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Experimental Measurements of Fault Level For Sceco West, Kingdom of Saudi Arabia

EMAD S. IBRAHIM

P.O.Box 80204,Jeddah 21589, Faculty of Engineering,
King Abdulaziz University, K.S.A
emadsedeek@hotmail.com

ABSTRACT. The fault level represents the maximum short circuit current that a power system causes to flow to the point of short circuit. Due to change of network configuration, the fault level at any point of the power system network changes accordingly. It is not practical to apply full short circuit on the system in order to determine the fault level. This paper describes scheme for continuous measuring of the fault level at any point of the power system network. This scheme is composed of an antiparallel thyristor pair. The thyristor current, which is controlled by the firing angle, can be used to perform the on-line fault level measurement. Saudi Consolidated Electric Company (SCECO) West network has been simulated in the lab and the invented scheme has been applied to the network to measure the short circuit currents. The comparison between the measured and calculated short circuit currents shows results with high accuracy.

KEYWORDS: Short circuit, Fault level, Protection

1. Introduction

The proper selection of protective devices and their selective trip settings is based on the value of short circuit current. A short circuit protective device can be defined as an electrical device inserted in a circuit to protect it against damage from an overload or short circuit. This is achieved by automatically interrupting any excessive current in accordance with the device's short circuit capability [1].

The chief short circuit protective devices are of course, circuit breakers and fuses. Circuit breakers automatically protect the circuit by means of relays (separate or built-in) that sense abnormal currents and command the breaker to trip. Fuses both sense the abnormal current and interrupt it with an element, which melts and opens the circuit.

Inadequate short circuit protection often is the source of disastrous failures that result in unnecessary damage, power interruption, injury of personnel and expensive production shutdowns. Conversely, arbitrary oversized or overrated protective devices constitute a waste in unnecessary extra cost equipment. It follows that exact determination of short circuit conditions on an electric power system is of paramount importance. Interrupting capacity represents the maximum short circuit current that a power system causes to flow through a breaker or a fuse when a fault occurs in the circuit. Even more important, non-interrupting devices such as cables, bus-ducts, disconnect switches must withstand thermal and mechanical stresses of high short circuit currents. For suitable application of breakers and fuses, selection must be made on the basis of proper and safe operation. The magnitude of the power system supplying the load dictates the amount of short circuit current. Under normal operation, the load draws a current proportional to the voltage applied and the load impedance. If a short circuit occurs, the voltage is applied across a low impedance of only the conductors and transformer from the source of voltage to the point of the short circuit; it is no longer opposed by the normal load impedance.

Breakers, which are selected on the basis of the continuous current they carry, must also be capable of withstanding and interrupting the high short circuit currents that occur. The load current is determined by the normal load that the breaker carries and has no relationship to the size of the system supplying the load. The magnitude of the short circuit current, however, is dependent on the size of the supplying system and independent of the normal load [1,2].

Coordinated selective protection in modern power systems assures effective isolation of faulted sections of the systems, allowing the rest of the system to operate normally. Clearing of faults by the breakers nearest to the faults is achieved by the following: careful short circuit measurement: a detailed study of the time current characteristics of the protective devices: proper selection for short circuit withstandability [1].

At present there is no easy method of measuring the fault level at a particular point on a network. In theory an assessment of the supply impedance can be made from naturally occurring disturbances. Ref. [3] presents an instrument based on this principle to make an estimate of both the source impedance, and also the contribution from induction motors downstream of the measuring point.

2. Fault Level

2.1 *Concept of Fault Level*

The fault level is defined as the product of the magnitude of the prefault voltage at a bus and the postfault current, which would flow if that bus was shorted. The fault level or short circuit capacity is a measure of interconnections at any point in the power system network.

In the event of a short circuit occurring at a bus in an interconnected system, the prefault voltage of the bus is near to the nominal value 1 p.u. and as soon as the fault takes place, the voltage of the bus reduces to almost zero. The voltage of the other buses will sag during the fault. The reduction in voltage of the various buses is a function of the strength of the network and the proximity of the fault. We are normally interested in knowing system strength because it indicates the severity of the short circuit stresses. Both these objectives are met by a quantity known as short circuit capacity or fault level of the bus in question. By strength of a bus is meant the ability of the bus to maintain its voltage when a fault takes place at another bus.

Since the strength of a bus is directly related to the short circuit level, the higher the short circuit level of the bus, the more it is able to maintain its voltage in case of a fault on any other bus. Also, it can be seen that the higher the short circuit capacity, the lower will be the equivalent impedance as seen between the faulted bus and the zero potential bus of the system.

2.2 *Fault Level in Power System*

Fault level is an important parameter of any power system network. Protective devices for electrical distribution systems such as circuit breakers, protective relays and fuses, provide adequate protection and isolate trouble properly only if they operate within their design short circuit current values. To insure adequacy of short circuit protection, and to prevent accidents:

(1) Available short circuit current must be accurately determined. Only then can short circuit protection devices be carefully selected.
(2) The load growth of the plant and the knowledge that interrupting devices in their short circuit capability depend on the magnitude of the power system must be kept in mind. Their selection should be made with an eye to future growth; otherwise; these interrupting devices will have to be replaced when the plant expands.
(3) All circuit stresses in bus bars, etc. have to be checked. These stresses are proportional to the square of the short circuit current.

(4) Cable size, besides their normal current carrying capabilities, must be able to withstand short circuit heating due to the high short circuit current to which they may be subjected.

