SHORT CIRCUIT ANALYSIS OF THE SIX–PHASE SYNCHRONOUS MACHINE

Yusuf A. Al-Turki [1] and Saud M. Al-Zahrani [2]

1:Professor, Electrical Engineering Department, King Abdul–Aziz University
2:Engineer, Electrical Engineering Department, King Abdul–Aziz University

ABSTARCT

Six–phase power transmission is gaining popularity as an economic alternative to the construction of more UHV transmission lines. Six–phase synchronous machine will be the core of such a new technology. Various aspects of this machine need to be studied thoroughly. Short–circuit analysis is an important part of such study, which helps in assessing the need of suitable switchgear and protection schemes. This paper presents a systematic approach to study the short–circuit cases of six–phase salient–pole synchronous machine under steady state conditions. The proposed procedure is demonstrated by studying a number of possible short–circuit cases. Experimental verification is carried out to check the validity of the theoretical results obtained.

Keywords: *synchronous machine, six–phase systems, steady–state short–circuit analysis, symmetrical components, experimental six–phase machine, symbolic equation.*

الملخص

بدأت نظم نقل الطاقة الكهربائية سداسية الأطوار بكسب الاهتمام كبديل اقتصادي عوضاً عن بناء المزيد من خطوط نقل الطاقة ذات الجهد العالي. و حيث أن المكائن المتزامنة سداسية الأطوار هي الجزء الرئيس في هذه التقنية الجديدة, فإنه اصبح من الضروري دراسة الجوانب المختلفة لهذه الآلة بالتفصيل . ويعتبر تحليل دوائر القصر جزءاً هاماً من هذه الدراسة مما يساعد على تقييم الحاجة لنظم الحماية و القواطع الملائمة.

إن هذا البحث يقدم طريقة منهجية لدراسة حالات القصر للماكينة المتزامنة سداسية الأطوار ذات الأقطاب البارزة وذلك في حالة الاستقرار, كما أن الطريقة المقترحة تم توضيحها بدراسة عدد من حالات القصر الممكنة . و قد تم إجراء دراسة معملية للتأكد من دقة النتائج النظرية التي تم الحصول عليها.

1. INTRODUCTION

The use of six–phase (and other higher order) power transmission was proposed as an alternative to use electrical right–of–way more efficiently and to meet the increase in power transmission demand. At present, six–phase transmission appears to be the most promising among high–phase order (HPO) systems. It provides an increasing transmission capability, more efficient utilization of right–of–way, better stability than three–phase systems, better transmission efficiency, improvement of the voltage regulation...etc. [Venkata et al., 1976].

Barthold and Barnes [1972] proposed the use of multi–phase (higher than three–phase) power transmission systems to meet the future demand for electrical energy in place of conventional three–phase power systems. [Bhatt N. et. al., 1977] have presented the theory of symmetrical components for six–phase power system. They dealt with fault analysis for: 6–phase, 1–phase to ground, 3–phase 120^o apart to ground, and 5–phase to ground short circuits. However, other types such as faults through impedances and fault analysis of combined 3–phase and 6–phase systems have not been analyzed. [Portela and Tavares, 1993] proposed a transformation applicable for six-phase line studies, allowing its representation by two uncoupled three-phase lines. Numeric results for an example line of 500 kV were represented. [Tiwari and Singh, 1982] have presented the various representations of multi– phase power transmission system including the transformation required for conversion from 3–phase to multi–phase systems. The study carried out on a test system of 6–buses and 8–lines reveals that when more multi-phase (six–phase) lines are added in place of existing three–phase (double–circuit) networks, the performance of overall system improves in terms of better voltage regulation and transmission capability. [Mishra and Chandrasekaran, 1994] compared power transfer capability of six-phase line with equivalent double circuit three-phase line under normal and ground fault conditions. Numerical results of a demonstration example show that the six-phase line transfer more power than the double circuit three-phase line under fault conditions. [Bhatt and Sharma, 1989] have developed two matrices to analyze the simultaneous ground and phase faults on a six–phase power system. [Landers et al., 1998] have compared the installation costs of constructing a standard 115 KV double circuit three–phase transmission line to constructing a 66 KV six–phase transmission line. Stamp and [Girgis, 1999] proposed an algorithm for fault location estimation for a six-phase line using its impedance matrices (without assuming conductor transposition). The distance to the fault was calculated using the unsynchronized voltage and current phasors from both ends of a faulted line. The algorithm was tested for specific faults at varying locations along simple transmission line to develop a better qualitative understanding of its accuracy. [Yukseler and Bagriyanik, 1999] have discussed the fault effects of a double three–phase line converted for six–phase operation.

