abnormal condition.

**e. Re-closing on a Three phase Fault**

To study the effects of the severe power swings on the relaying algorithm, re-closing of the circuit breakers on a three-phase fault was also included in these simulations Two cases are studied, in which the re-closing delay time was varied as shown in figures 6.10 and 6.11 respectively. It can be pointed out that:

- Figure 6.10a shows the field current ($I_f$) flowing in the field winding during this study case. It is clear that after re-closing, the field current increases to about 18 pu, and then it starts to decrease to its final steady state value. The field current also contains oscillations super-imposed on it as a result of the dc-offset current during this fault.

- Figure 6.10b shows the components of the reactive power output of the generator. They also contain oscillations due to the existence of dc-offset current in the armature winding of the generator.

- Figure 6.10c shows the rotor load angle δ as a function of time. This curve show that the rotor load angle was subjected to a very high severe swings as a result of this re-closing. The load angle finally settles down to its normal value after clearing of the fault.

- Figure 6.10d shows the response of the new relaying algorithm. It is clear that no trip signal was issued, and the algorithm stayed stable.

The same comments could be applied to the results shown in figure 6.11 as that to the previous figure.

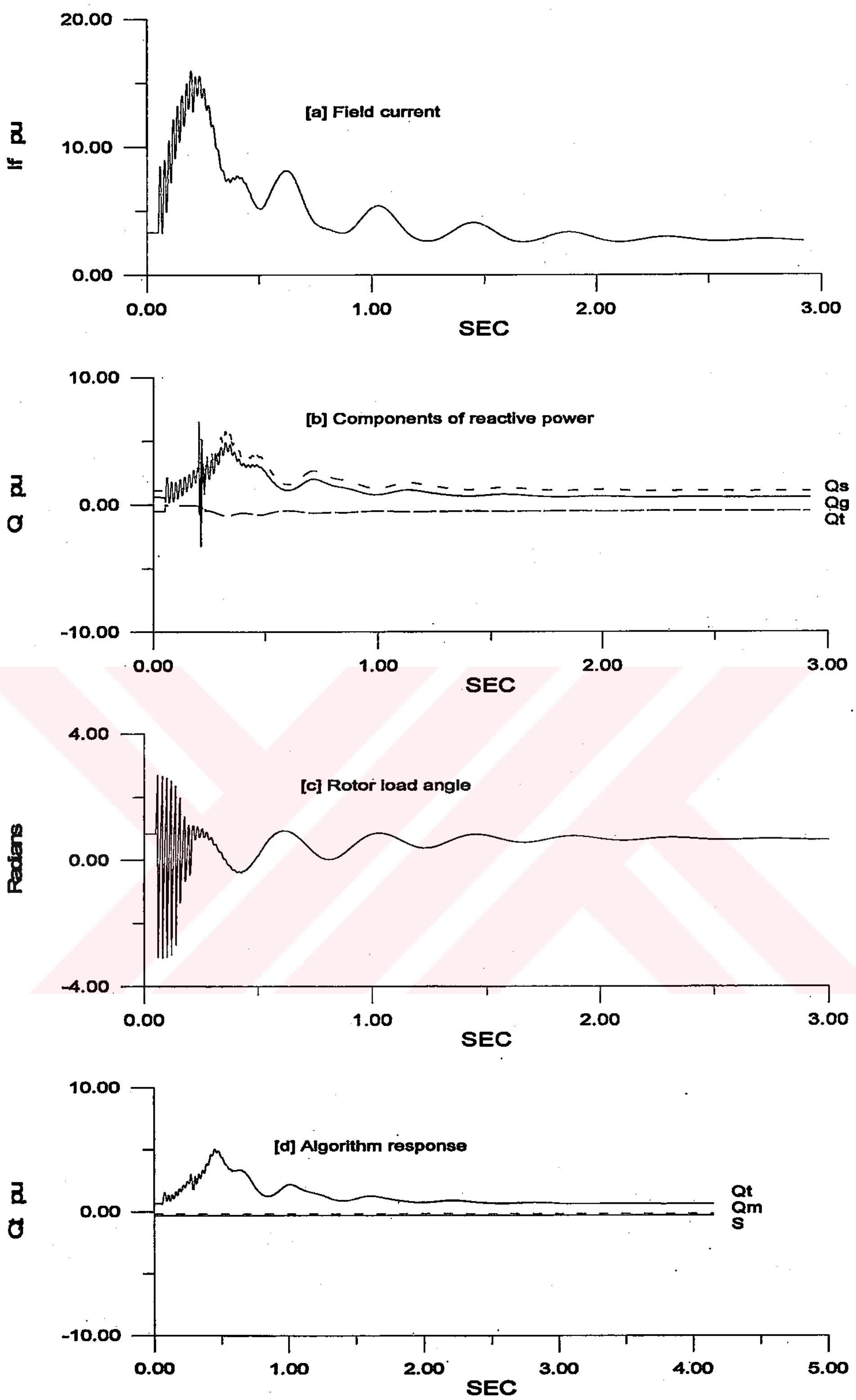



Figure 6.2 Response to an external three phase fault while the generator operating at no-load

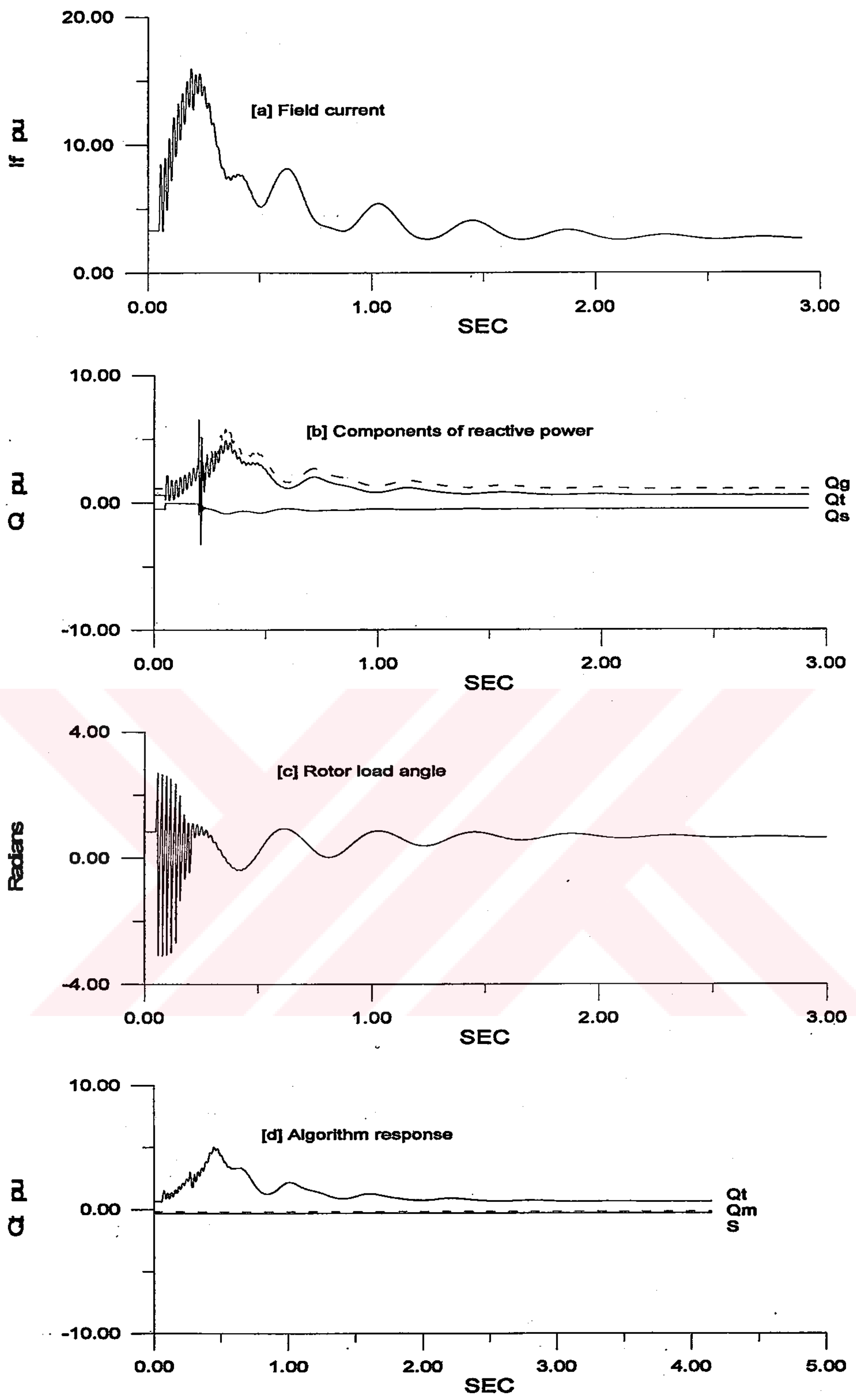



Figure 6.3 Response to an external three-phase fault while generator operating at full load.

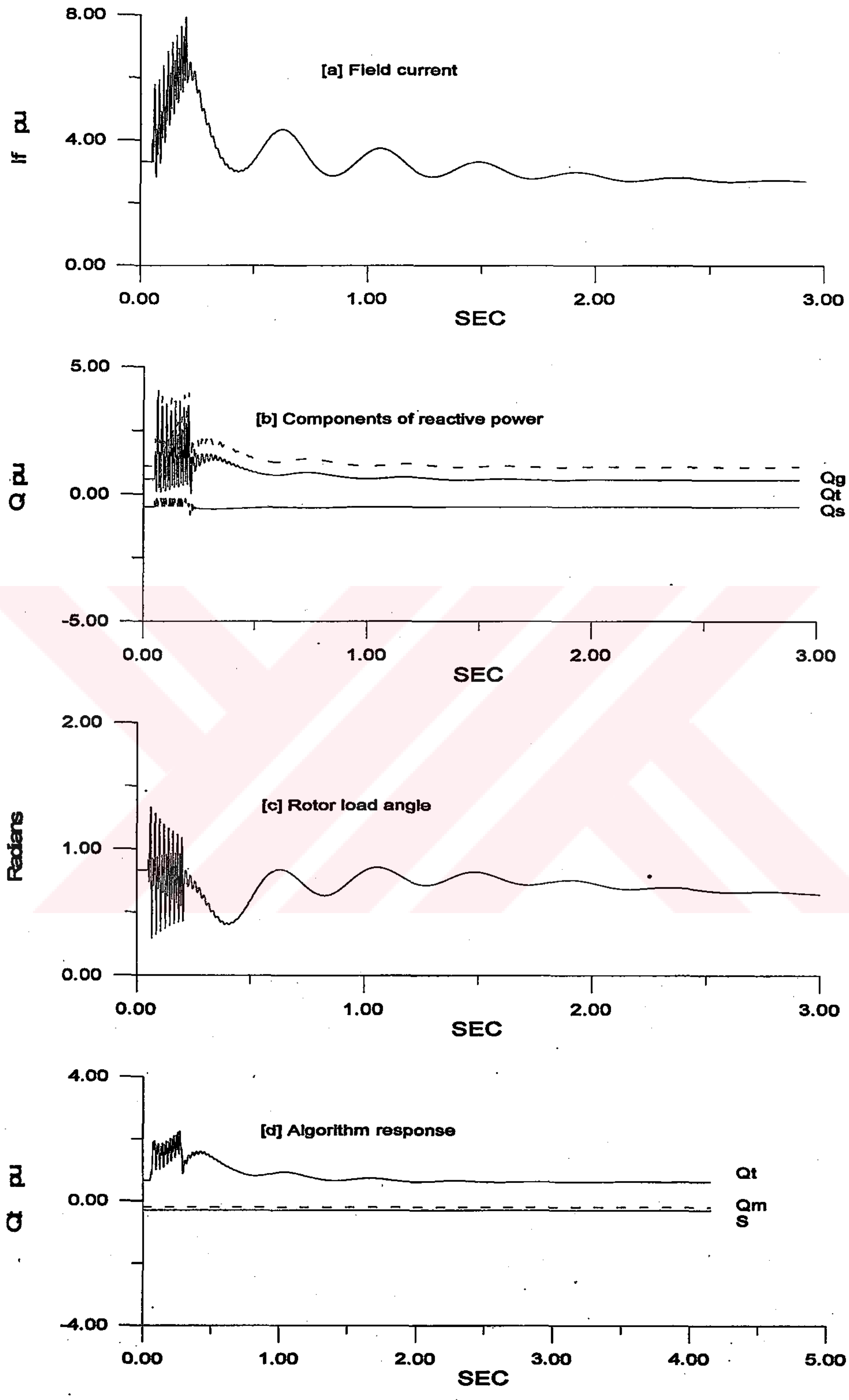



Figure 6.4 Response to an external line-ground fault while generator operating at no-load.

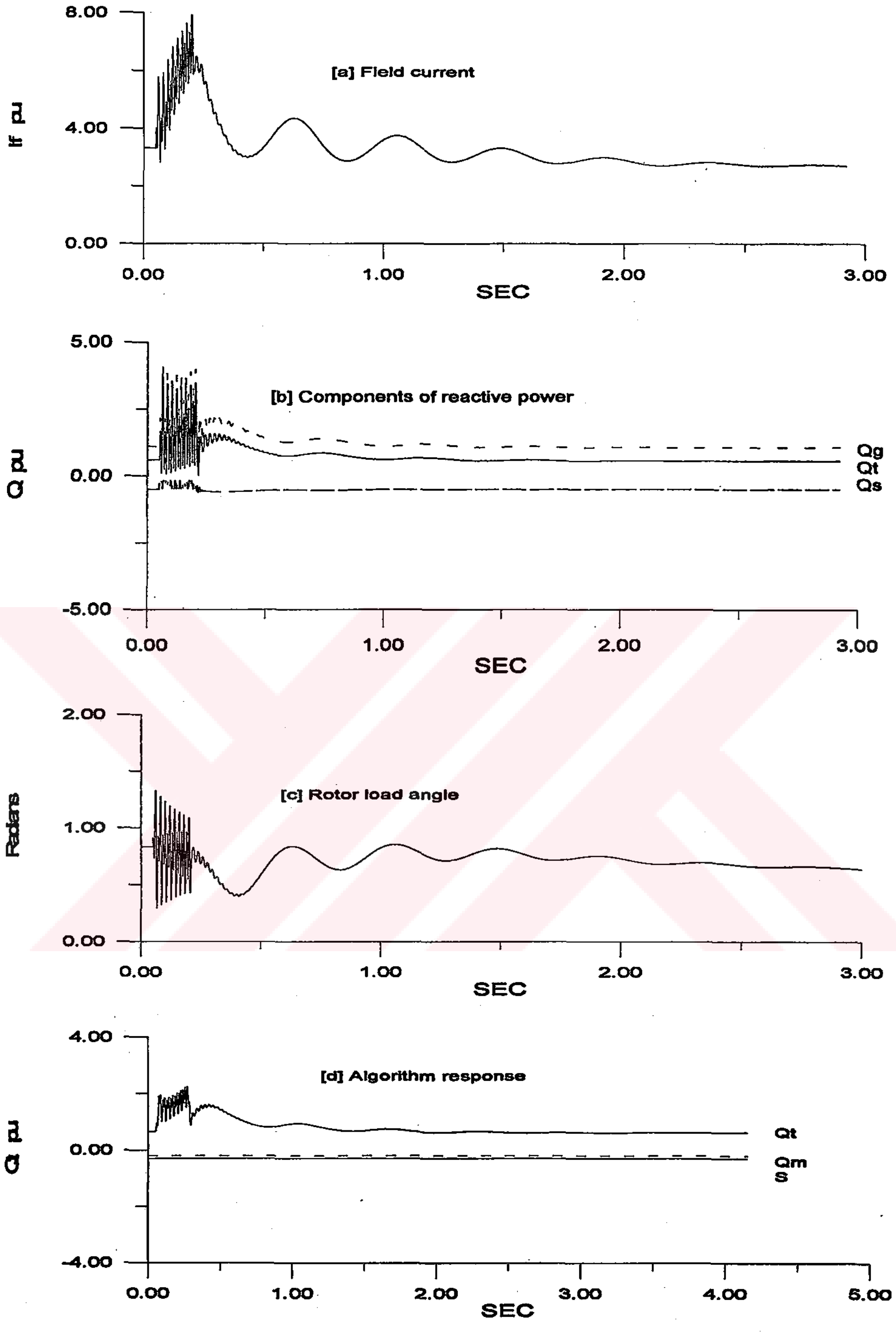



Figure 6.5 Response to an external line-ground fault while generator operating at full load.