(5) Check all of the power system, from the supply side down to the last motor, for short circuit safety.

(6) Approach the problem of short circuit determination on an engineering analysis rather than on the basis of "good luck" "Hoping" that failures will not occur is a bad policy. This is proved by countless recorded mishaps caused by improper interrupting devices.

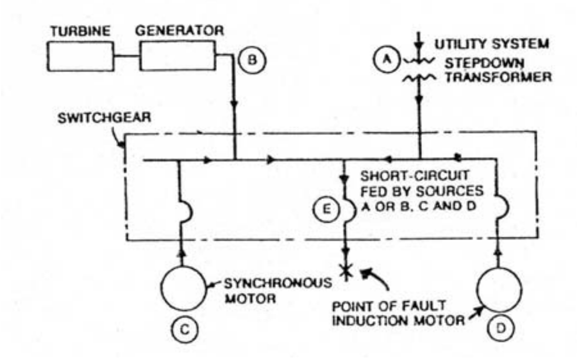

Fig. (1): Short circuit current sources.

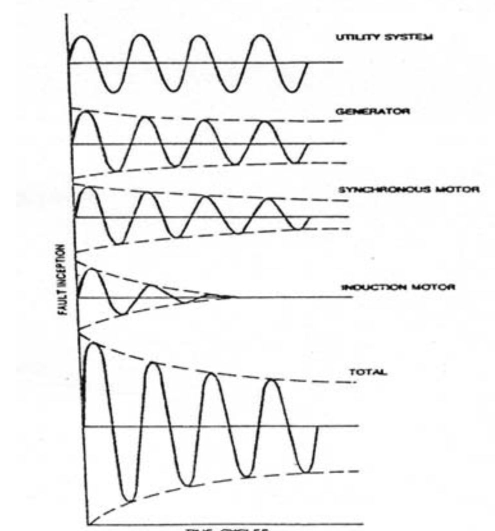

Fig. (2): Short circuit currents.

2.3 *Sources for Fault Current*

In order to obtain the magnitude of short circuit current, it is necessary to consider all the possible sources along with their reactances, which can feed the fault current. Mainly, there are four sources which can feed into the short circuit as shown in Fig. (1), they are: utility systems, generators, synchronous motors and induction motors.

The utility system usually supplies power through a step down transformer at the consumer's desired voltage. The short circuit current delivered through a transformer depends on its secondary voltage rating and its reactance. It also depends on the reactance of generators and system down to the terminals of the transformer as well as on the reactance of the circuit between transformer and fault.

Utility supply, generators, synchronous and induction motors all contribute short circuit current into a fault. Fig. (2) shows the contribution and the total symmetrical short circuit current.

2.4 *DC Component*

So far, the symmetrical component of short circuit current contribution has been considered. The magnitude of short circuit is further increased during the first few cycles by the so-called dc component. The dc component causes the short circuit wave to be asymmetrical, and decays with time, resulting in a still greater difference in magnitude between the first cycle after fault inception and several cycles later [8].

The existence of three phases with voltages at 120^O phase displacement means that whenever the fault is created, there will be an asymmetrical component in at least two phases. Fig. (3) shows one possibility when a three-phase short circuit takes place under the usually highly inductive condition. In this instance the voltage in Y phase is at zero, leading to a maximum DC component in that phase current. A corresponding DC component of half the amplitude and opposite polarity exists in the other two phases. Obviously, any combination of degrees of asymmetry can occur depending on the switching moment, the only criterion being that the sum of the DC components in all three phases at any point in time must be zero assuming that there is no fourth wire for neutral current flow.

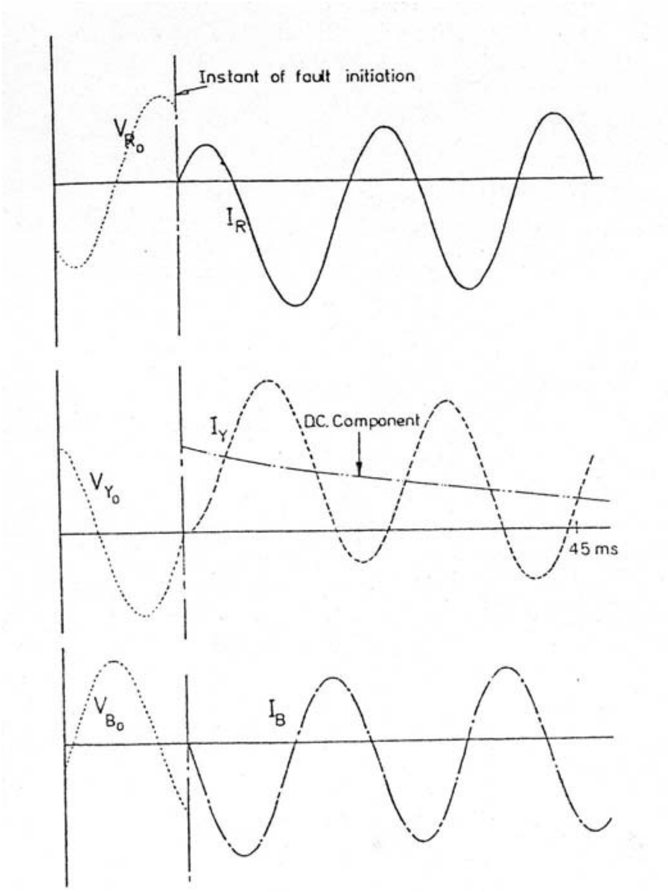

Fig. (3): Fault currents in a three-phase reactive circuit.