In the six–phase system, energy could be generated from a six–phase alternator. The design of an adequate protection scheme for six–phase power transmission system depends on detailed fault analysis, accurate relaying and fault location algorithm. Utilities are interested in investigating the various aspects related to machine. Therefore, fault analysis is considered amongst the major issues of this machine. Regarding high phase order machine analysis, [El-Serafi et al., 1975] have presented a generalized analysis for an n–m phase salient pole machine. The mathematical model of this machine is formulated in the symmetrical components, the two phases and d–q reference frame. Regardless of the number of phases, it has been found that the analysis of such a machine is remarkably simplified through its replacement by an equivalent two–phase commutator one. [Ben Ali, 1989] worked on developing current and voltage expressions for the various cases of basic faults. His approach relied on manual solution of the equations that results from the several transformations, (six-phase symmetrical component, general two–phase transformation and d–q transformation). The equations are lengthy and complicated, which makes manual handling of such equations difficult and prone to human errors. [Hegner et al., 1996] described a method for measuring the parameters of a six phase synchronous machine. The measured parameters were used in a computer simulation of a machine/cyclo–converter system.

In this paper, a procedure for steady–state short circuit analysis of the six–phase salient–pole synchronous machine is developed. This approach will utilize a commercially available software package (MathCAD) in solving the equations. The method developed is used to deduce voltage and current expressions of short circuit cases. Finally, the theoretical results obtained will be verified experimentally. A three–phase synchronous machine will be reconnected as a six–phase salient–pole machine. Faults will be applied on this real machine. Experimental results are used to cross check theoretical finding.

Symbols

E_m	: Amplitude of phase e.m.f.
I_s	: Symmetrical component vector of the stator currents,$[I_1, I_p, I_3, I_4, I_5, I_n]$.
I_{Ph}	: Steady-state stator phase currents vector.
r_s	: Armature resistance.
r_{fd} , r_{kd} , r_{kq}	: Field winding, *d* and *q*–axis damper winding resistances referred to the stator, respectively.
X_o , X_n , X_p	: Zero, negative and positive sequence reactances, respectively.
V_s	: Symmetrical component vector of the stator voltages, $[V_1, V_p, V_3, V_4, V_5, V_n]$.
V_{Ph}	: Steady-state stator phase voltage vector.
Z_s	: Stator self-impedance matrix.
λ_s , λ_r	: Stator and rotor flux linkages in webers.
Φ_s	: Symmetrical component transformation matrix.

2. MATHEMATICAL MODEL OF A SIX–PHASE SALIENT–POLE SYNCHRONOUS MACHINE

The synchronous machine under consideration is assumed to have six identical windings on the stator and one field winding on the rotor. Damper winding are not represented on the steady state analysis, winding arrangement of the machine is shown in Fig. (1). Machine windings are magnetically coupled. The coupling between the windings is a function of the rotor position. Magnetic paths of the rotor and its electrical circuits are assumed to be symmetrical with respect to the pole axes.

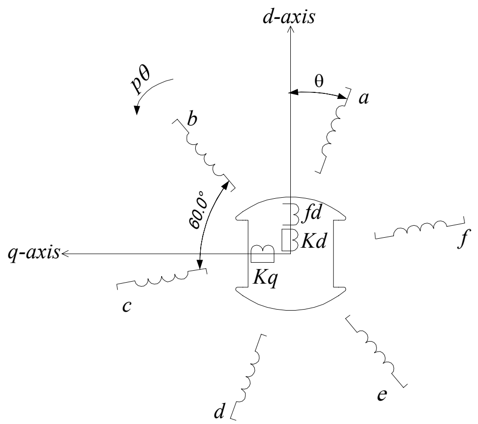

Fig. 1: Winding arrangement of the six–phase synchronous machine.