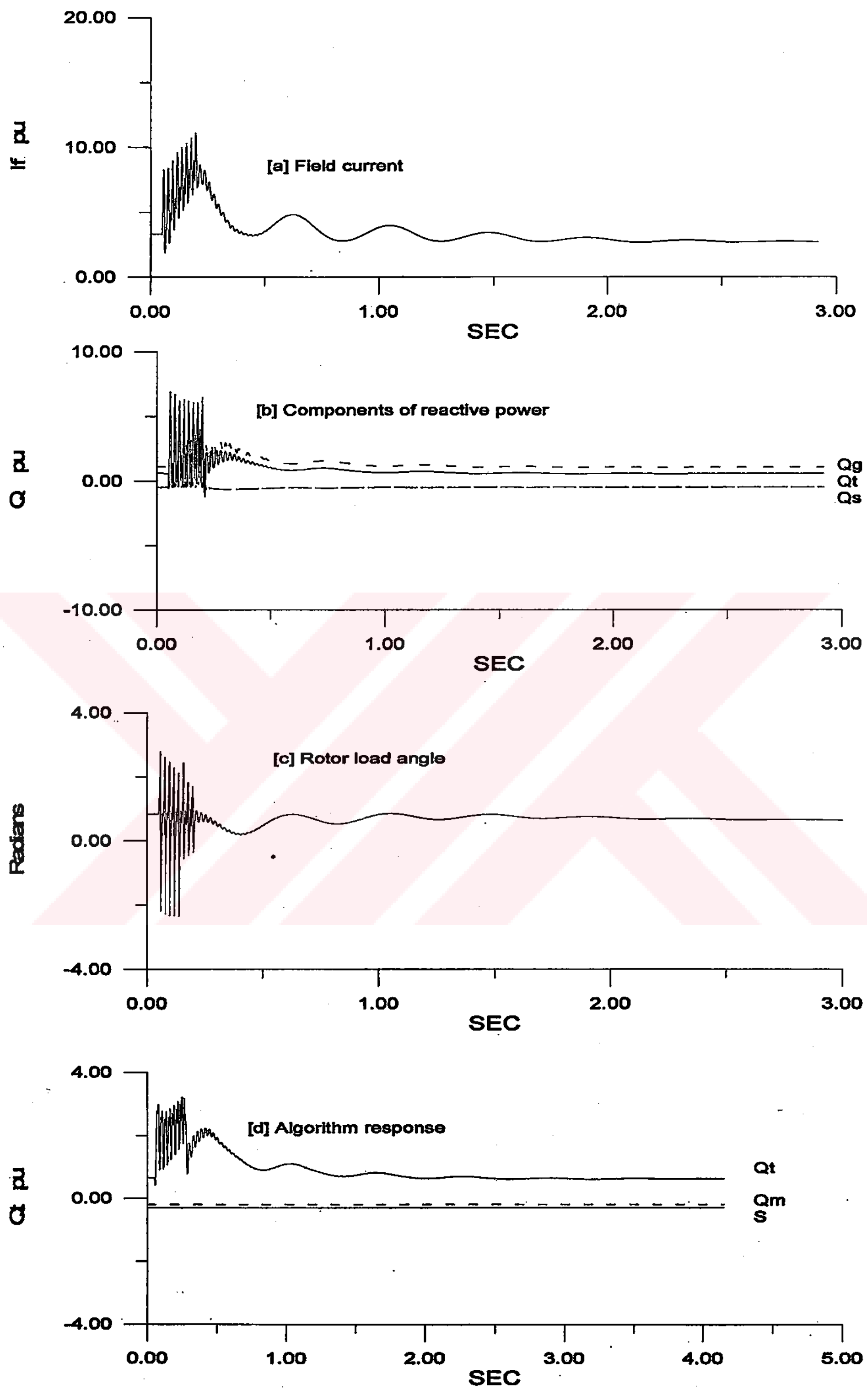



Figure 6.6 Response to an external line-line fault while generator operating at no-load.

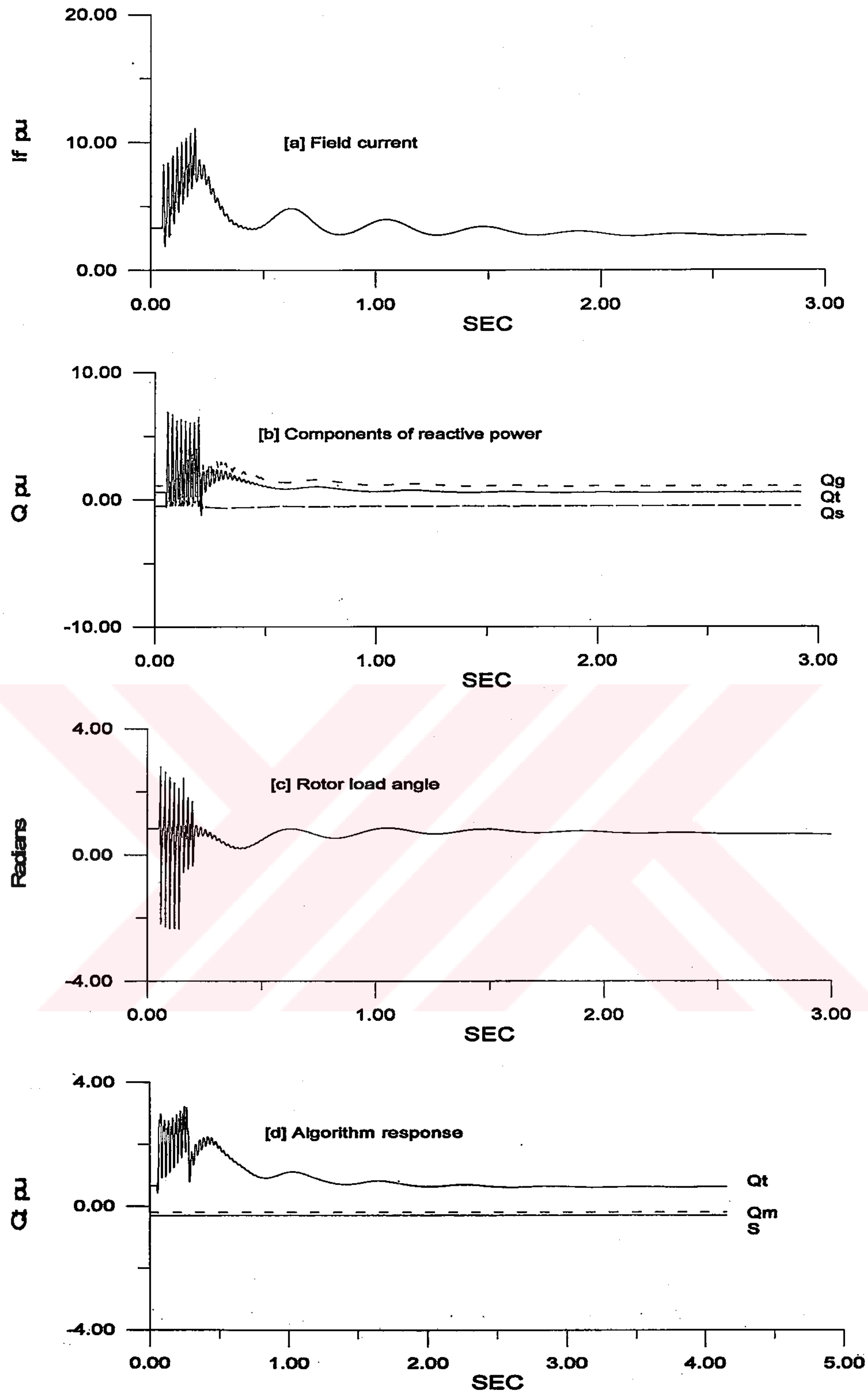



Figure 6.7 Response to an external line-line fault while generator operating at full load.

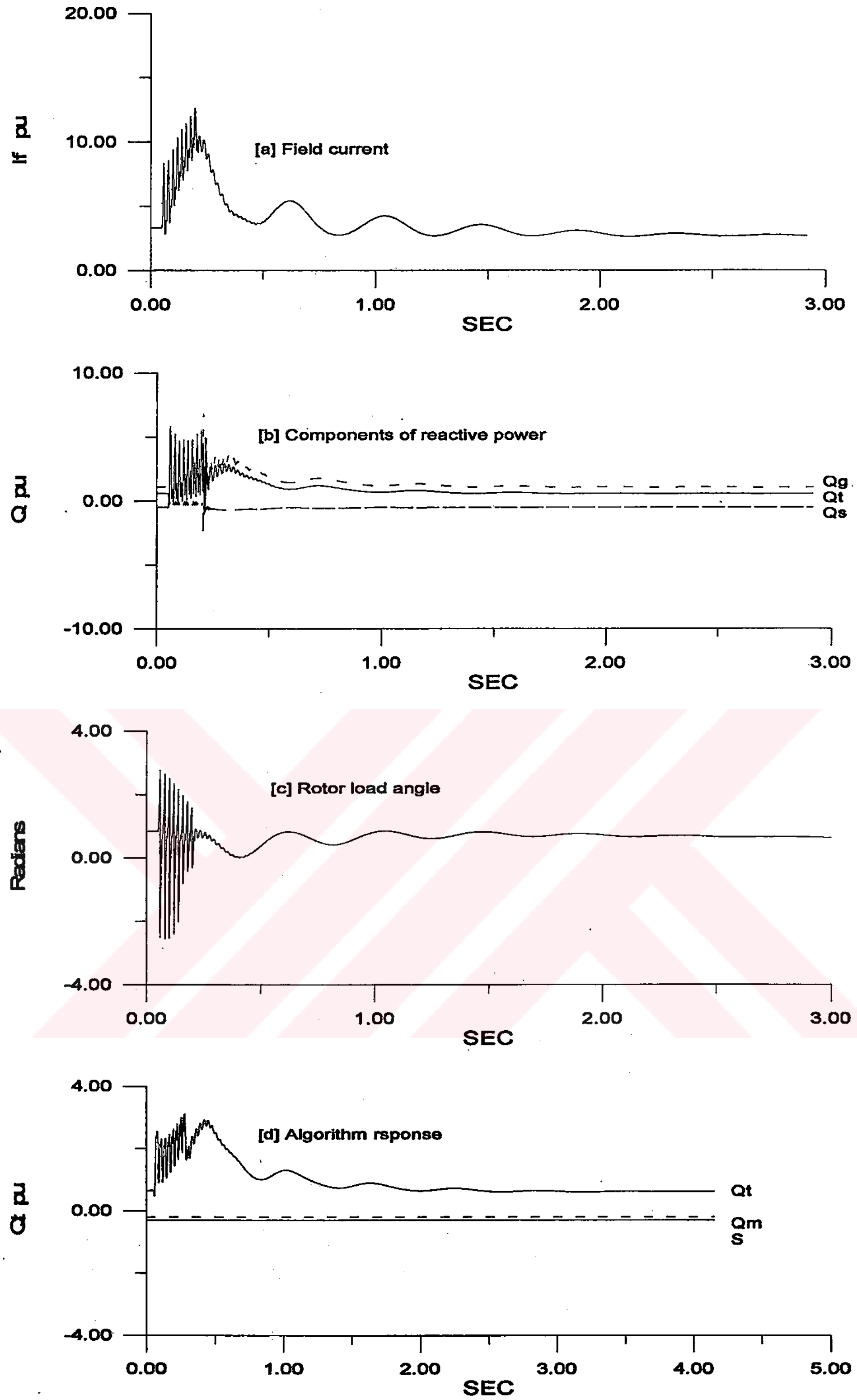



Figure 6.8 Response to an external line-line-ground fault, while generator operating at no-load.

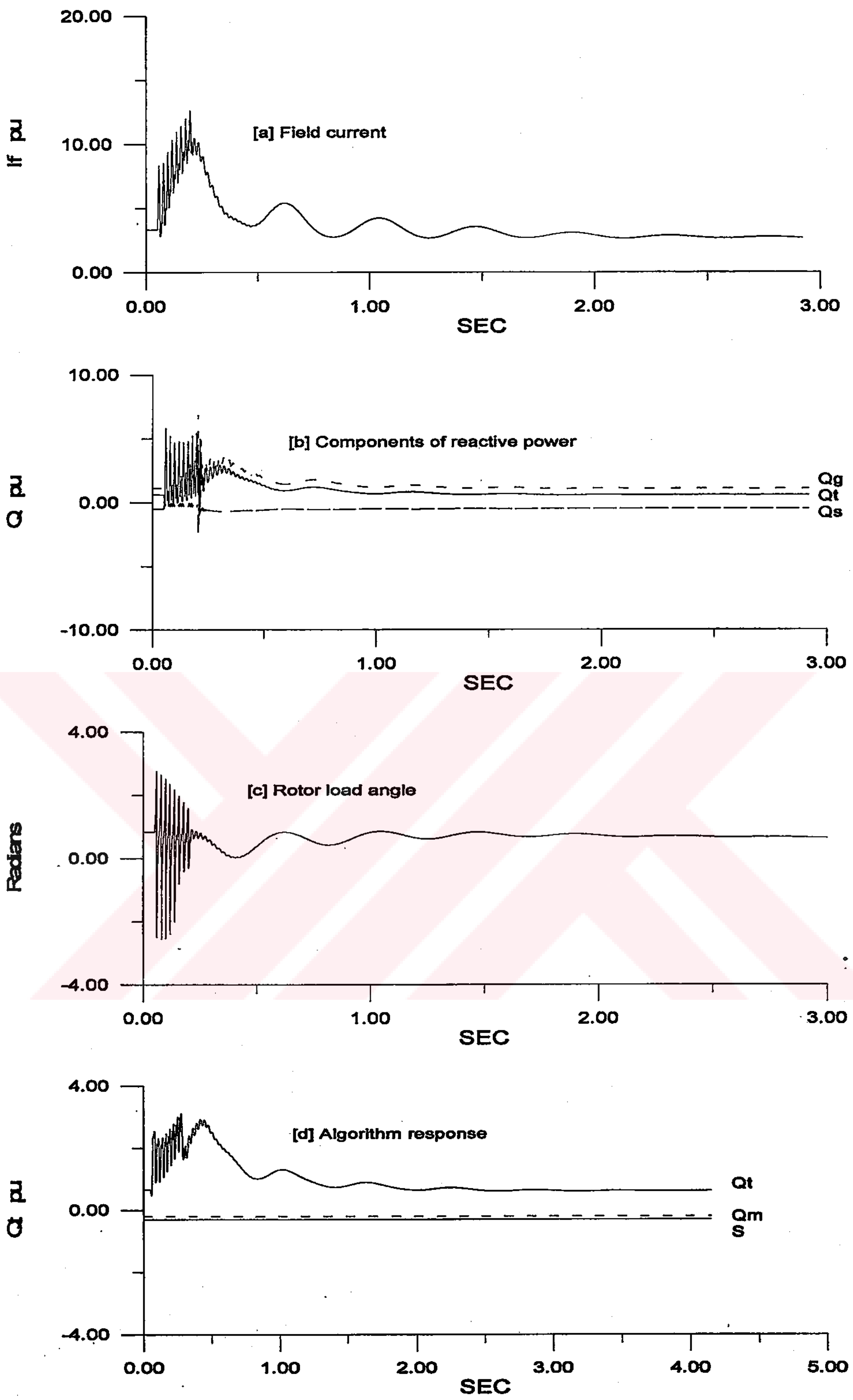



Figure 6.9 Response to an external LLG fault while generator operating at full load.

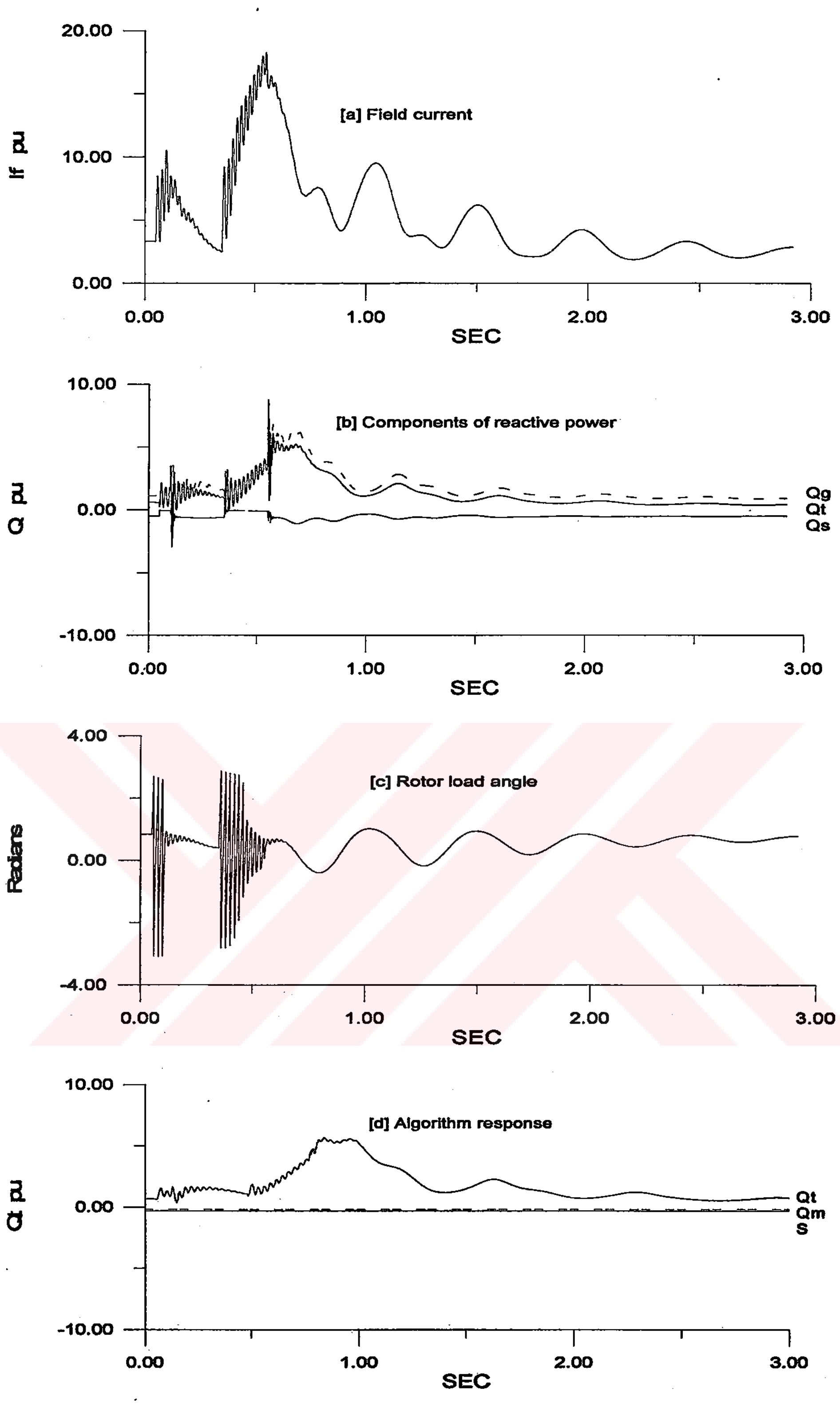



Figure 6.10 Response to re-closing operation on three phase fault while the generator was fully loaded.