2.5 *X/R Ratio*

X/R ratio is the reactance to resistance ratio of the circuit considered. The decay (or decrement) of the DC component depends on the X/R ratio, X and R being formed by the reactance and resistance of all the circuit components between the source and fault. If R=0, the ratio is infinity and the DC component, will never decay. If X=0, the ratio is zero and the DC component decays instantly. For ratios in between, the DC component decays in time to zero, the time depending on the particular X/R ratio. The greater the reactance in relation to the resistance, the longer it will take for the DC component to decay.

3. Saudi Consolidated Electric Company In The Western Region (Sceco West)

3.1 *Network Data*

The Kingdom's area is very wide with scattered towns, cities, villages and settlements. This necessitated the construction of long distance high-tension transmission network to transmit energy from its generation sources to far off areas and then to distribute such energy on different voltage and to connect it to the consumers.

Total transmission networks lengths in the Kingdom had been more than 17 thousand kilometers and also total lengths of distribution networks had been more than 103 thousands kilometers. In addition, the length of service connection to consumers sites which had been more than 106 thousand kilometers for 380, 220, 127 V. Electricity system in different areas of the kingdom constitute developed and integrated system. So, interconnections between these systems give high economical and technical return, since it will attain a low operation cost and improve the station utilization factor as well as decreasing generation reserves with dependable continuity of electric current. Therefore and in order to interconnect generation stations and loads centers, high voltage networks have been established with many interconnection lines.

Fig. (4) shows the single line diagram of the 380 KV Western Region network. Appendix A contains the SCECO West network data: generators, transformers and transmission lines.

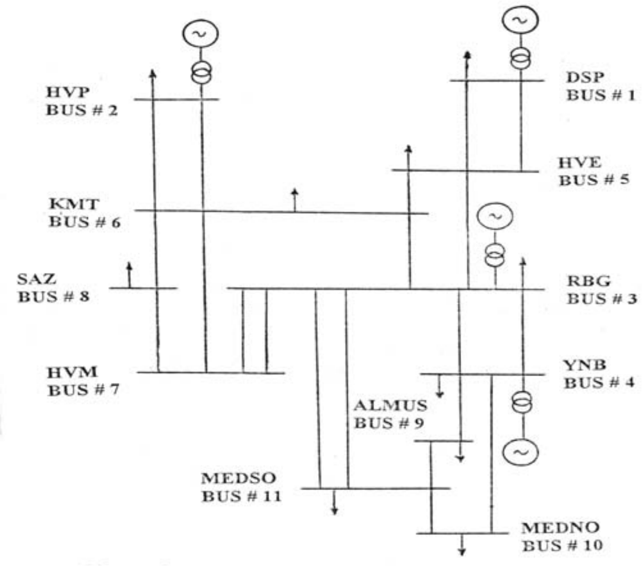

Fig. (4): Single line diagram 0f SCECO West network.

3.2 *Fault Level Theoretical Calculations*

The short circuit current at each bus bar can be calculated through the application of Thevenin theorem at that bus bar. When the theorem is applied to the network, the equivalent circuit is a single generator and single impedance terminating at the point of application of the fault. The new generator has an internal voltage equal to the voltage at the fault point before the fault occurs. The impedance is that measured at the point of application of the fault looking back into the circuit with all the generated voltages short-circuited. Subtransient reactances should be used if the initial current is desired.

- network base calculation

MVA_b = 100 MVA, KV_b = 380 KV,

$Z_b = (KV_b)^2/MVA_b$=1444 Ω, $I_b = MVA_b/(\sqrt{3}\ KV_b)$ = 151.934 Amp

$$I_f(p.u) = \frac{1}{|Z_{Th}(p.u)|}$$

$$I_f(Amp.) = I_f(p.u) * I_b$$

- fault level theoretical calculation

$$I_f(p.u) = \frac{1}{10.000155 + j0.0099025} = 100.9845998(p.u)$$

$$I_f(Amp.) = 100.9845998 * 151.934 = 15342.99419(Amp.)$$

For example, the fault current calculation for bus # 1 is:

Table (1): Thevenin equivalents and fault currents.

Bus #	R_{Th}	X_{Th}	X/R	Fault	current
				p.u	Amp.
1	0.000155	0.0099025	63.92834	100.9845998	15342.99419
2	0.000157	0.009798	62.40573	102.0647703	15507.10881
3	0.000141	0.008173	57.87506	122.3540927	18589.74673
4	0.00346	0.019666	5.683815	50.84918133	7725.719516
5	0.001762	0.010075	5.717553	99.2565683	15080.44745
6	0.000151	0.009498	63.00915	105.2853232	15996.4203
7	0.002523	0.014604	5.788268	68.47532834	10403.73054
8	0.003153	0.019217	6.094764	52.03617555	7906.064296
9	0.004803	0.029914	6.228212	33.42905185	5079.009564
10	0.005107	0.028965	5.672261	34.52394926	5245.361707
11	0.003918	0.024666	6.295559	40.54163626	6159.652964

Table (1) shows the equivalent R_{Th}, X_{Th}, X/R ratio and the fault level for the eleven bus-bars of the SCECO Western Region network.