The voltage equations of the machine of the stator and rotor windings referred to one of the stator windings can be arranged into the form:

$$\begin{bmatrix} v_s \\ v_r \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_r \end{bmatrix} \begin{bmatrix} i_s \\ i_r \end{bmatrix} + p \begin{bmatrix} \lambda_s \\ \lambda_r \end{bmatrix} \tag{1}$$

where:

$$v_s = \begin{bmatrix} v_a & v_b & v_c & v_d & v_e & v_f \end{bmatrix}^T$$

$$v_r = \begin{bmatrix} v_{fd} & v_{kd} & v_{kq} \end{bmatrix}^T$$

$$i_s = \begin{bmatrix} i_a & i_b & i_c & i_d & i_e & i_f \end{bmatrix}^T$$

$$i_r = \begin{bmatrix} i_{fd} & i_{kd} & i_{kq} \end{bmatrix}^T$$

$$r_s = diag\begin{bmatrix} r_a & r_b & r_c & r_d & r_e & r_f \end{bmatrix}$$

$$r_r = diag\begin{bmatrix} r_{fd} & r_{kd} & r_{kq} \end{bmatrix}$$

$$\lambda_s = \begin{bmatrix} \lambda_a & \lambda_b & \lambda_c & \lambda_d & \lambda_e & \lambda_f \end{bmatrix}^T$$

$$\lambda_r = \begin{bmatrix} \lambda_{fd} & \lambda_{kd} & \lambda_{kq} \end{bmatrix}^T$$

For steady–state analysis damper windings are ineffective.

According to Fortescue's theorem, unbalanced six–phase system can be resolved into six balanced systems of phasors using the six–phase symmetrical component transformation [Φ_s], [Bhatt, et al. 1977].

$$\Phi_s = \frac{1}{6}\begin{pmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & b & b^2 & -1 & b^4 & b^5 \\ 1 & b^2 & b^4 & 1 & b^2 & b^4 \\ 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & b^4 & b^2 & 1 & b^4 & b^2 \\ 1 & b^5 & b^4 & -1 & b^2 & b^1 \end{pmatrix} \tag{2}$$

where $b = e^{\left(j\frac{2\pi}{6}\right)}$

Thus, phasor currents and voltages of a six-phase synchronous machine could be related through the following equation [Khalil, 1981].

$$\begin{pmatrix} V_1 \\ V_p \\ V_3 \\ V_4 \\ V_5 \\ V_n \end{pmatrix} = \begin{pmatrix} 0 \\ \sqrt{6}E_m \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} X_o & & & & & \\ & X_p & & & & \\ & & X_o & & & \\ & & & X_o & & \\ & & & & X_o & \\ & & & & & X_n \end{pmatrix}\begin{pmatrix} I_1 \\ I_p \\ I_3 \\ I_4 \\ I_5 \\ I_n \end{pmatrix} \tag{3}$$

$$V_s = E - Z_s \cdot I_s \tag{4}$$

It should be noted in Eq. (3) that the factor j is not shown and is included with the reactance for simplicity.

3. PROCEDURE FOR STEADY–STATE SHORT–CIRCUIT ANALYSIS OF THE MACHINE

The main possible cases for short circuit of a six–phase synchronous machine are numerous (23 cases). Therefore it is important to adopt a unified approach for deriving voltages and currents. The approach proposed by the authors is as follows:

1. Terminal conditions (according to the type of short–circuit) are defined.

2. Symmetrical component transformation (Φ_S) of Eq. (2) is applied to stator currents to obtain its symmetrical component in terms of phase currents.

$$I_s = \Phi_s \cdot I_{Ph} \tag{5}$$

3. The result of step(2) is substituted into Eq. (3),

$$V_s = E - Z_s \cdot \Phi_s \cdot I_{Ph} \tag{6}$$

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4. The inverse of symmetrical component transformation $[\Phi_s^{-1}]$is applied to Eq.(6) to obtain the terminal voltages of the synchronous machine as a function of phase currents, $E_,$ and synchronous machine impedances.

$$V_{Ph} = \Phi_s^{-1} \cdot \left(E - Z_s \cdot \Phi_s \cdot I_{Ph} \right) \tag{7}$$

5. Equalizing Eq. (7), to terminal voltages obtained in step(1) yields six equations with six unknown of voltages and currents. These equations are symbolic, i.e. functions of symmetrical component reactances X_p, X_n, X_o, and E_m.