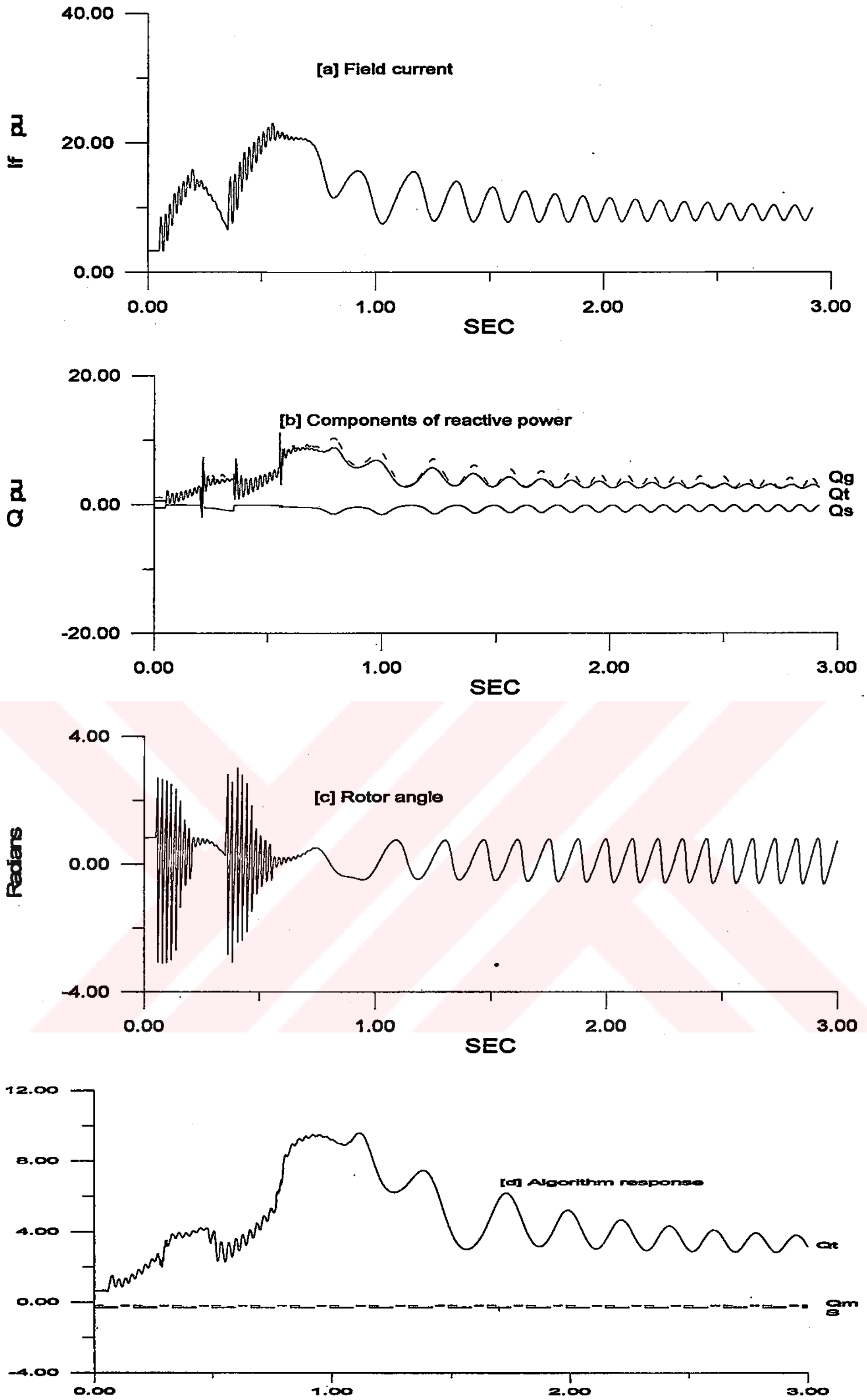



Figure 6.11 Response to re-closing on three phase fault while the generator was fully loaded. Here a shorter re-closing time was used.

### 6.2.2. Loss of Field Studies

Loss of field resulting from either short-circuited or open circuited field winding was also studied. The percentage loading of the generator as well as the generator power factor was varied over a wide range in order to see the effect of loading of the generator, and its power factor on the performance of the new relaying algorithm.

**I- Complete Loss of Field Studies**

The results of the simulation of these cases are shown in figures 6.12 to 6.20, where it can be seen that:

- The first curve *a* represents the field current flowing in the field winding during the loss of field. This current starts to decrease exponentially with time up to the point where the generator losses its stability with the power system, when it starts to oscillate about its decaying curve. From this curve it is clear that loss of field of the generator manifest itself in a decaying exponential form as it is usual in inductive circuits.

- Curve *b* shows the components of the reactive power output of the generator. In this curve it is clear that the internally generated reactive power $Q_g$ decays first in an exponential form in accordance with the decay of the field current. Then when the generator losses its stability with the power system, it start to oscillate at the same frequency as that of the field current. While on the other hand the reactive power supplied by the system $Q_s$ follows the changes in the terminal voltage of the generator, and is not affected by the changes in the field current. This is true up to the point where the generator losses stability with the power system, when it also start to oscillate too. The sum of the above two components is the total output reactive power $Q_t$. In all of the above study cases the total reactive power goes negative flowing from the power system back to the generator.

- Curve *c* shows the rotor load angle δ as function of simulation time. As expected the rotor load angle start to increase when the generator losses its field due to the increase in the generator speed. Then when the generator losses its stability with the power system, this angle oscillates at the same frequency as that of the field current.

- Curve *d* shows the response of the new relaying algorithm, where in all loss of field study cases, the algorithm manage to detect the loss of field early enough before the generator losses its stability with the power system. This result is what is needed from this algorithm to do (to detect and issue trip signal before the generator losses its stability with the power system). Also from these results it can be seen that the trip time decreases as the power factor becomes closer to unity as in this case the total reactive power gets close to zero, and so it is easier to go negative The trip time also gets smaller as the percentage loading of the generator decreases, since in this case the total output reactive power of the generator gets smaller.

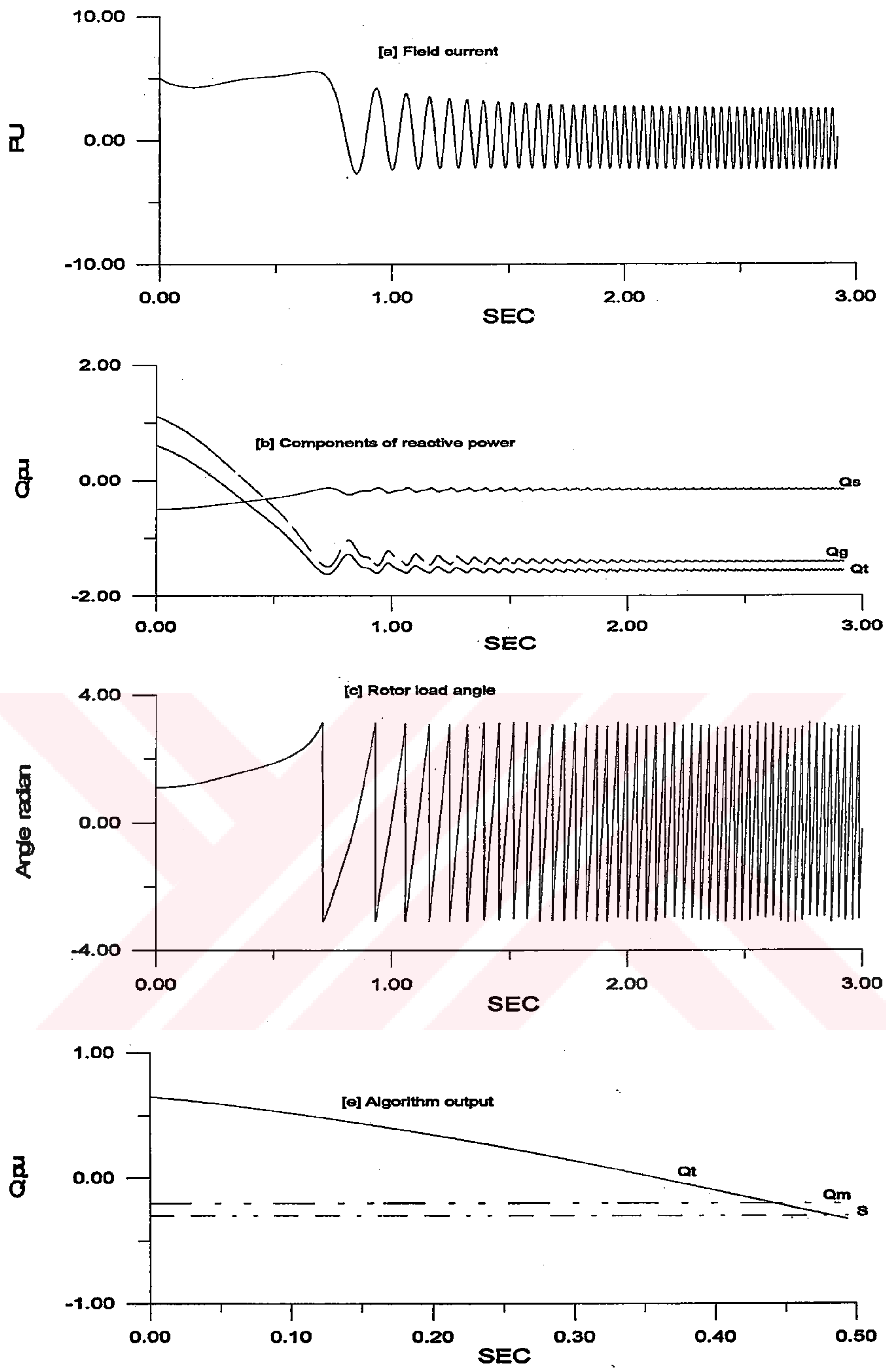



Figure 6.12 Response to loss of field of a generator with a 100% loading, and unity power factor.

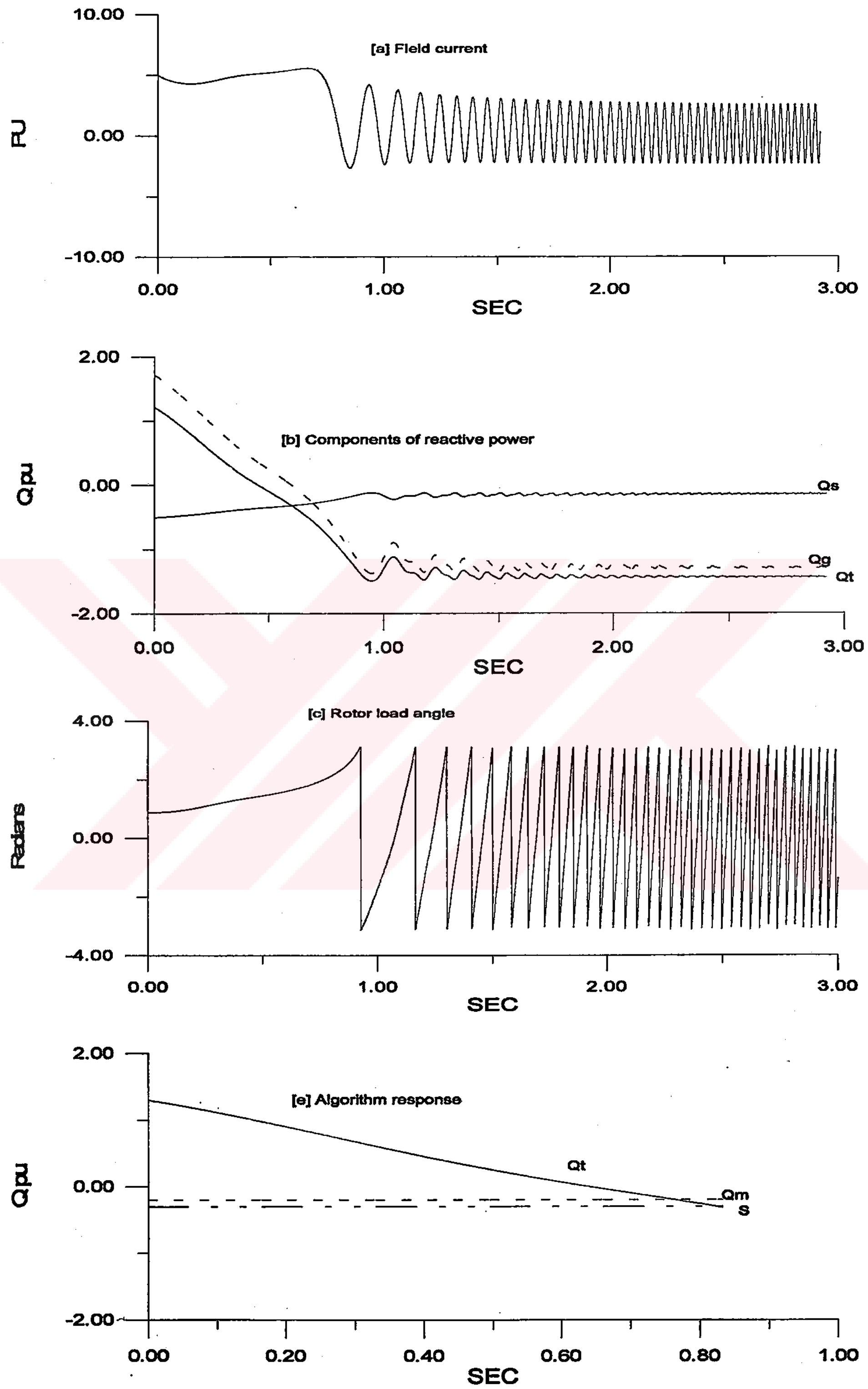



**Figure 6.13 Response to loss of field of a generator at full load, and .8 lagging power factor.**

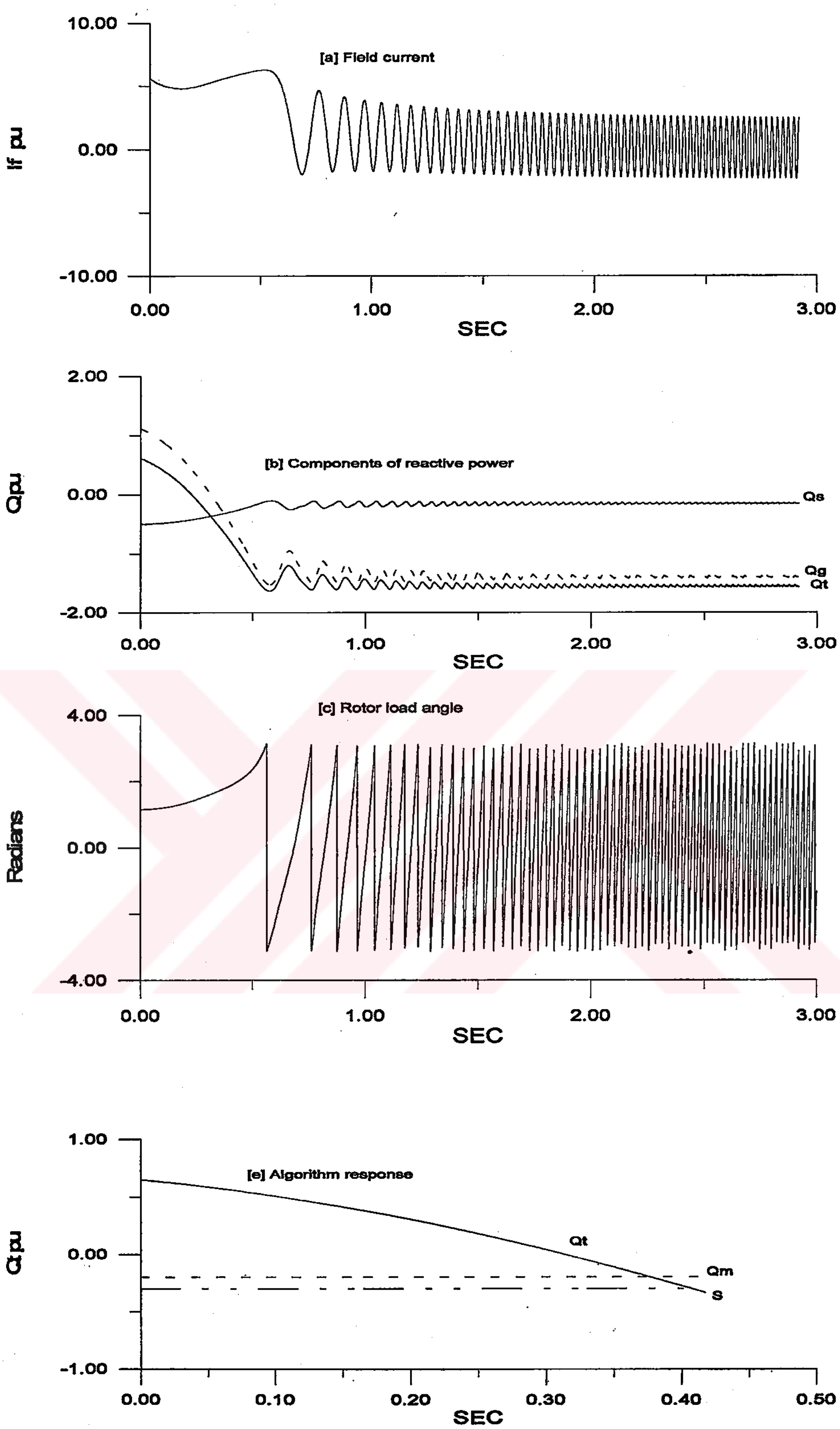



Figure 6.14 Response to loss of field of a generator at 75% loading, and unity power factor.