4. On-Line Fault Level Measurements

4.1 *Basic Circuit*

Figure (5) shows the equivalent power system consisting of E, R and X. X and R being formed by the reactance and resistance of all the circuit components between the source E and the fault, while V is the voltage of the busbar at which it is required to measure the fault level. Also, the Figure shows the basic circuit of on-line fault level measurement device when connected to the system.

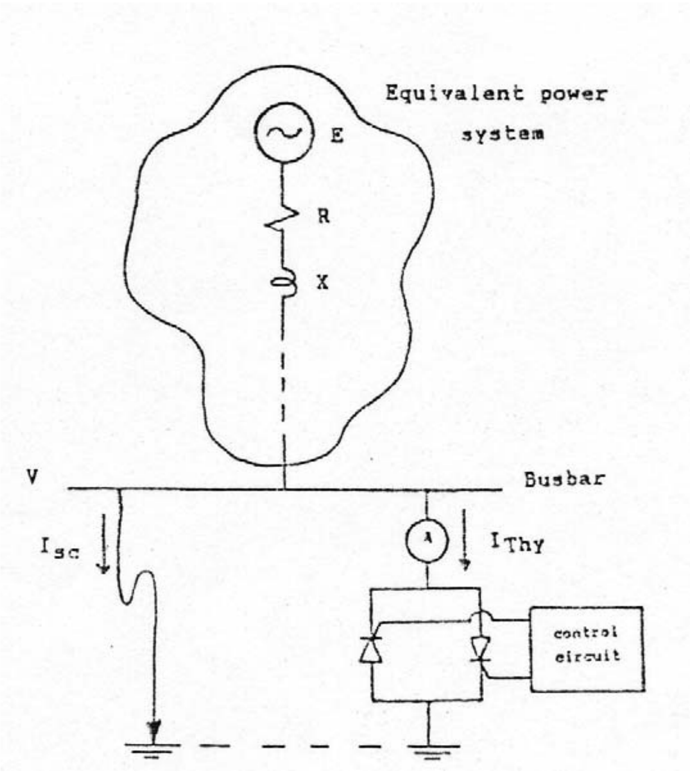

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Fig. (5): On-Line fault level measurement.

The controlled short circuit is applied through the anti-parallel thyristor pair. The function of the control circuit associated with it is to derive different signals from the system voltage, process these signals, and then issue the appropriate pulse to turn the thyristor on and off. The firing angle of the thyristor can be controlled, thus allowing a very small current to flow in the short circuit path. A minimum and, therefore, safer current is obtained when the thyristor is fired at an angle close to 180^{O}. Consequently, the system is less disturbed.

4.2 *Theory of Fault Level Measurement Circuit*

In the case where the system impedance is a combination of resistance and inductance, the thyristor rms current is [10,11]:

$$
\begin{aligned}
I_{Thy} = \left(E/\sqrt{\Pi}\,|Z|\right)\Big[&(x-\alpha) - 0.5\left[\sin 2(x-\phi) - \sin 2(\alpha-\phi)\right] \\
&+ \frac{\sin^{2}(\alpha-\phi)}{\cot\phi}\left[1 - e^{2\cot\phi(\alpha-x)}\right] \\
&+ 4\sin\phi\sin(\alpha-\phi)\left[\sin x e^{\cot\phi(\alpha-x)} - \sin\alpha\right]\Big]^{1/2}
\end{aligned}
\tag{1}
$$

where E is the rms system voltage, Φ is the fundamental phase angle [$\Phi=\tan^{-1}$ (wL/R), α is the triggering angle, and x is the extinction angle. The extinction angle x can be determined by the transcendental equation

$$\sin(x-\phi) - \sin(\alpha-\phi)e^{-\cot\phi(x-\alpha)} = 0 \tag{2}$$

Equation (1) can be represented by:

$$I_{Thy} = \frac{E}{Z}K \tag{3}$$

The fault level expression for a resistive-inductive system is therefore:

$$FL = VI_{sc} = \frac{VE}{Z} = V\frac{E}{Z} = \frac{V}{K}I_{Thy} \tag{4}$$

As shown from eq. (4), the fault level can be expressed as a function of the thyristor current. This is done by keeping the firing angle constant at an appropriate value. This value should be chosen so that the maximum current, which may flow in the short circuit path, will not disturb the system. The current and, therefore, the fault level are now dependent on the system impedance and eventually the X/R ratio. A reduction in the system impedance gives rise to the current and vice versa. Consequently, the fault level can be measured instantaneously by an ammeter having a suitable scale [Fig. (5)]. A transformer can be used to reduce the voltage imposed on the thyristors to their ratings.

Equation (4) shows that when both the system voltage and the firing angle are constant, the short circuit level is not only a function of the rms current, but it depends also on the system impedance phase angle or the X/R ratio. It should be noted here that the extinction angle is related to the X/R ratio. Consequently, in a given system, if the reduction or the increase of the system impedance occurs by the variation of the resistance and the reactance in the same proportion, the X/R ratio remains constant. In this situation, the problem is simplified and the FL is measured as a function of the rms current only.

4.3 *Computer Results*

A computer analysis of the variation of the fault level FL using Equations (1)&(4) is carried out. Figure (6) shows the variation of the FL as a function of thyristor rms current, where it can be shown that;

1. The increase of FL is proportional to the increase of thyristor rms current.
2. For the same FL, as the firing angle α increases the thyristor rms current decreases.
3. For the same thyristor rms current, as the firing angle α increases the FL increases.