6. The manual solution of these simultaneous equations is tedious and takes a very long time. There is a possibility of unseen mistakes in handling these lengthy equations. However, a software package (Math Cad computer program) is used to solve these symbolic algebraic equations to obtain current and voltage expressions.

4. DEMONSTRATING EXAMPLE

The method mentioned in the previous section will be demonstrated in the following case**:**

Short circuit applied to 4-Phases, 60^o apart, as shown in Fig. (2). This case is represented by a short circuit on c-d-e-f phases.

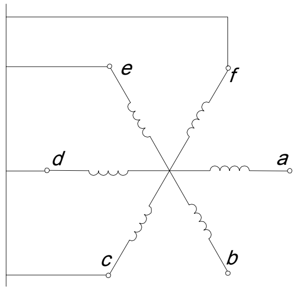

Fig. 2, 4-phase short circuit 60^{o}apart between open phases

1. Terminal conditions

$$I_{ph} = \begin{pmatrix} 0 & 0 & I_c & I_d & I_e & -(I_c + I_d + I_{e)} \end{pmatrix}^T$$
$$\text{where} \quad I_c + I_d + I_e + I_f = 0 \tag{8}$$

$$V_{ph} = \begin{pmatrix} V_a & V_b & V_c & V_c & V_c & V_c \end{pmatrix}$$
$$\text{where} \quad V_c = V_d = V_e = V_f \tag{9}$$

The number of unknowns is six : (I_c, I_d, I_e, V_a, V_b, and V_c).

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2. The symmetrical component transformation (Φ_s)is applied to I_{ph} .

$$I_s = \begin{pmatrix} 0 \\ \left(\frac{-1}{6}+j\frac{\sqrt{3}}{6}\right)I_c - \left(\frac{1}{4}-j\frac{\sqrt{3}}{12}\right)I_d - \frac{1}{6}I_e \\ \left(\frac{1}{4}+j\frac{\sqrt{3}}{12}\right)I_d + j\frac{1}{6}I_e \\ \frac{1}{3}\left(I_c + I_e\right) \\ \left(\frac{1}{4}-j\frac{\sqrt{3}}{12}\right)I_d - j\frac{1}{6}I_e \\ \left(\frac{-1}{6}-j\frac{\sqrt{3}}{6}\right)I_c - \left(\frac{1}{4}+j\frac{\sqrt{3}}{12}\right)I_d - \frac{1}{6}I_e \end{pmatrix} = \begin{pmatrix} I_1 \\ I_p \\ I_3 \\ I_4 \\ I_5 \\ I_n \end{pmatrix} \tag{10}$$

3. Substituting Eq. (10), into Eq. (3), yields

$$\begin{pmatrix} V_1 \\ V_p \\ V_3 \\ V_4 \\ V_5 \\ V_n \end{pmatrix} = \begin{pmatrix} 0 \\ \sqrt{6}E_m \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} - \begin{pmatrix} X_o & & & & & \\ & X_p & & & & \\ & & X_o & & & \\ & & & X_o & & \\ & & & & X_o & \\ & & & & & X_n \end{pmatrix} \begin{pmatrix} 0 \\ \left(\frac{-1}{6}+j\frac{\sqrt{3}}{6}\right)I_c - \left(\frac{1}{4}-j\frac{\sqrt{3}}{12}\right)I_d - \frac{1}{6}I_e \\ \left(\frac{1}{4}+j\frac{\sqrt{3}}{12}\right)I_d + j\frac{1}{6}I_e \\ \frac{1}{3}\left(I_c + I_e\right) \\ \left(\frac{1}{4}-j\frac{\sqrt{3}}{12}\right)I_d - j\frac{1}{6}I_e \\ \left(\frac{-1}{6}-j\frac{\sqrt{3}}{6}\right)I_c - \left(\frac{1}{4}+j\frac{\sqrt{3}}{12}\right)I_d - \frac{1}{6}I_e \end{pmatrix} \tag{11}$$