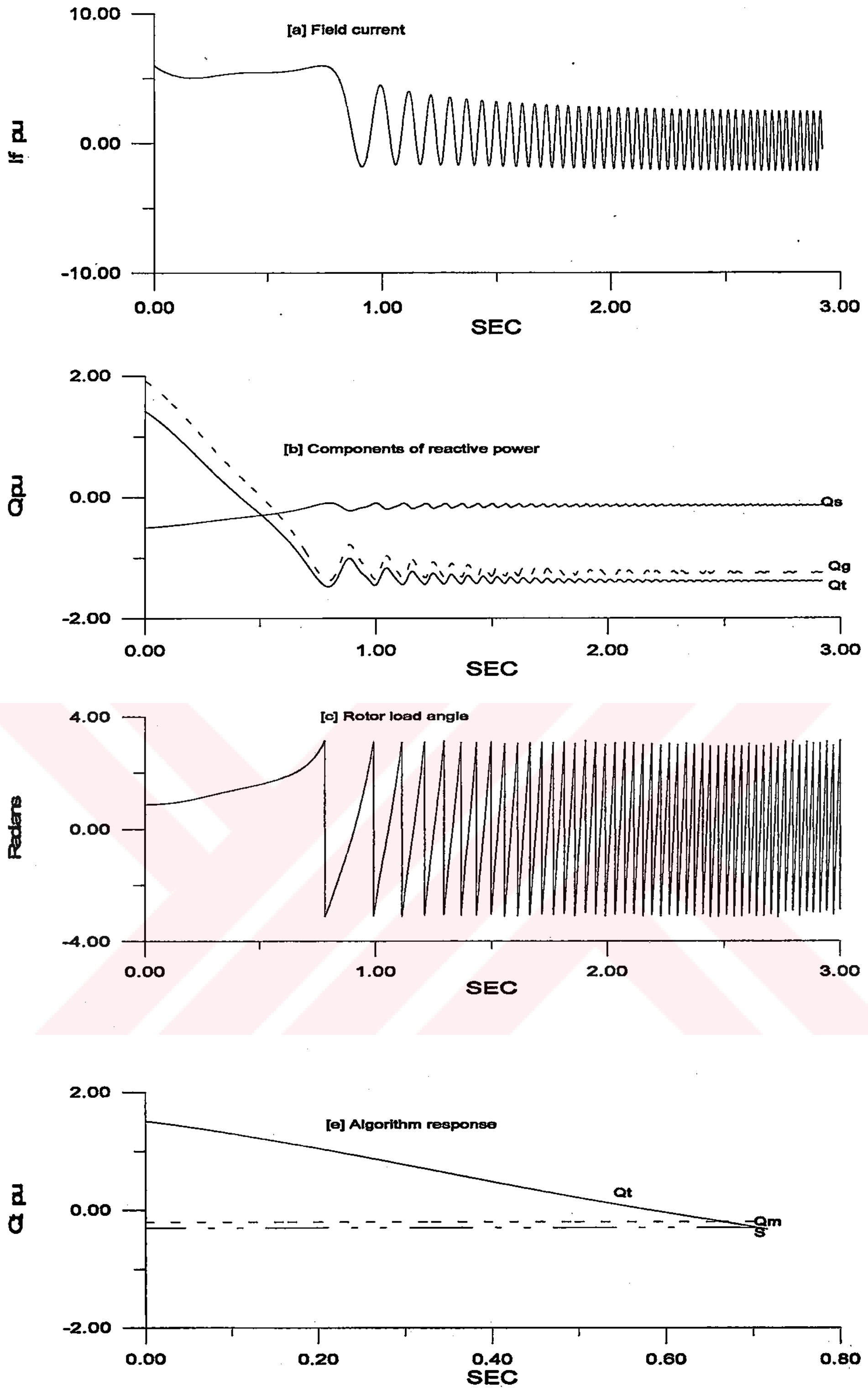



Figure 6.15 Response to loss of field of a generator at 75% loading, and .8 lagging power factor.

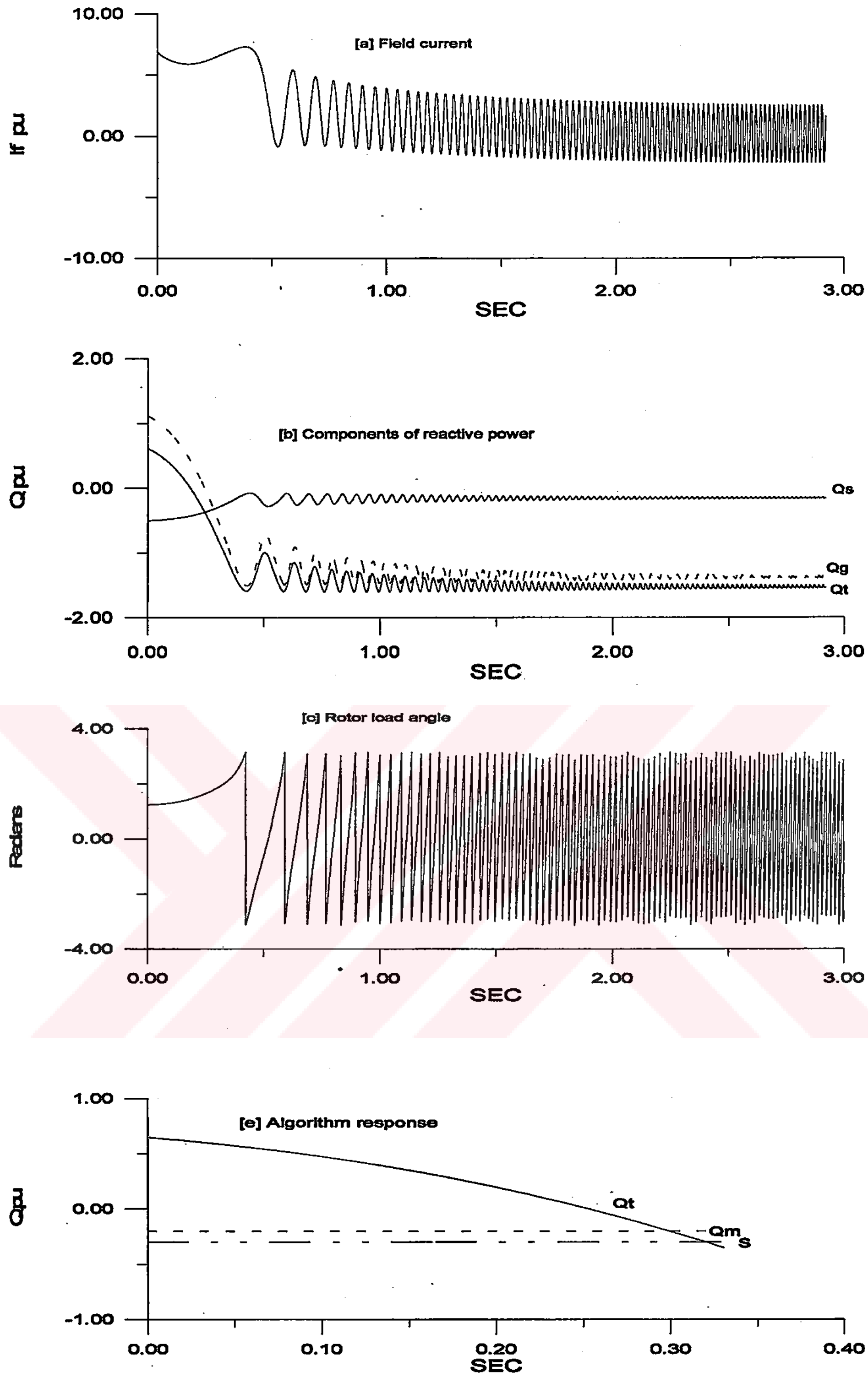



Figure 6.16 Response to loss of field of a generator at 50% loading, and unity power factor.

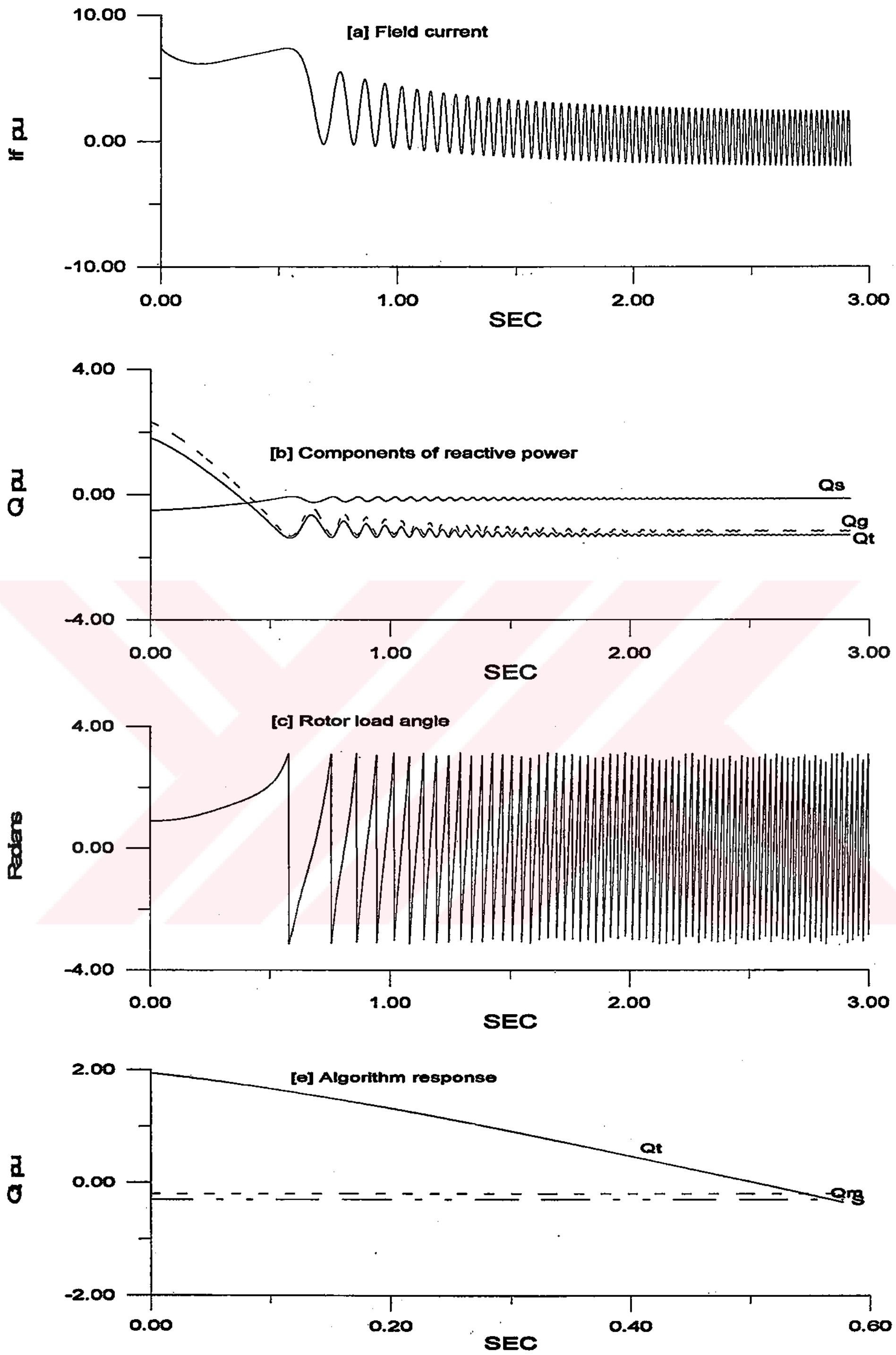



Figure 6.17 Response to loss of field of generator at 50% loading, and .8 lagging power factor.

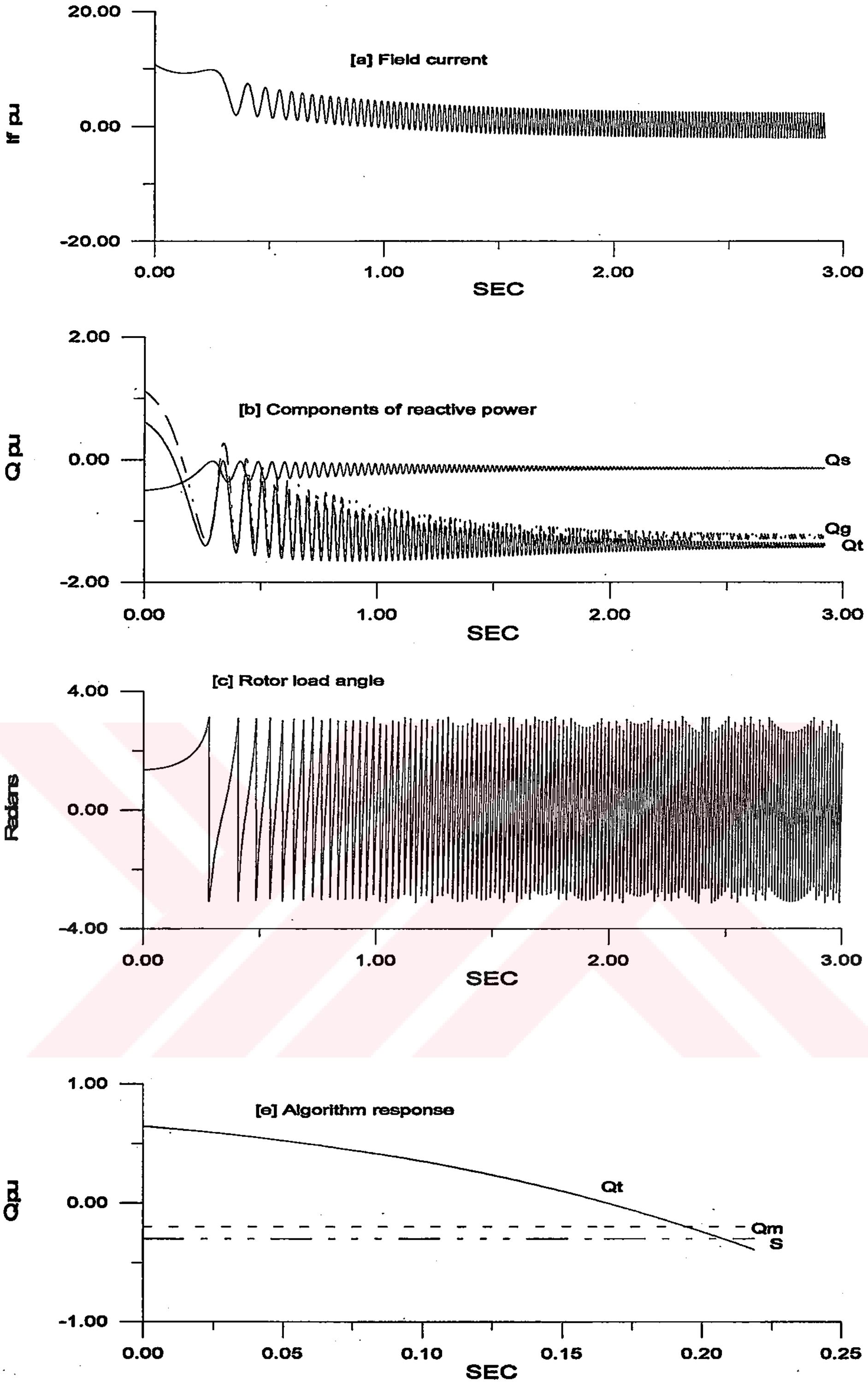



Figure 6.18 Response to loss of field of generator at 25% loading, and unity power factor.