Keeping the thyristor rms current constant (1 p.u.) and expressing the FL as a function of the X/R ratio (or phase angle), Fig. (7) can be obtained. In this Figure, it can be noticed that:

1. The effect of X/R ratio is negligible when the phase angle is between 60 and 70, but for a phase angle ranging from 70 to 90, the effect of the X/R ratio becomes significant.
2. For constant X/R ratio (constant phase angle), the FL increases with the increase of the firing angle α.

Figure (8) shows the FL against the firing angle α with the system phase angle as a parameter and the current is considered as constant (1 p.u.). It is shown that the FL increases with the increase of the firing angle α.

5. Experimental Measurements of Fl for 380 Kv Sceco West

5.1 *Control Circuit*

To operate the on-line fault level measurement device at any desired point on the wave of the voltage, the thyristors need to be equipped with a firing circuit, which incorporates a controller, which responds to a desired characteristic. Figure (9) shows the hardware details of the control circuit. Figure (10) shows the output oscillogram at different points of the control circuit.

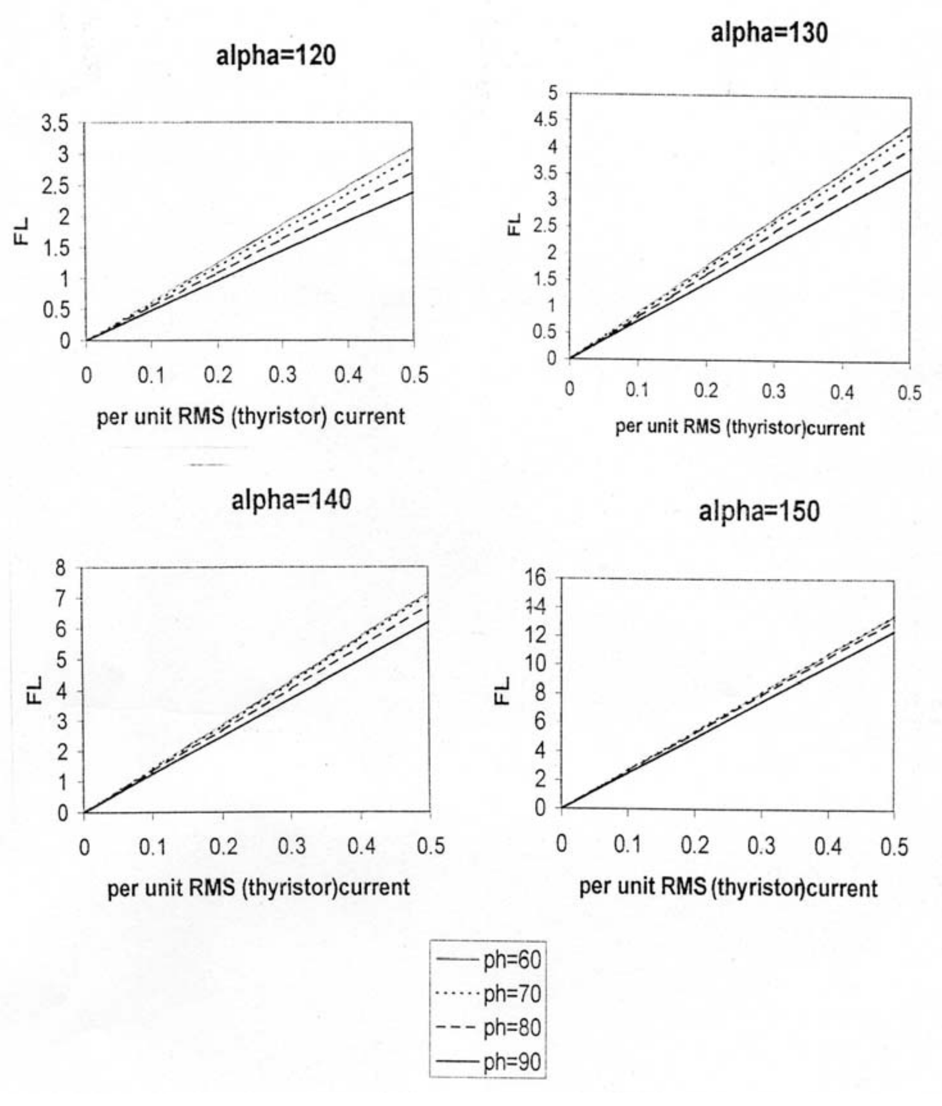


Fig. (6): Fault level as a function of rms thyristor current.

5.2 Measurements

The SCECO West network have been simulated in the lab taking into account only the reactances of the transmission lines, while, the resistances have been neglected. Moreover, the reactances have been represented in the lab as pure resistances for accurate measurements of fault currents. Experimental measurements were carried out using a supply voltage of 100 volt.

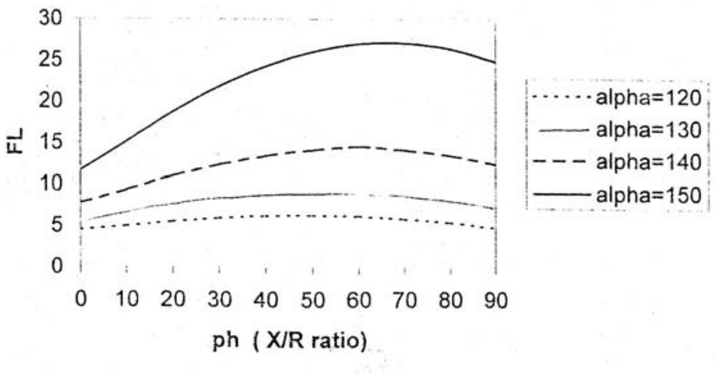


Fig. (7): Fault level as a function of X/R ratio (phase angle).