4. appling [Φ_s^{-1}] matrix to Eq.(11)

$$\Phi_s^{-1} \cdot \left(V_1 \quad V_p \quad V_3 \quad V_4 \quad V_5 \quad V_n\right)^T = \left(V_a \quad V_b \quad V_c \quad V_c \quad V_c \quad V_c\right)^T \tag{12}$$

So,

$$V_a = \frac{1}{6}\left(\left(1 - j\sqrt{3}\right)X_p + \left(1 + j\sqrt{3}\right)X_n - 2X_o\right)I_c + \frac{1}{12}\left(\left(3 - i\sqrt{3}\right)X_p + \left(3 + j\sqrt{3}\right)X_n - 6X_o\right)I_d + \frac{1}{6}\left(X_p + X_n - 2X_o\right)I_e + E_m \tag{13}$$

$$V_b = \frac{-1}{6}\left(\left(1 + j\sqrt{3}\right)X_p + \left(1 - j\sqrt{3}\right)X_n - 2X_o\right)I_c - \frac{i\sqrt{3}}{6}\left(X_p - X_n\right)I_d + \frac{1}{12}\left(\left(1 - j\sqrt{3}\right)X_p + \left(1 + j\sqrt{3}\right)X_n - 2X_o\right)I_e + \frac{1}{2}E_m\left(1 - j\sqrt{3}\right) \tag{14}$$

$$V_c = \frac{-1}{3}\left(X_p + X_n + X_o\right)I_c - \frac{1}{12}\left(\left(3 + j\sqrt{3}\right)X_p + \left(3 - j\sqrt{3}\right)X_n - 6X_o\right)I_d - \frac{1}{12}\left(\left(1 + j\sqrt{3}\right)X_p + \left(1 - j\sqrt{3}\right)X_n - 2X_o\right)I_e - \frac{1}{2}E_m\left(1 + j\sqrt{3}\right) \quad (15)$$

$$V_c = \frac{-1}{6}\left(\left(1 - j\sqrt{3}\right)X_p + \left(1 + j\sqrt{3}\right)X_n - 2X_o\right)I_c - \frac{1}{12}\left(\left(3 - j\sqrt{3}\right)X_p + \left(3 + j\sqrt{3}\right)X_n + 6X_o\right)I_d - \frac{1}{6}\left(X_p + X_n - 2X_o\right)I_e - E_m \quad (16)$$

$$V_c = \frac{1}{6}\left(\left(1 + j\sqrt{3}\right)X_p + \left(1 - j\sqrt{3}\right)X_n - 2X_o\right)I_c + j\frac{\sqrt{3}}{6}\left(X_p - X_n\right)I_d - \frac{1}{12}\left(\left(1 + j\sqrt{3}\right)X_p + \left(1 + j\sqrt{3}\right)X_n + 10X_o\right)I_e - \frac{1}{2}E_m\left(1 - j\sqrt{3}\right) \quad (17)$$

$$V_c = \frac{1}{3}\left(X_p + X_n + X_o\right)I_c + \frac{1}{12}\left(\left(3 + j\sqrt{3}\right)X_p + \left(3 - j\sqrt{3}\right)X_n + 6X_o\right)I_d + \frac{1}{12}\left(\left(1 + j\sqrt{3}\right)X_p + \left(1 - j\sqrt{3}\right)X_n + 10X_o\right)I_e + \frac{1}{2}E_m\left(1 + j\sqrt{3}\right) \quad (18)$$