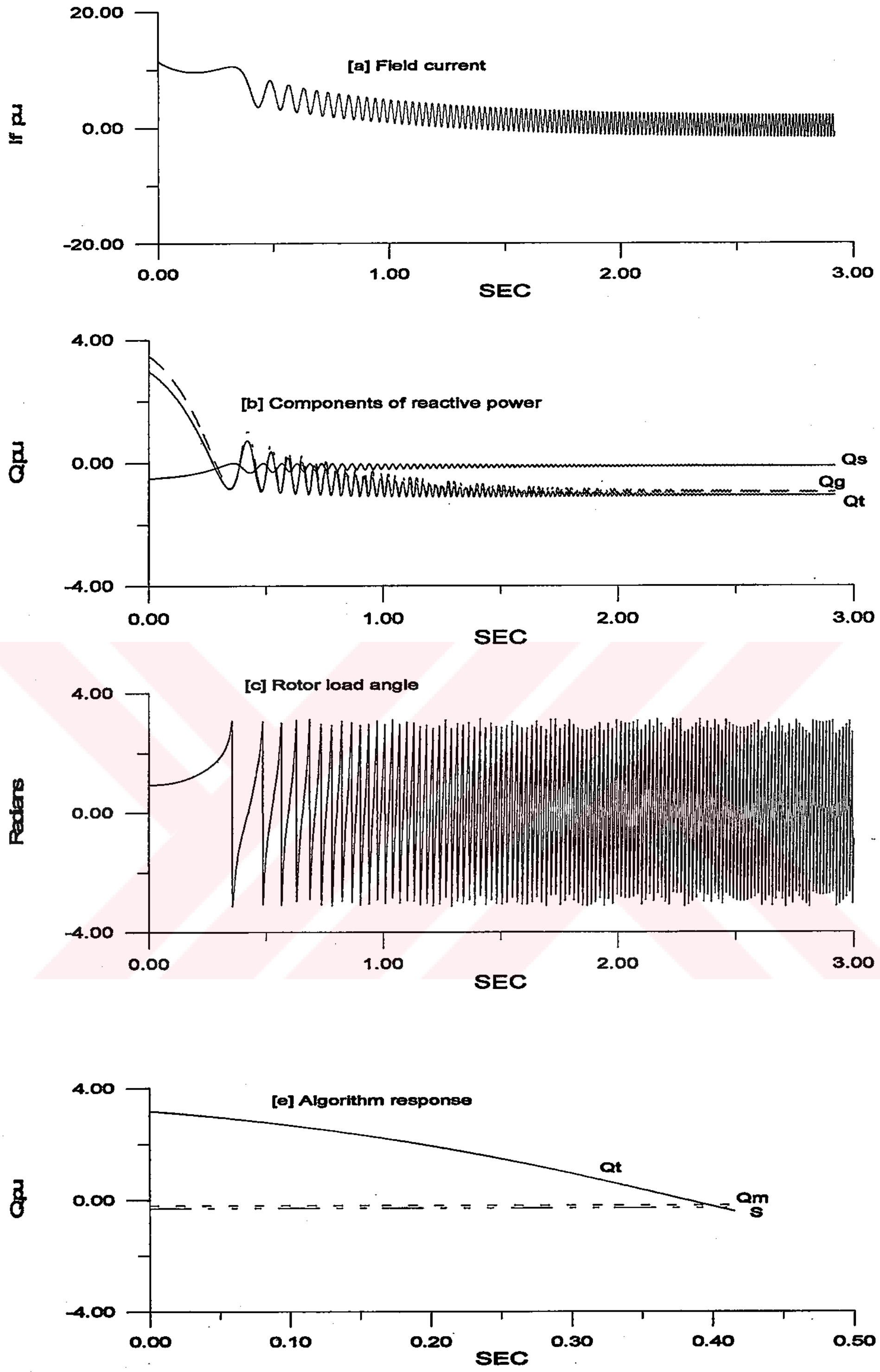



Figure 6.19 Response to loss of field of generator at 25% loading, and 0.8 lagging power factor.

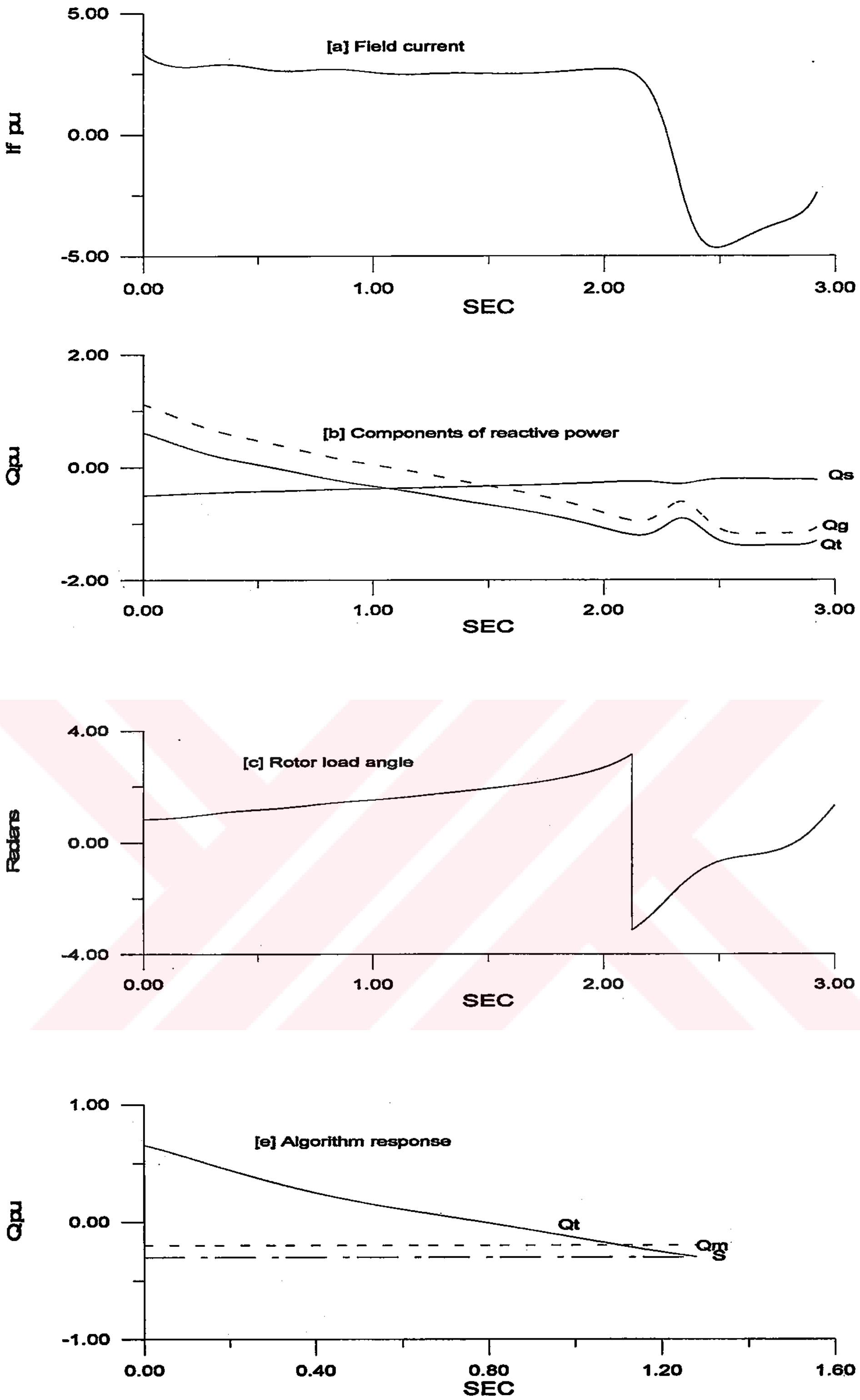



Figure 6.20 Response to loss of field of generator at no-load.

The results of these study cases are collected in table 6.1.

Table 6.1 Loss of excitation results of the new algorithm.

| Percentage loading | Load power factor | Trip time in sec |
|---|---|---|
| 100 | 1.0 | 0.4826 |
| 100 | 0.8 lagg. | 0.833 |
| 75 | 1.0 | 0.4175 |
| 75 | 0.8 lagg. | 0.4175 |
| 50 | 1.0 | 0.3306 |
| 50 | 0.8 lagg. | 0.5778 |
| 25 | 1.0 | 0.2188 |
| 25 | 0.8 lagg. | 0.4158 |
| 0.0 | | 1.281 |

**II- Partial Loss of Field Studies**

The curves related with partial loss of field are shown in figures 6.21 to 6.29. From these figures it can be seen:

- Curve *a* in each of the figures shows the field current as a function of time after the field has lost certain percentage of its winding. This curve shows that the field current starts to decay with time up to the point when the generator losses its stability with the power system, after which it start to oscillate.

- Curve *b* shows the instantaneous components of the reactive powers $Q_g$, $Q_s$, and $Q_t$.

- Curve *c* shows the rotor load angle δ as function of time. It is clear that partial loss of field results in an increase in the speed of the rotor (as δ start to increase), up to the point when the generator losses its stability.

- Curve *d* shows the response of the new algorithm. In this curve the total reactive power output of the generator is plotted against the running time of the algorithm. When conditions of loss of field are met, the algorithm produces a trip signal and ceases its operation.

A collection of these results is given in table 6.2.

Table 6.2 Results of partial loss of field winding.

| **% loading** | **Power factor** | **% partial loss** | **Trip time sec** |
|---|---|---|---|
| 100 | 1.0 | 75 | 0.6546 |
| 100 | 1.0 | 50 | 1.6098 |
| 100 | 1.0 | 25 | 1.685 |
| 100 | 0.8 | 75 | 1.1022 |
| 100 | 0.8 | 50 | 0.9703 |
| 100 | 0.8 | 25 | 3.004 |
| 50 | 0.8 | 75 | 1.3694 |
| 50 | 0.8 | 25 | 4.1132 |
| 25 | 0.8 | 75 | 1.5564 |
| 25 | 0.8 | 25 | No trip |

From these simulations, and the results collected in table 6.2 it can be seen that:

- In nearly all of these cases the new algorithm was capable of detecting partial loss of field.

- The time needed by the algorithm to detect partial loss of field decreases as the percentage of the field winding lost increases

- When we lose only small percent of the field winding, and as the loading of the generator decreases, it takes longer time for the algorithm to detect that case. In this case the partial loss of field appears to the algorithm as an abnormal leading operation, where the algorithm introduces an adaptive time delay before producing a trip signal.

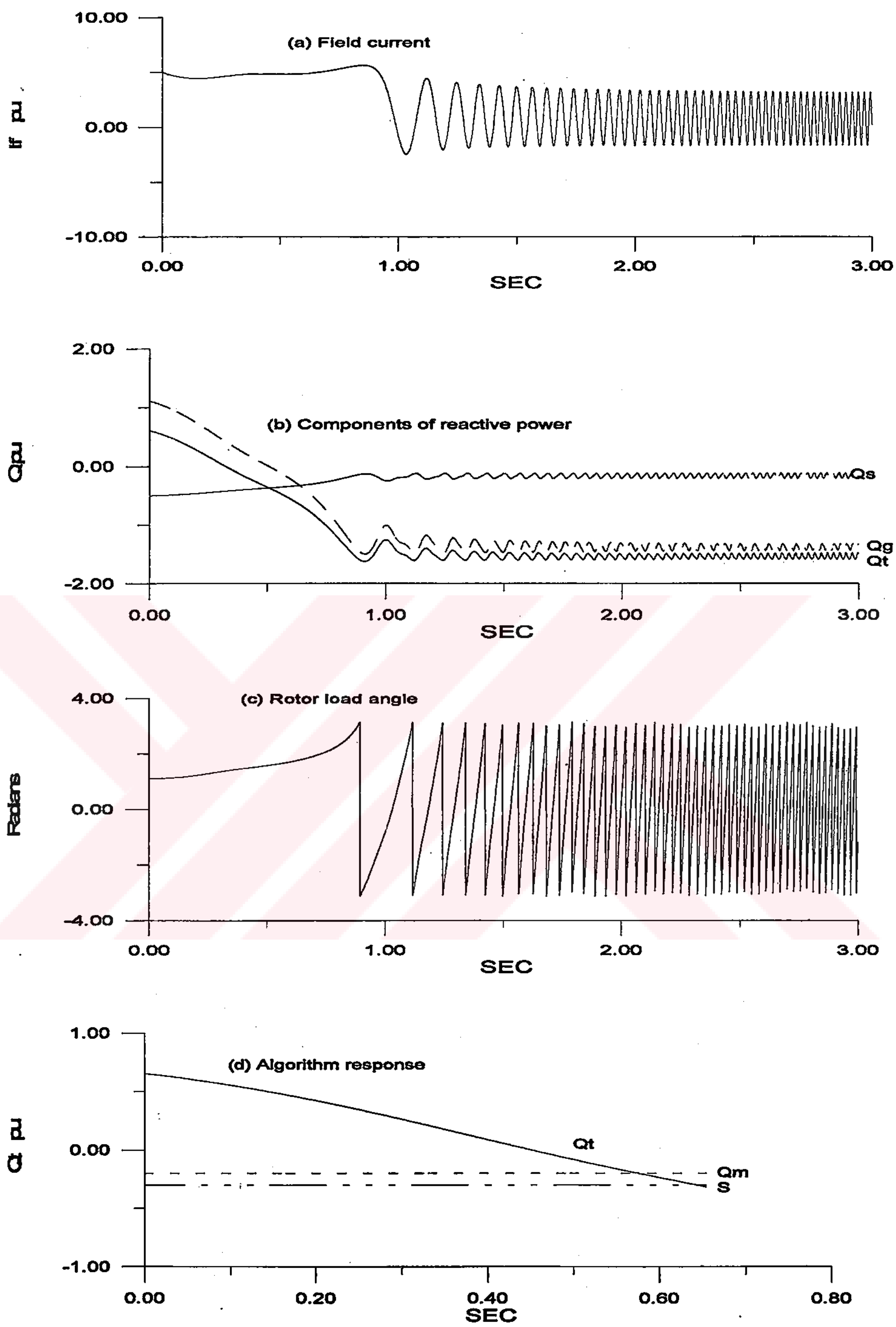



Figure 6.21 Response to partial loss of 75% of the field winding of a generator at full load with unity power factor.

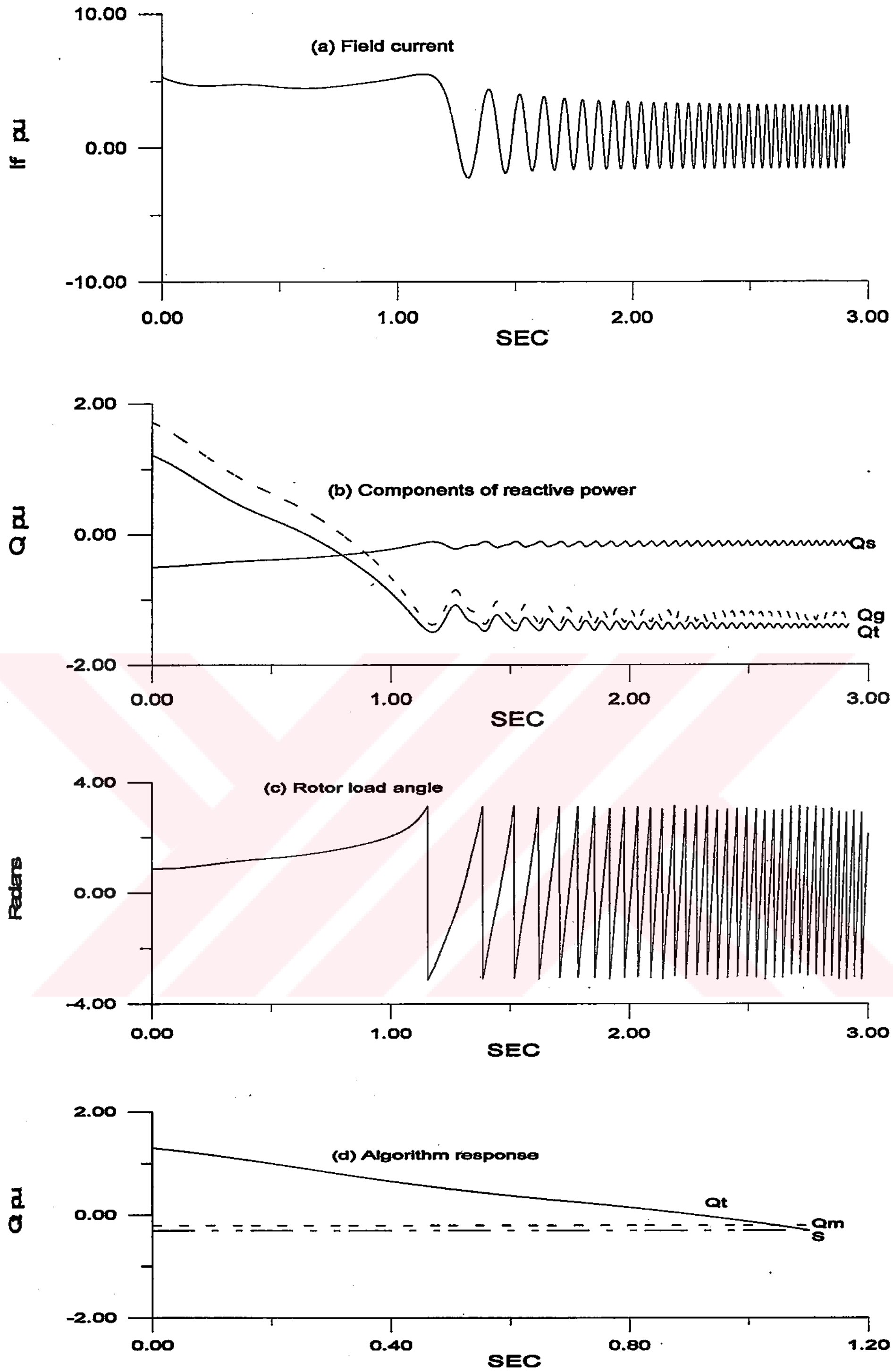



Figure 6.22 Response to a loss of 75% of the field winding of a generator operating at full load, and 0.8 lagging power factor.