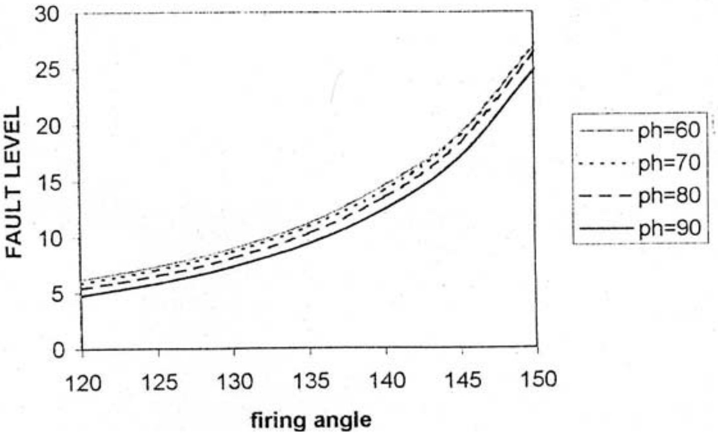


Fig. (8): Fault level as a function of firing angle.

Table (2) shows the experimental results of I_{Thy} and I_f at the lab for different firing angle (110 to 160) where the short circuit occurs at busbar no. 1. For every firing angle there is a corresponding (1/K) value. The corresponding actual short circuit current for the actual network can be calculated using:

I_f (network) = $I_{f\text{-p.u}}$ (lab)* I_b (network) Amp.

The last column in Table (2) shows these values of I_f (network). Comparing the calculated values of I_f shown in Table (1) with the last column of Table (2), then the firing angle can be obtained by interpolation. The calculated value of firing angle is 126.77^O. The thyristors have been triggered by angle 126.77^O and the corresponding measurements of I_{Thy}, and I_f have been obtained. Last row in Table (2) shows the results.

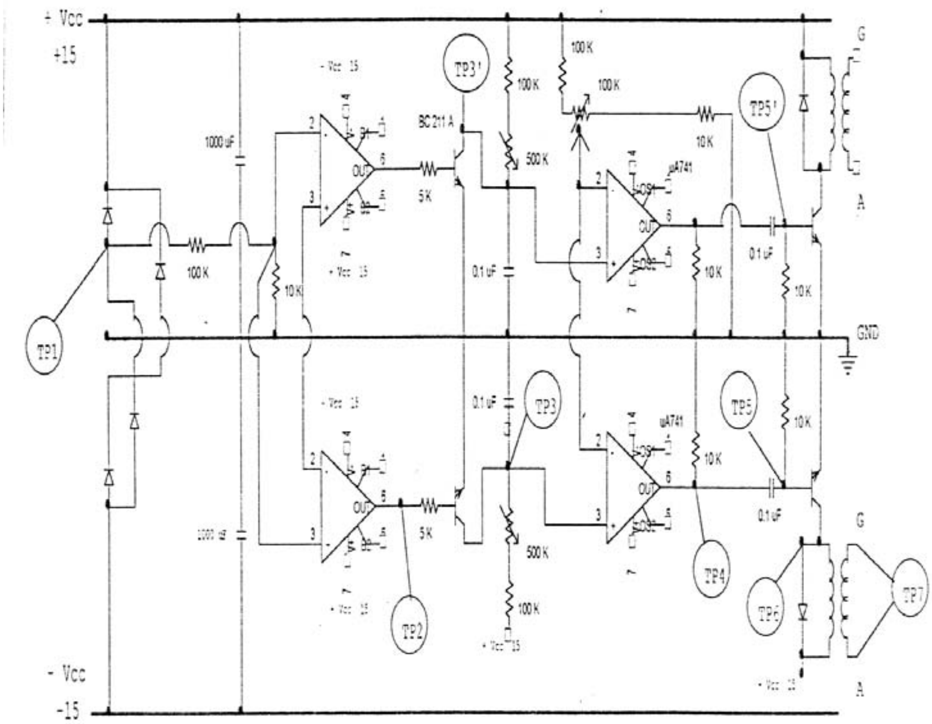
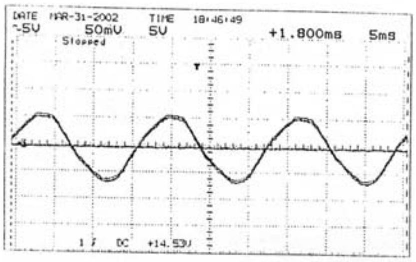


Fig. (9): Hardware details of the control circuit.