5. Solving the equations (13)–to–(18), for I_c, I_d, I_e, V_a, V_b, and V_c, the following expressions are obtained:

$$I_c = \frac{1}{2}E_m \frac{(9X_n - 15X_o) - j\sqrt{3}(11X_n + 19X_o)}{3X_o^2 + 8X_oX_p + 8X_oX_n + 5X_nX_p} \quad (19)$$

$$I_d = E_m \frac{(-9X_n - 6X_o) + j\sqrt{3}(X_n - 4X_o)}{3X_o^2 + 8X_oX_p + 8X_oX_n + 5X_nX_p} \quad (20)$$

$$I_e = E_m \frac{(-6X_n + 3X_o) + j\sqrt{3}(4X_n + 5X_o)}{3X_o^2 + 8X_oX_p + 8X_oX_n + 5X_nX_p} \quad (21)$$

$$I_f = \frac{1}{2}E_m \frac{(21X_n + 21X_o) - j\sqrt{3}(X_n + 17X_o)}{3X_o^2 + 8X_oX_p + 8X_oX_n + 5X_nX_p} \quad (22)$$

$$V_a = \frac{1}{2}E_m X_o \frac{(15X_o + 33X_n) + j7\sqrt{3}(X_o - X_n)}{3X_o^2 + 8X_oX_p + 8X_oX_n + 5X_nX_p} \quad (23)$$

$$V_b = \frac{1}{2}E_m X_o \frac{(-3X_o + 27X_n) - j\sqrt{3}(11X_o + 13X_n)}{3X_o^2 + 8X_oX_p + 8X_oX_n + 5X_nX_p} \quad (24)$$

$$V_c = \frac{1}{2}E_m X_o \frac{(-3X_o - 15X_n) + j\sqrt{3}(X_o + 5X_n)}{3X_o^2 + 8X_oX_p + 8X_oX_n + 5X_nX_p} \quad (25)$$

5. EXPERIMENTAL VERIFICATION

The theoretical steady–state short–circuit results need to be verified experimentally. Tests were conducted on three-phase, star connected, 6-pole, 54 double layer, 208 Vac, 60 Hz, 2 KVA, 1200 rpm synchronous machine. The coil groups of this machine were reconnected to form a six-phase machine. Various machine parameters (X_p, X_n, X_o) were determined experimentally. Open circuit characteristics were obtained, and it is used later in relating the field current (I_{fd}) to open circuit rms phase voltage (E_m). The short–circuit under consideration is 4-phases 60^o apart between open circuit phases, (the short circuit is applied on c–d-e-f phases). The machine is run at rated speed open circuited. The field current is changed in steps. In each step the fault is applied and various terminal voltages and currents were measured. This gives a wide range of short–circuit points corresponding to various excitations (I_{fd}). Experimental and theoretical results are shown in Fig. (3).

To calculate theoretical results for each field current point (I_{fd}) the corresponding (E_m) is found from the open–circuit characteristics of the machine, then theoretical terminal quantities are calculated based on equations [(19)–(25)]. For the sake of comparison, these theoretical results are also plotted in Fig. 3.

As shown in Fig. 3 there is a slight difference between theoretical and experimental results. This difference is mainly due to the study assumptions of neglecting armature resistance, saturation and space harmonics.