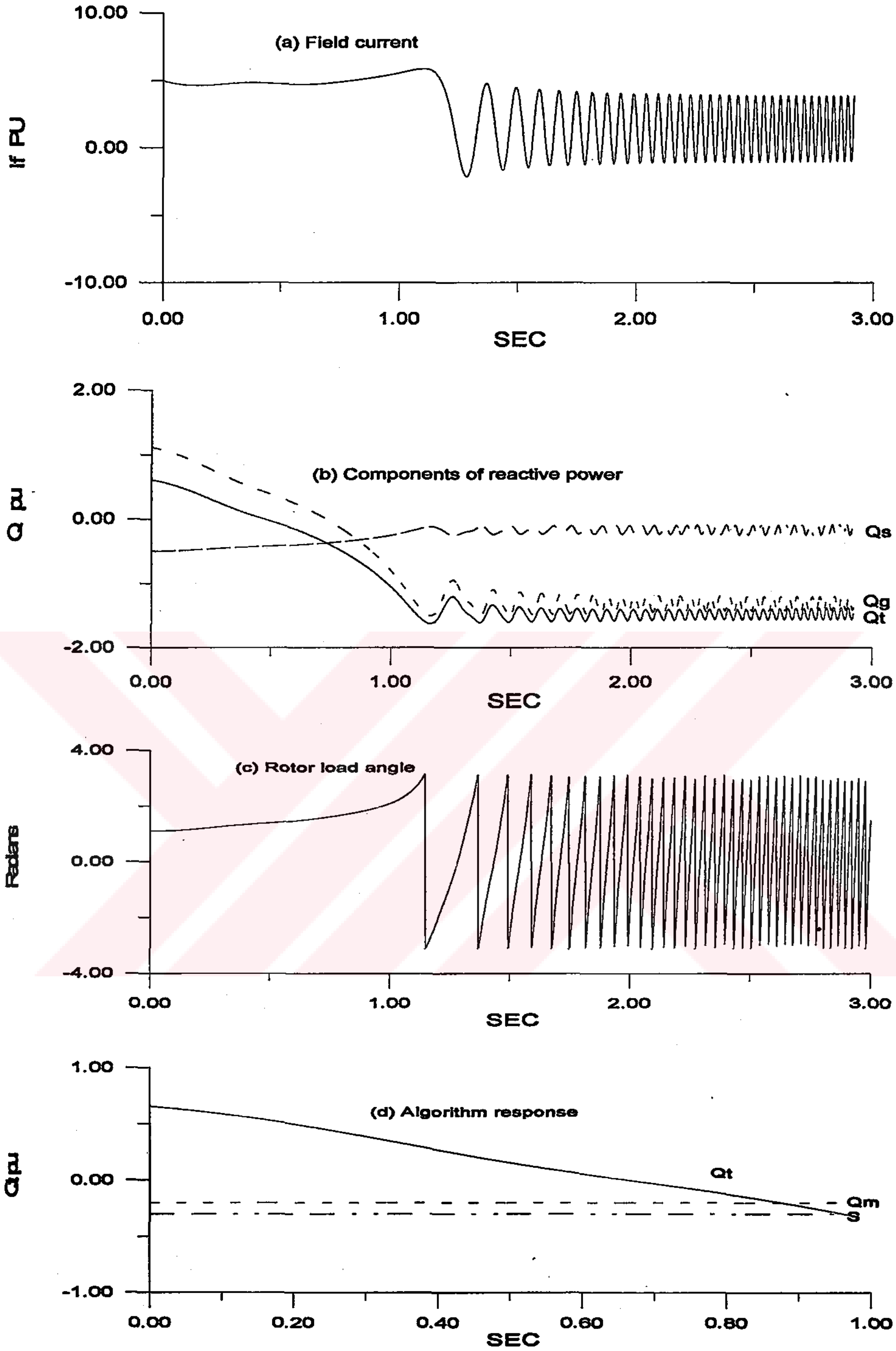



Figure 6.23 Response to a loss of 50% of the field winding of a generator operating at full-load, and unity power factor.

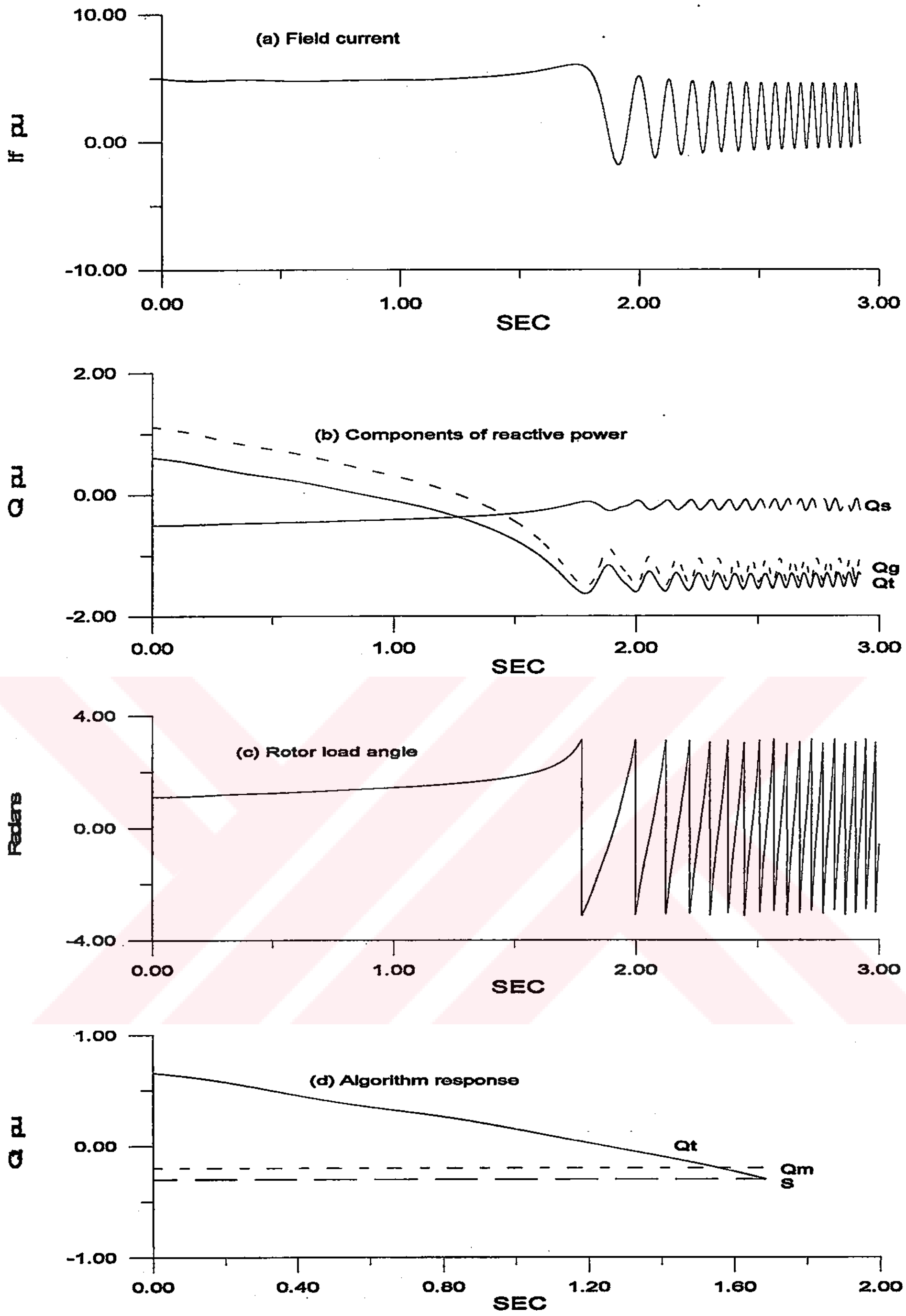



Figure 6.24 Response to a loss of 25% of the field winding of a generator operating at full-load, and a unity power factor.

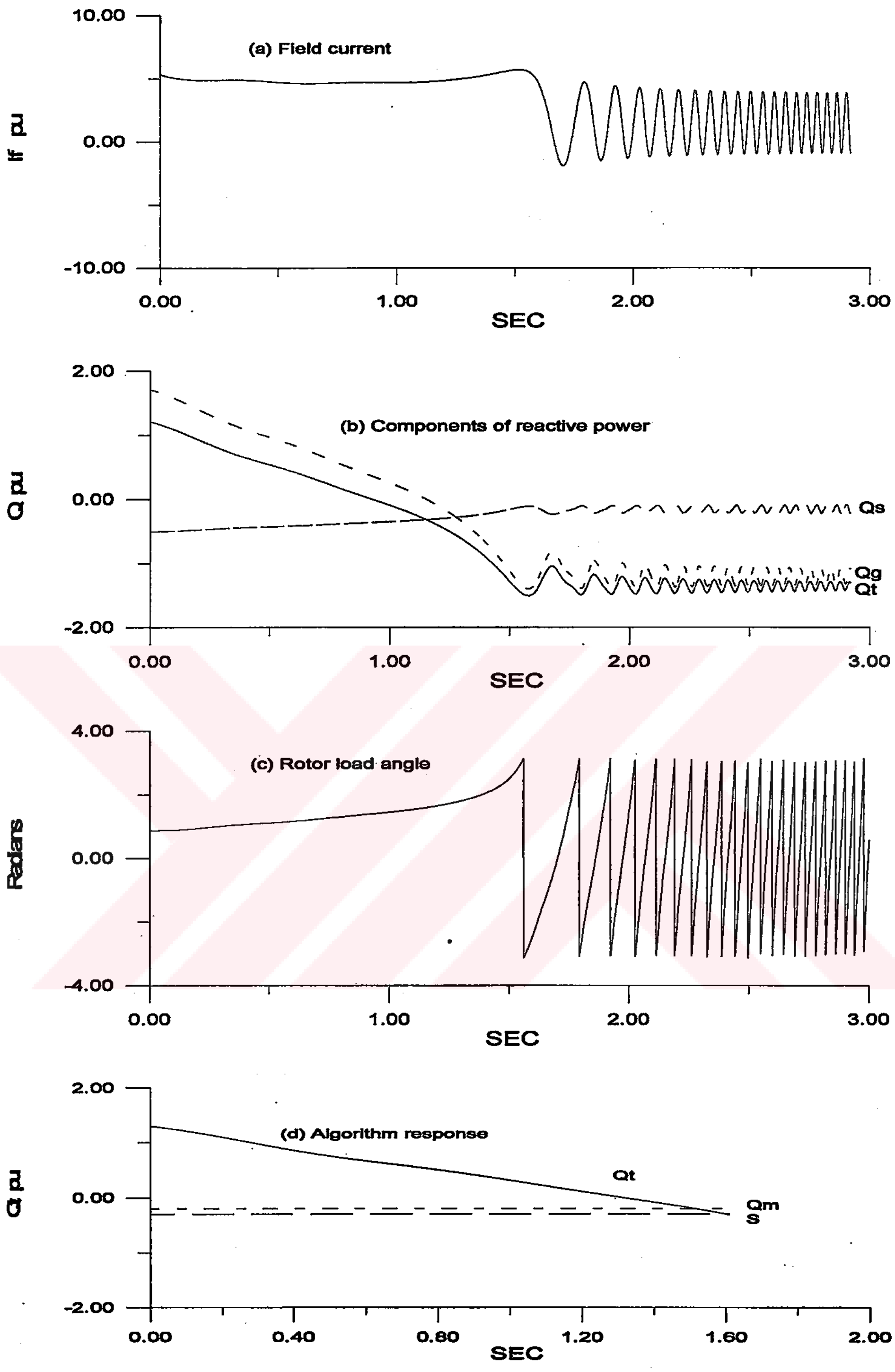



Figure 6.25 Response to a loss of 50% of the field winding of a generator operating at full load, and unity power factor.

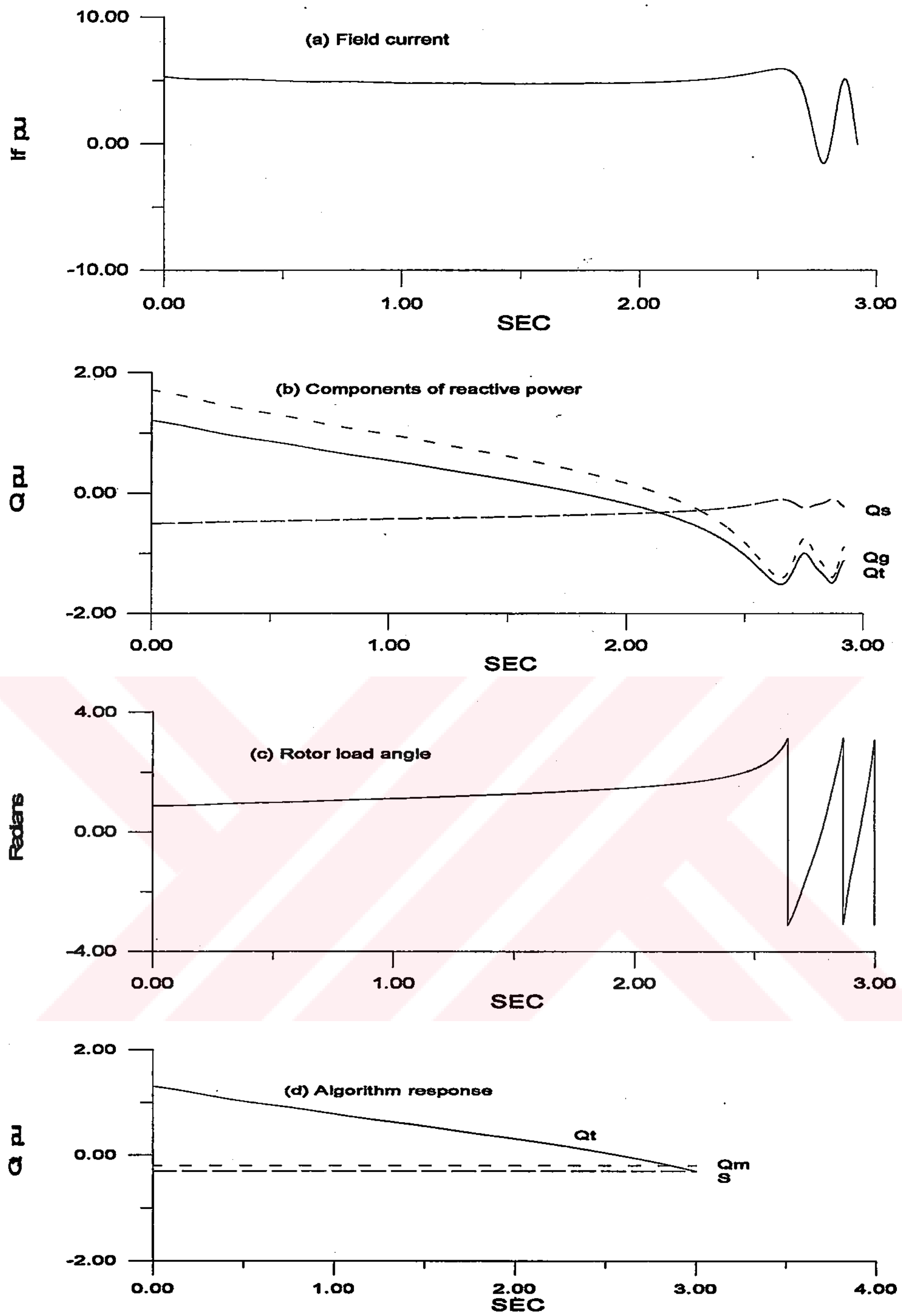



Figure 6.26 Response to a loss of 25% of the field winding of a generator operating at full load, and 0.8 lagging power factor.