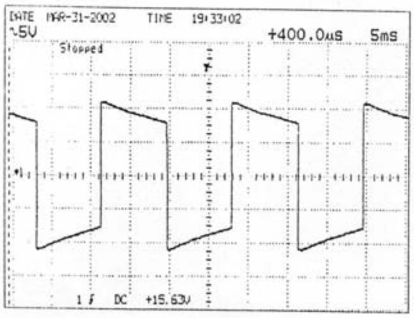
During short circuit at the buses from bus 2 to bus 11, the firing angle has been fixed to 126.77^{O} to measure the thyristor current I_{Thy} and fault current I_f. The results are shown in Table (3). The error between the calculated short circuit and the experimental short circuit current can be represented as:

$$\%error = \frac{I_f(calc.) - I_f(lab)}{I_f(calc)} x100$$

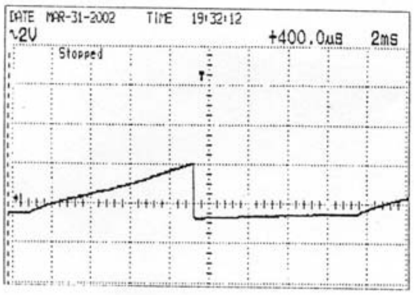
Table (4) shows the percentage error (%error) between the calculated and experimental short circuit currents. It is noticed from the table that the error can be neglected. It is worth noting that this error is due to neglecting the real part of the transmission line in the lab simulation.



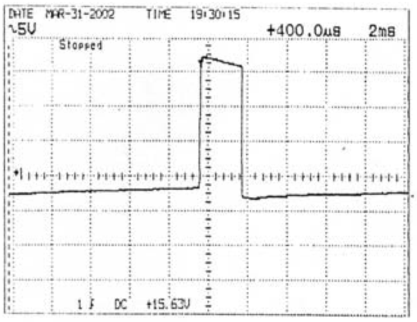
Oscillogram of the TP1



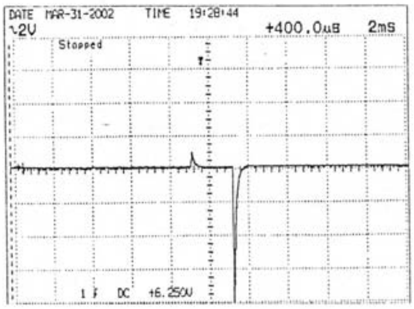
Oscillogram of the TP2



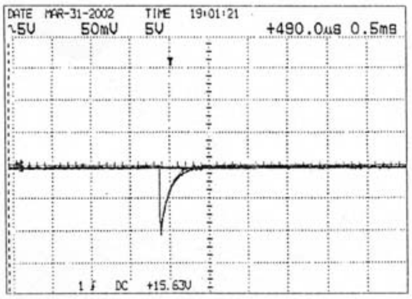
Oscillogram of the TP3



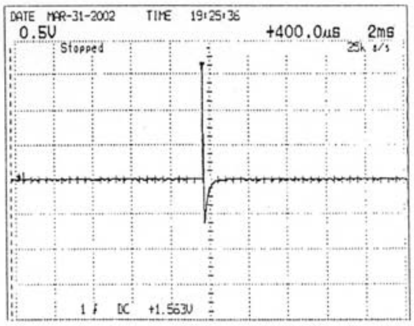
Oscillogram of the TP4



Oscillogram of the TP5



Oscillogram of the TP6



Oscillogram of the TP7

Fig. (10): Oscillogram outputs.

Table (2): Short circuit at bus # 1.

α	1/K	I_{Thy}		I_f - Lab		I_f network Amp.
		Amp.	p.u.	Amp.	p.u.	
110	2.2823	0.548	55.33676664	1.2507004	126.2951025	19188.5201
120	2.465	0.4217	42.58305564	1.0394905	104.9672322	15948.09145
130	2.7004	0.3634	36.69595072	0.98132536	99.09374533	15055.7091
140	3.0192	0.2227	22.48813491	0.67237584	67.89617692	10315.73774
150	3.4862	0.1554	15.69221448	0.54175548	54.70619812	8311.731505
160	4.2697	0.0935	9.441583359	0.39921695	40.31272847	6124.874087
126.77	2.738	0.3652	36.87771382	0.9999176	100.9711805	15340.95533

Table (3): Short circuit at other buses

Busbar #	I_{Thy} (p.u)	I_f - Lab (p.u)	I_f network , Amp.
2	37.27291284	102.0532354	15505.35626
3	44.68371467	122.3440108	18588.21493
4	18.57012102	50.84499136	7725.082917
5	36.24849874	99.24838956	15079.20482
6	38.45020004	105.2766477	15995.10219
7	25.0071899	68.469686	10402.87327
8	19.0036113	52.031888	7905.412836
9	12.2082897	33.426297	5078.591054
10	12.6081463	34.521104	5244.92949
11	14.8058056	40.538296	6159.145408

Table (4): %Error

Bus #	I_f Calculation	I_f Lab	% error
1	15342.99419	15340.95533	0.013288563
2	15507.10881	15505.35626	0.011301599
3	18589.74673	18588.21493	0.00824001
4	7725.719516	7725.082917	0.008239995
5	15080.44745	15079.20482	0.008239998
6	15996.4203	15995.10219	0.008240025
7	10403.73054	10402.87327	0.008239986
8	7906.064296	7905.412836	0.008240003
9	5079.009564	5078.591054	0.008239993
10	5245.361707	5244.92949	0.008239993
11	6159.652964	6159.145408	0.008240003

6. Conclusions

1. An essential requirement in all aspects of power system design is an evaluation of the fault levels at a particular switching or control point on the network. This evaluation is covered in IEC 909. The fault level can vary

according to the supply configuration and load, particularly where rotating plant is involved. Inadequate short circuit protection is a source of disastrous failures that result in unnecessary damage and expensive protection shut downs. Conversely, oversized protection devices constitute a waste in an unnecessary extra cost equipment. Little work has been done in the past to justify the calculated values of circuit fault levels and there is some belief that the values obtained could be unduly pessimistic. At present there is no easy method of measuring the fault level at a particular point on a network