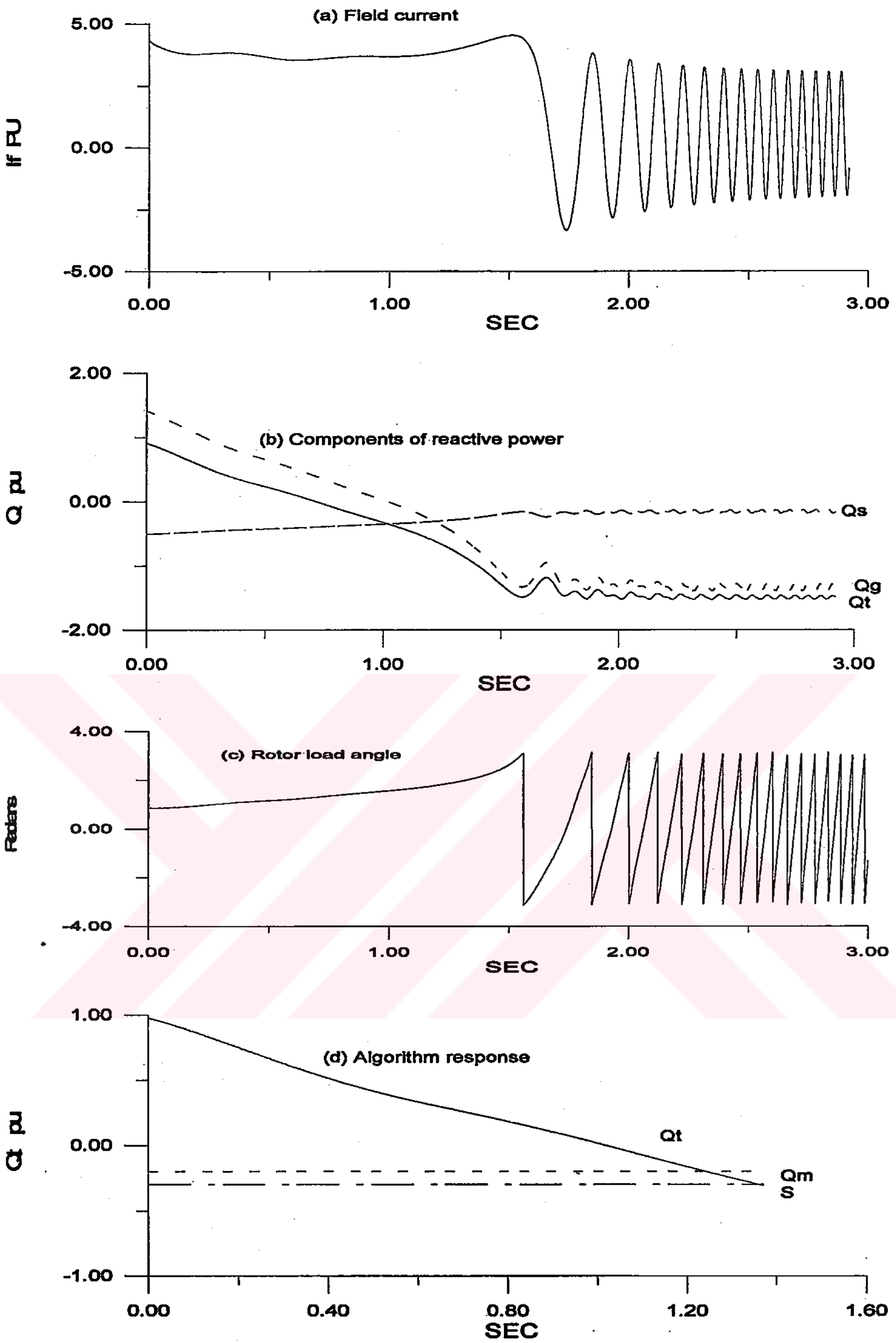



**Figure 6.27 Response to a loss of 75% of the field winding of a generator operating at 50% loading, and 0.8 lagging power factor.**

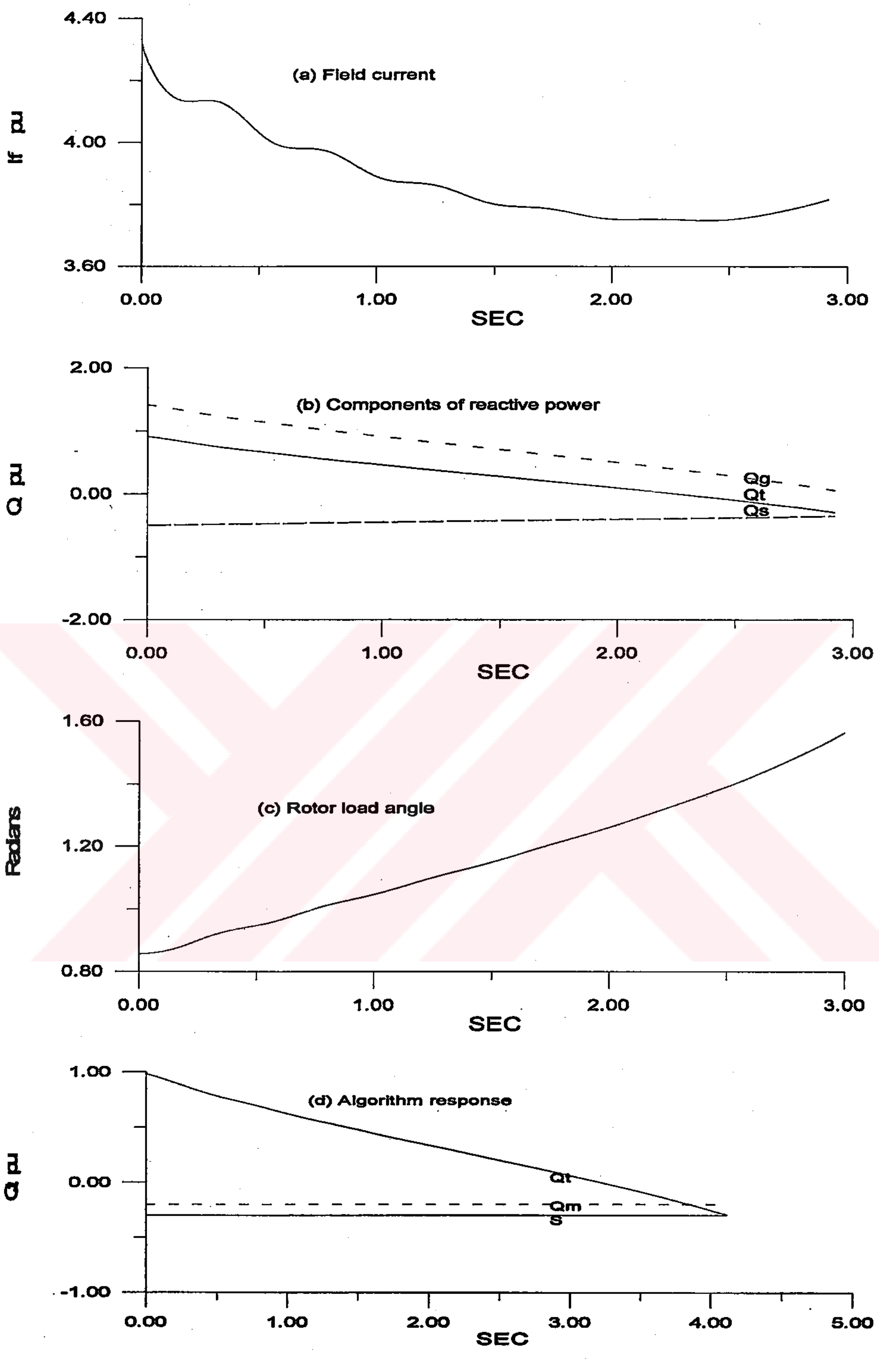



Figure 6.28 Response to a loss of 25% of the field winding of a generator operating at 50% loading, and 0.8 lagging power factor.

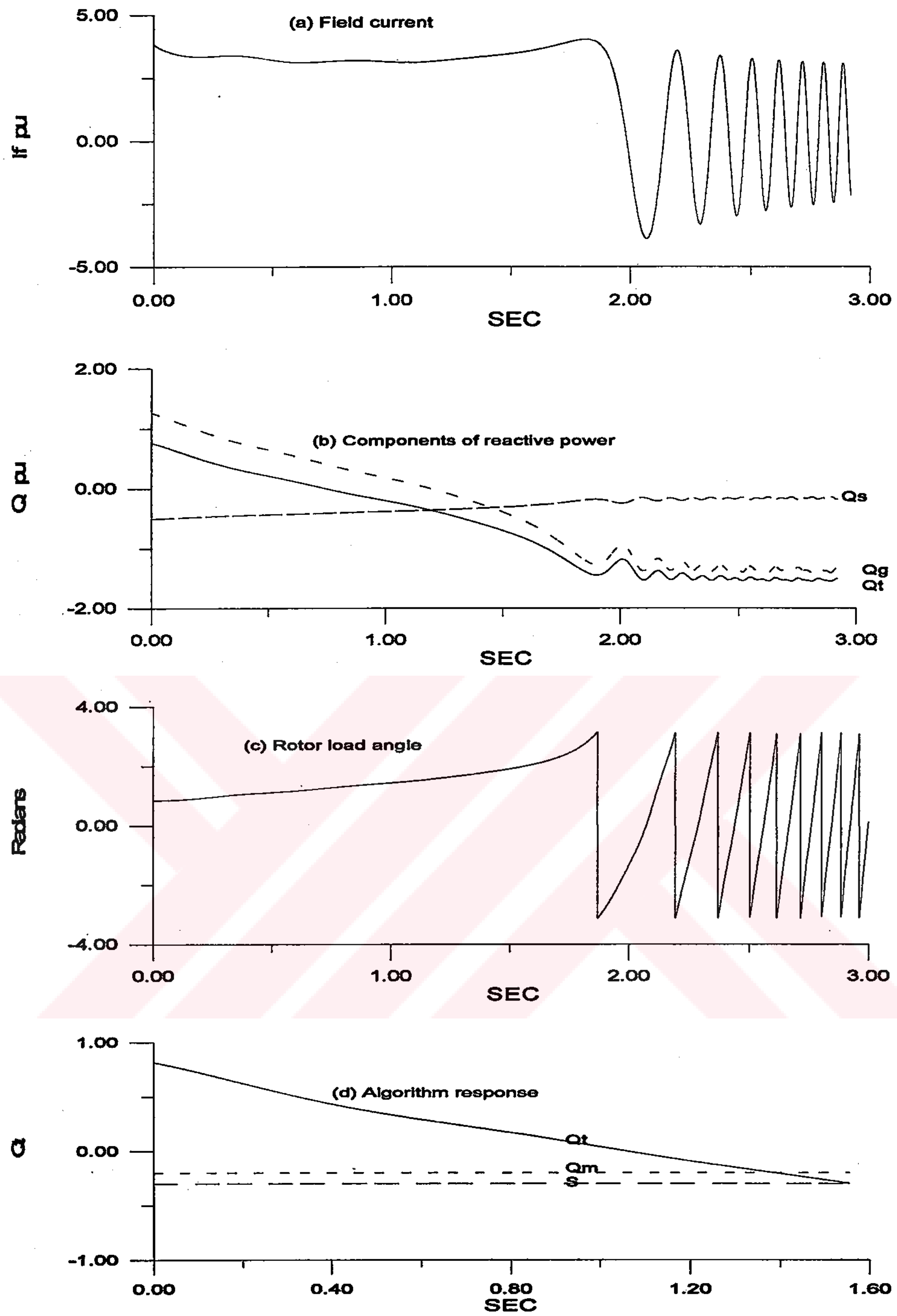



Figure 6.29 Response to a loss of 75% of the field winding of a generator operating at 25% loading, and 0.8 lagging power factor.

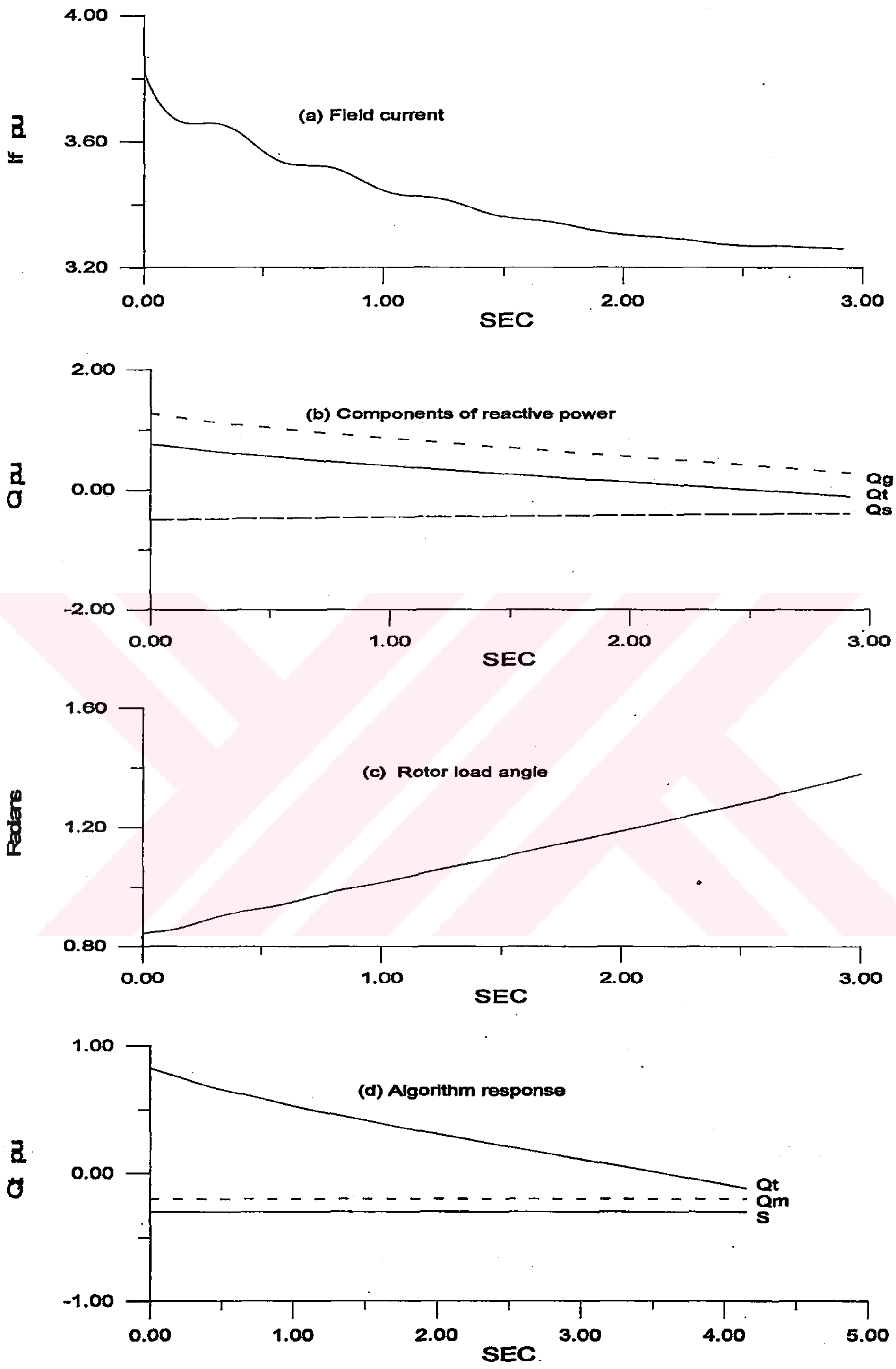



Figure 6.30 Response to partial loss of 25% of the field winding of a generator at 25% load, and 0.8 lagging power factor ( no trip).

## 7. CONCLUSION AND SUGGESTIONS

In this thesis a new digital relaying algorithm for the protection of a generator when it losses its field current has been introduced. Computer simulation studies performed on this algorithm proves that it operates as it is intended during its design. The following points can be collected as:

- Protection devices are used in electric power systems to remove the faulty equipment from service as fast as possible to limit damage to these equipment, hazards to personal, and interruption to the continuity of supply. Protection devices are designed to detect faults or the abnormal operating conditions slow enough to allow the external transients and recoverable swings to be by-passed, such that security and reliability are provided to the power system.

- Synchronous generators as they are the primary sources of electric energy, and the most expensive devices in power systems must be given the highest priority in protection application in order to keep them operating in a safe and economic operation mode.

- Loss of the excitation current of an electric generator is a damaging one to the affected generator as well as to the power system as a whole. So loss of excitation protection relays must be installed on all generators.

- For proper detection of loss of excitation from any machine loading conditions, the operating characteristics of the traditional offset mho distance relay must be set with a diameter equal to $X_d$ with a total time delay more than 2.0 sec after loss of field introduced to the relay to prevent it from operation during recoverable power swings. This represents one of the disadvantages of this method since this time delay can be a destructive one to the affected generator and to the power system.

- A new digital relaying algorithm has been introduced, which is mainly based on the measurement of the total reactive power output at the terminals of the generator.

- This new digital relaying algorithm has been designed such that:

  a- It shouldn't operate for all other faults and abnormal operating conditions other than the actual loss of field.

  b- It shouldn't operate during recoverable power swings.

  c- It should perform a tripping of the generator within 100 msec after detecting a confirmed loss of field.

  d- It should provide an adaptive time delayed signal in case of excessive leading operation, and for partial loss of field.

  e- It shouldn't operate during normal leading operation.

- The setting values of this new relaying algorithm are obtained from the capability loading curves of the generator. These setting values take into consideration the allowable steady state reactive power flow during normal leading operation of the generator. While in case of abnormal leading operation this algorithm introduces an adaptive time delay function and an alarming signal. If these conditions are not corrected within this time the generator will be tripped out. By this method an unnecessary tripping of the generator can be avoided during short periods of abnormal leading operation.

- Computer simulation studies performed on this new relaying algorithm shows that it provides all the design criteria mentioned above. It is found capable of discriminating confidentially between actual loss of field and other abnormal operating conditions (such as other different phase faults whether they are internal or external ones) before the affected generator losses its stability with the power system.

- This new algorithm proves to be much faster than the conventional mho relay in detecting loss of field and issuing a trip signal.

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- Computer simulation studies performed on this new relaying algorithm shows that it provides all the design criteria mentioned above. It is found capable of discriminating confidentially between actual loss of field and other abnormal operating conditions (such as other different phase faults whether they are internal or external ones) before the affected generator losses its stability with the power system.

- This new algorithm proves to be much faster than the conventional mho relay in detecting loss of field and issuing a trip signal.

- Also these computer simulation studies shows that the new relaying algorithm stayed stable during severe recoverable power swings resulting from external heavy faults. This proves that this new relaying algorithm is much secure than conventional mho relay during severe recoverable power swings.

- In cases of a confirmed loss of field the new algorithm managed to detect the fault and produced a trip signal to remove the generator within 100 msec after its detection. This proves that this new relaying algorithm provide a very fast tripping signal to the affected generator which will prevent damage to the generator or to the power system as a whole.

- In case of partial loss of field winding the new relaying algorithm manage to detect it especially when the percentage of the field winding lost is large. In this case the algorithm treats the partial loss of the field winding as an abnormal leading operation and it introduces an adaptive time delayed signal.

**Suggestions and Possible Future Work**

The following points can be considered as suggestions and recommendation for future work to improve the capability of this new digital relaying algorithm

- The ability of this new relaying algorithm to detect loss of field of an electric generator can be improved (specially for partial loss of field winding) by using the rate of decay of the internally generated reactive power $Q_g$, as a detecting parameter instead of using the direction of reactive power flow. This is true because when a generator losses its field, the internally generated reactive power will decay exponentially with a decaying time constant equal to the time constant of the field winding $T_o$, which will be different from other time constants occurring during other abnormal operating conditions (such as other phase faults).

- To improve the ability of this new relaying algorithm, and to overcome any possible disadvantages, it is suggested to run a real time tests to compare the response of this relaying algorithm to that obtained from computer simulations.

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# APPENDIX A : MATHEMATICAL MODEL OF SYNCHRONOUS GENERATOR

## Introduction

Synchronous generators generally consist of the following main parts:

- The stator: The stator is the stationary part of the generator in which the armature windings are uniformly distributed in slots around its inner perphery. The armature windings consist of three phases displaced in space by 120 electrical degrees from each other.
- The rotor: The rotor is the rotating part of the machine. It carries the field winding which is placed in slots digged in the outer surface of the rotor. These field windings are supplied by dc current to produce the magnetic flux, which is used as the coupling medium in the energy conversion process.

The Mathematical Model:

In establishing the mathematical model of the generator, the following assumptions are considered:

1. The magnetic circuit is assumed to be a linear one.
2. Saturation effects are neglected.
3. Stator and rotor windings are sinusoidal distributed around their respective magnetic axes.

Here the machine is represented by 6 windings, which are magnetically coupled to each other. The flux linkage equation for these windings is

$$[\lambda] = [L][I] \qquad \text{(A.1)}$$

Where

$$[\lambda]^t = [\lambda_a \lambda_b \lambda_c \lambda_f \lambda_D \lambda_Q] \text{ and } [I]^t = [i_a i_b i_c i_f i_D i_Q]$$

$$[L] = \begin{array}{c|c} L_{ss} & L_{sr} \\ \hline L_{rs} & L_{rr} \end{array}$$

- For round rotor synchronous generator the air-gap is uniform and so the stator and rotor self inductances as well as the stator to stator mutual inductances will be of constant value. Then

$$[L_{ss}] = \begin{bmatrix} L_s & -M & -M \\ -M & L_s & -M \\ -M & -M & L_s \end{bmatrix} \text{ and } [L_{rr}] = \begin{bmatrix} L_f & M_R & 0 \\ M_R & L_D & 0 \\ 0 & 0 & L_Q \end{bmatrix}$$

$$[L_{sr}] = \begin{bmatrix} M_f \cos\theta & M_D \cos\theta & M_Q \sin\theta \\ M_f \cos(\theta - 120) & M_D \cos(\theta - 120) & M_D \cos(\theta - 120) \\ M_f \cos(\theta + 120) & M_D \cos(\theta + 120) & M_D \cos(\theta + 120) \end{bmatrix}$$

$$[L_{rs}] = [L_{sr}]^t$$

- While for salient pole machine the air-gap is not uniform, and the above equations are:

$$[L_{ss}] = \begin{bmatrix} L_s + L_m \cos 2\theta & -M_s + L_m \cos(2\theta - 120) & -M_s + L_m \cos(2\theta + 120) \\ -M_s + L_m \cos(2\theta - 120) & L_s + L_m \cos(2\theta + 120) & -M_s + L_m \cos(2\theta) \\ -M_s + L_m \cos(2\theta + 120) & -M_s + L_m \cos(2\theta) & L_s + L_m \cos(2\theta - 120) \end{bmatrix}$$

The other matrices are as given before for round rotor type.

**Voltage equations**

The voltage equation for this machine is

$$\begin{bmatrix} v_{abc} \\ v_{fDQ} \end{bmatrix} = \begin{bmatrix} -R_s & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} i_{abc} \\ i_{fDQ} \end{bmatrix} + \begin{bmatrix} -\lambda_{abc}^{\bullet} \\ \lambda_{fDQ}^{\bullet} \end{bmatrix} + \begin{bmatrix} v_n \\ 0 \end{bmatrix} \quad \text{(A.2)}$$

Equation (A.2) is difficult to solve since all of its parameters are dependent on the rotor position θ, which is variable with time as the rotor is a rotating one. To simplify this mathematical equations a transformation of variables known as Park's transformation is used, which transform the stator stationary windings into a rotating one. The rotational speed of these windings is in the same direction as that of the rotor, and is equal to it. The transformation equation is given by:

$$\chi_{0dq} = P.\chi_{abc} \quad \text{(A.3)}$$

Where $P$ is Park's transformation, which is given by

$$P = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta & \cos(\theta - 120) & \cos(\theta + 120) \\ \sin(\theta) & \sin(\theta - 120) & \sin(\theta + 120) \end{bmatrix} \quad \text{(A.4)}$$

This transformation is an orthogonal one.

Using equation (A.3), the equation (A.2) becomes

$$\begin{bmatrix} v_{0dq} \\ v_{fDQ} \end{bmatrix} = \begin{bmatrix} P & 0 \\ 0 & U \end{bmatrix} \begin{bmatrix} v_{abc} \\ v_{fDQ} \end{bmatrix} \quad \text{(A.5)}$$

Noting that

$$\lambda_{0dq}^{\bullet} = P^{\bullet}\lambda_{abc} + \lambda_{0dq}^{\bullet} - P^{\bullet}P^{-1}\lambda_{0dq} \text{ and } P^{\bullet}P^{-1} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -\omega \\ 0 & \omega & 0 \end{bmatrix}$$

$$\omega = \frac{d}{dt}\theta \quad \text{(A.6)}$$

The voltage equation (A.5) finally becomes

$$
\begin{aligned}
v_0 &= -(r+3r_n)i_0 - (L_0 + 3L_n)\dot{i}_0 \\
v_d &= -ri_d - \omega(L_q i_q + kM_Q i_Q) - (L_d \dot{i}_d + kM_f \dot{i}_f + kM_D \dot{i}_D) \\
v_q &= -ri_q + \omega(L_d i_d + kM_f i_f + kM_D i_D) - (L_q \dot{i}_q + kM_Q \dot{i}_Q) \\
v_f &= r_f i_f + (kM_f \dot{i}_d + L_f \dot{i}_f + M_R \dot{i}_D) \\
0 &= r_D i_D + (kM_D \dot{i}_d + M_D \dot{i}_f + L_D \dot{i}_D) \\
0 &= r_Q i_Q + (kM_Q \dot{i}_q + L_D \dot{i}_d)
\end{aligned}
\tag{A.7}
$$

From (A.7) it can be seen that:

- The zero sequence terms has no mutual coupling with all other windings. Then this term can be separated from the above equation.
- There is a voltage term known as the speed voltage proportional the flux linkage perpendicular to the respective winding.

Steady State:

At steady state conditions the speed of the synchronous is constant, the flux linkages are also constant, and the three phases are balanced. Then at no-load:

$$
\begin{aligned}
&i_a = i_b = i_c = 0 \\
&i_D = i_Q = 0 \\
&\omega = constant
\end{aligned}
$$

When these terms are subsituted in equation (A.7), the resultant voltages are

$$
\begin{aligned}
v_a &= M_f I_f \omega \cos\theta \\
v_b &= M_f I_f \omega \cos(\theta - 120) \\
v_c &= M_f I_f \omega \cos(\theta + 120) \\
V_f &= r_f I_f
\end{aligned}
$$

When the generator supplies a balanced load, the armature phase currents are balanced and the generator speed is also constant, then

$$i_D = i_Q = 0 \ \text{ and } \ \dot{i}_d = \dot{i}_q = \dot{i}_f = \dot{i}_D = \dot{i}_Q = 0$$

Then the voltage equation becomes

$$v_0 = 0$$
$$v_d = -ri_d - \omega L_q i_q$$
$$v_q = -ri_q + \omega(L_d i_d + kM_f I_f)$$
$$V_f = r_f I_f$$

If the power factor of the loads on the generator is a lagging one with an angle of φ, and if the angle θ is replaced by the generator load angle δ given by

θ = ωt + δ + 90° then

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \sqrt{3}I \begin{bmatrix} 0 \\ -\sin(\delta - \varphi) \\ \cos(\delta - \varphi) \end{bmatrix}$$

Where $I$ is the *rms* phase current.

By subsituting in the voltage equation using the currents given above, then

$$V_a = (V_q + jV_d)e^{j\delta} = \left[(-rI_q + X_d I_d + E_q) + j(-rI_d - X_q I_q)\right]e^{j\delta}$$

This equation can be manipulated to give the terminal voltage equation as

$$E_q^{\rightarrow} = V_t^{\rightarrow} + rI_a^{\rightarrow} + jX_q I_a^{\rightarrow} + j(X_d - X_q)I_d^{\rightarrow} \qquad \text{(A.8)}$$

Where the currents used in this equation are in *rms* value.

In the case of round rotor generator both reactance $X_d, X_q$ are equal. Then equation (A.8) is reduced to

$$E_q^{\rightarrow} = V_t^{\rightarrow} + (r + jX_d)I_a^{\rightarrow} \qquad \text{(A.9)}$$

Equations (A.8) and (A.9) can be represented by an equivalent circuits as shown in figures (A-a) and (A-b) respectively.

The parameters used in the equation (A.9) are

$E_q = kX_{mf} I_f$
$X_{mf} = \omega M_f$
$\omega = 2\pi f$ rad./sec

In the equivalent circuits shown in figure A.1, the internal voltage $E_q$ leads the terminal voltage $V_t$ by an angle δ, then at steady state the current flowing out of the generator per phase can be found as:

$$I = \frac{E_q\angle\delta - V_t}{jX_d} = \frac{E_q\angle\delta - \pi/2}{X_d} - \frac{V_t\angle -\pi/2}{X_d}$$

From this equation the active power output per phase can be found as:

$$P = \left(V.I^*\right) = \frac{E_q.V_t}{X_d}\sin\delta$$

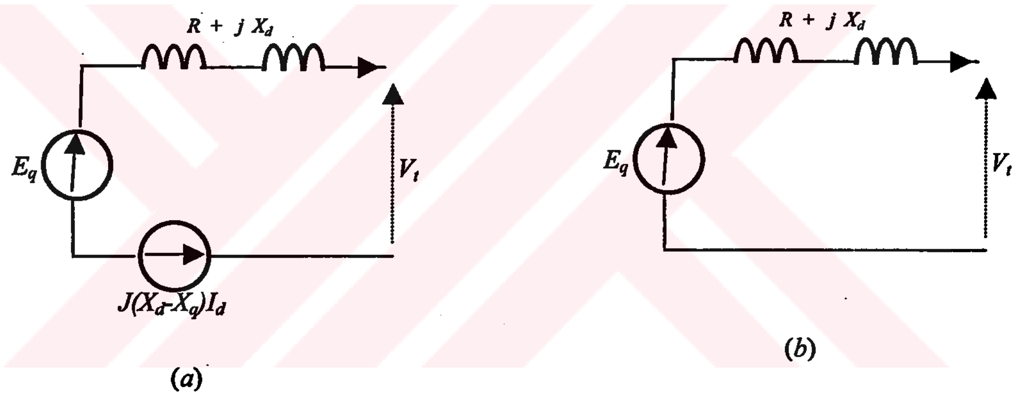


Figure A.1 Equivalent circuits of synchronous generators
a-Equivalent circuit of a salient pole generator
b-Equivalent circuit of round rotor generator.

## APPENDIX B : GENERATOR DATA

The generator used in this computer simulation has the following data:

| Generator parameter | Magnitude | Units |
|---|---|---|
| Total rating | 991.0 | MVA |
| Rated line voltage | 24.0 | *KV* |
| Rated field current | 1640.0 | A |
| Number of poles | 2 | |
| Moment of inertia | 0.95 | M.Pound.Feet$^2$ |
| Armature resistance | .00312 | pu |
| Armature leakage reactance | 0.15 | pu |
| d-axis reactance | 1.99 | pu |
| d-axis transient reactance | 0.245 | pu |
| d-axis sub-transient reactance | 0.2 | pu |
| q-axis reactance | 1.9 | pu |
| q-axis transient reactance | 0.42 | pu |
| q-axis sub-transient reactance | 0.2 | pu |
| d-axis open-circuit time constant | 4.6 | sec. |
| d-axis sub-transient time constant | .03 | sec. |
| q-axis open-circuit time constant | .66 | sec. |
| q-axis sub-transient time constant | .06 | sec. |

## NETWORK PARAMETERS

The Parameters of the equivalent circuit used in computer simulation studies shown in figure 6.1 are as follows:

- The low voltage cable used to connect the generator to the low voltage side of the power transformer has the following series impedance

  $Z = r + jx = 0ç4 + j\,4.0$ Ohms/phase.

- The step-up power transformer has the following characteristics:

Rated voltage = 24/ 240 *kv*

Connection Δ/λ with star point grounded.

Low voltage series impedance = 0.00035 + j 0.01368 Ω/ phase

High voltage series impedance = 0.135 + j 6.523 Ω/ phase

- High voltage transmission line has the following series impedance

  $Z = 2.08 + j\,20.8$ Ω/ phase

- The location of the fault point is at the point where the impedance up to the bus bar is

  $Z = 0.208 + j\,2.08$ Ω/ phase

## APPENDIX C : VOLTAGE REGULATOR

The voltage regulator used for the control the field voltage of the generator used in computer simulation is shown in figure (C.1) [87,88,89,90]. It perform the following functions:

- Calculating the *rms* voltage of each phase, and controlling the terminal voltage $V_t$ by the first control block $G_1$(s).
- The error voltage signal is controlled by blocks $G_2$(s), $G_3$(s), and compared to certain specified limits, and the result is fed back through block $G_4$(s). The final voltage $E_{f0}$ is obtained.

The control blocks of this voltage regulator are given by the following equations:

$$G_1(s)=\frac{A}{1+k_1 s}$$
$$G_2(s)=\frac{B}{1+k_2 s}$$
$$G_3(s)=\frac{B}{1+k_3 s} \qquad \text{(C.1)}$$
$$G_4(s)=\frac{C}{1+k_4 s}$$
$$V_f = KE_{f0}$$

Where:

$$\begin{array}{llll} A=1.0 & B=250.0 & C=1.0 & D=0.44 \\ k_1=.015 & k_2=.05 & k_3=.44 & k_4=0.8 \end{array} \qquad \text{(C.2)}$$

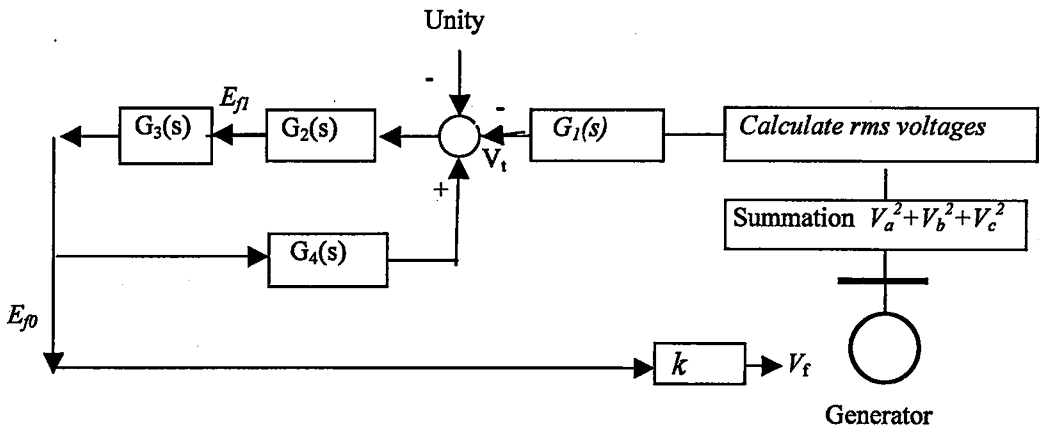


Figure C.1 Block diagram of the voltage regulator.

**PIBOLOGRAPHY**

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Febraury 2002.