2. Continuous measurement of the fault level at any point on the system network may be of importance in some circumstances for the power system utilities and the consumers. It enables supply authorities and industrial plants to improve the quality of service and increase the reliability of the supply. A design of continuous fault level measuring device and the analysis of system parameters incorporating it are described in this paper.
3. The invented device is a thyristor-based measurement scheme where the thyristor current is controlled by the firing angle to allow only small currents to flow in the short circuit path. Thus, the system will be less disturbed. The thyristor current is then used to perform the on-line fault level measurement.
4. The optimum firing angle is found to be 126.77^{O}. The constant value (1/K), which found to be 2.738, must be multiplied by the ammeter reading to get the actual short circuit current
5. The relation between fault level and thyristor current is presented for different values of X/R ratio and at constant firing angle. The paper describes the relation between the fault level and X/R ratio for different values of firing angle and at constant thyristor current. Also, the paper describes the relation between the fault level and the firing angle for different X/R ratio and at constant thyristor current.

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Appendix (A)

Table (A1): Gen. & Transf. Data at bus # 1

	Unit	1-4	5-9
Gen.	Rated power (MVA)	80	147.5
	Rated voltage (KV)	13.8	13.8
	X_D' (p.u)	0.14	0.125
Transf.	Rated power (MVA)	80	147.5
	Rated voltage (KV)	13.8/380	13.8/380
	Reactance%	13.4	15

Table (A2): Gen. & Transf. Data at bus # 2.

	Unit	1-3	4-13
Gen.	Rated power (MVA)	108.5	108.5
	Rated voltage (KV)	13.8	13.8
	X_D' (p.u)	0.16	0.16
Transf.	Rated power (MVA)	75	140
	Rated voltage (KV)	13.8/380	13.8/380
	Reactance%	8.4	15.65

Table (A3): Gen. & Transf. Data at bus # 3.

	Unit	1-4	5-8	9-10
Gen.	Rated power (MVA)	345	98	170
	Rated voltage (KV)	21	13.8	13.8
	X_D' (p.u)	0.2	0.168	0.125
Transf.	Rated power (MVA)	360	148	170
	Rated voltage (KV)	21/380	13.8/380	13.8/380
	Reactance%	13.8	22	14

Table (A4) Gen. & Transf. Data at bus # 4.

	Unit	1-5
Gen.	Rated power (MVA)	89.25
	Rated voltage (KV)	13.8
	X_D' (p.u)	0.186
Transf.	Rated power (MVA)	70
	Rated voltage (KV)	13.8/380
	Reactance%	16

Table (A5): 380 KV Transmission line data.

Line #	Bus # Send./Rec	Length Km	+ve seq. R Ω/Km	+ve seq. X Ω/Km
1	1 5	14.107	0.01554	0.2557
2	1 5	14.172	0.01554	0.2557
3	2 6	12.606	0.01554	0.2557
4	2 6	12.589	0.01554	0.2557
5	5 6	22.0	0.021	0.36
6	3 6	151.05	0.021	0.36
7	3 5	143.28	0.021	0.36
8	6 7	63.74	0.018	0.355
9	6 8	81.7	0.018	0.355
10	7 8	48.0	0.018	0.355
11	3 4	200.0	0.0186	0.34
12	3 4	200.0	0.0186	0.34
13	4 9	87.16	0.036	0.367
14	4 10	168.47	0.036	0.367
15	3 7	168.7	0.019	0.352
16	3 7	168.7	0.019	0.352
17	9 11	90.789	0.036	0.367
18	10 11	51.511	0.036	0.367
19	3 11	258.5	0.0193	0.329
20	3 11	258.5	0.0193	0.329

القياسات المعملية لمستوى القصر في الشبكة الكهربية للشركة السعودية الموحدة للكهرباء بالمنطقة الغربية- المملكة العربية السعودية

عماد صديق إبراهيم

كلية الهندسة - جامعة الملك عبد العزيز- ص .ب ٨٠٢٠٤ جدة ٢١٥٨٩
المملكة العربية السعودية

المستخلص : يمثل مستوى القصر أكبر تيار خطأ كهربائي يمكن أن يمر في نظام القوى إلي نقطة الخطأ. نتيجة تغير شكل الشبكة فإن مستوى القصر في أي نقطة في نظام القوى يتغير تبعًا لذلك. ليس من العملي أن نطبق خطأ كهربائي في النظام حتى نستطيع أن نحدد مستوى القصر. يصف هذا البحث منظومة للقياس المستمر لمستوى القصر عند أي نقطة في شبكة نظام القوى. وهذه المنظومة تتكون من زوج من الثيرستورز متصلان على التوازي باتجاه معاكس. ويمكن التحكم في تيار الثيرستور عن طريق زاوية التوصيل وبالتالي استخدامه للقيام بقياس مستوى القصر في الحال. وقد تم تمثيل الشبكة الكهربائية للشركة السعودية الموحدة للكهرباء في المنطقة الغربية في المعمل وأيضًا تم تطبيق المنظومة المقترحة لقياس تيارات الخطأ في المعمل. وقد بينت المقارنة بين قيم تيارات الخطأ المقاسة بالمعمل وقيم تيارات الخطأ المحسوبة بالحاسب الآلي درجة عالية من التطابق.