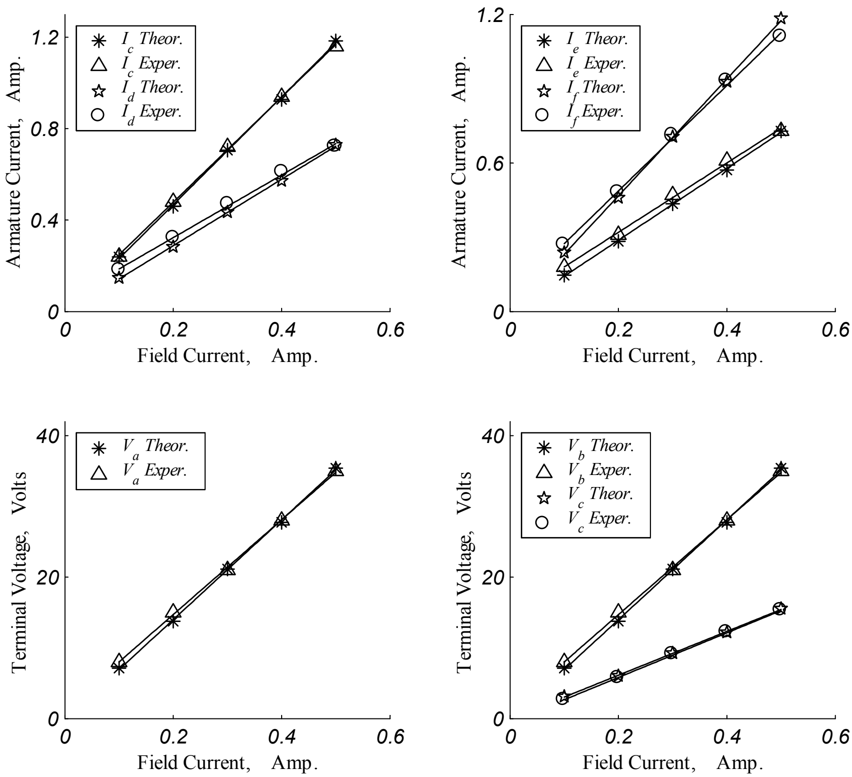

Fig. 3, 4–Phases 60^o apart between open Phases Short–Circuit

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6. RESULTS OF SHORT–CIRCUIT CASES

In this section results obtained for a number of different short–circuit cases, based on the proposed procedure, are presented. Due to paper space limitation, it is not possible to encounter various cases of short–circuit. Therefore two more cases will be presented.

6.1. 5-Phases Short–Circuit

This case is represented by a short circuit on b–c–d–e–f phases, as shown in Fig. 4.

Terminal Conditions:

$$I_a = 0 \tag{26}$$

$$I_b + I_c + I_d + I_e + I_f = 0 \tag{27}$$

$$V_b = V_c = V_d = V_e = V_f \tag{28}$$

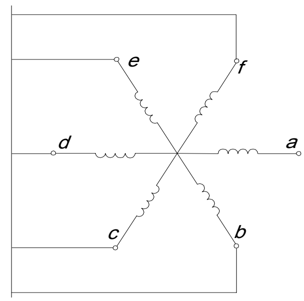

Fig. 4, 5-phase short circuit

Expressions:

$$I_b = \frac{1}{2} E_m \frac{7X_n - j\sqrt{3}(3X_n + 2X_o)}{3X_n X_p + X_o X_n + X_o X_p} \tag{29}$$

$$I_c = \frac{-1}{2} E_m \frac{3X_n + j\sqrt{3}(3X_n + 2X_o)}{(3X_n X_p + X_o X_n + X_o X_p} \tag{30}$$

$$I_d = -E_m \frac{4X_n}{3X_n X_p + X_o X_n + X_o X_p} \tag{31}$$

$$I_e = \frac{1}{2} E_m \frac{-3X_n + j\sqrt{3}(3X_n + 2X_o)}{3X_n X_p + X_o X_n + X_o X_p} \tag{32}$$

$$I_f = \frac{1}{2} E_m \frac{7X_n + j\sqrt{3}(3X_n + 2X_o)}{3X_n X_p + X_o X_n + X_o X_p} \tag{33}$$

$$V_a = -E_m \frac{5X_o X_n}{3X_n X_p + X_o X_n + X_o X_p} \tag{34}$$

$$V_b = -E_m \frac{X_o X_n}{3X_n X_p + X_o X_n + X_o X_p} \tag{35}$$

$$V_c = V_d = V_e = V_f = V_b \tag{36}$$

These Expressions were verified experimentally as shown in Fig. 5.

6.2. 3-Phase 60^o apart Short–Circuit

This case is represented by a short circuit on a–b–c phases, as shown in Fig.5.
Terminal conditions:

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$$I_d = I_e = I_f = 0 \quad (37)$$

$$V_a = V_b = V_c \quad (38)$$

$$I_a + I_b + I_c = 0 \quad (39)$$

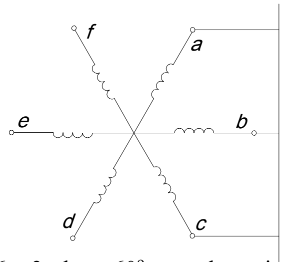

Fig. 6, 3-phase 60°apart short circuit

Expressions:

$$I_b = -3E_m \frac{-(X_n + X_o) + j\sqrt{3}(X_n + X_o)}{9X_oX_n + X_nX_p + 17X_o^2 + 9X_oX_p} \quad (40)$$

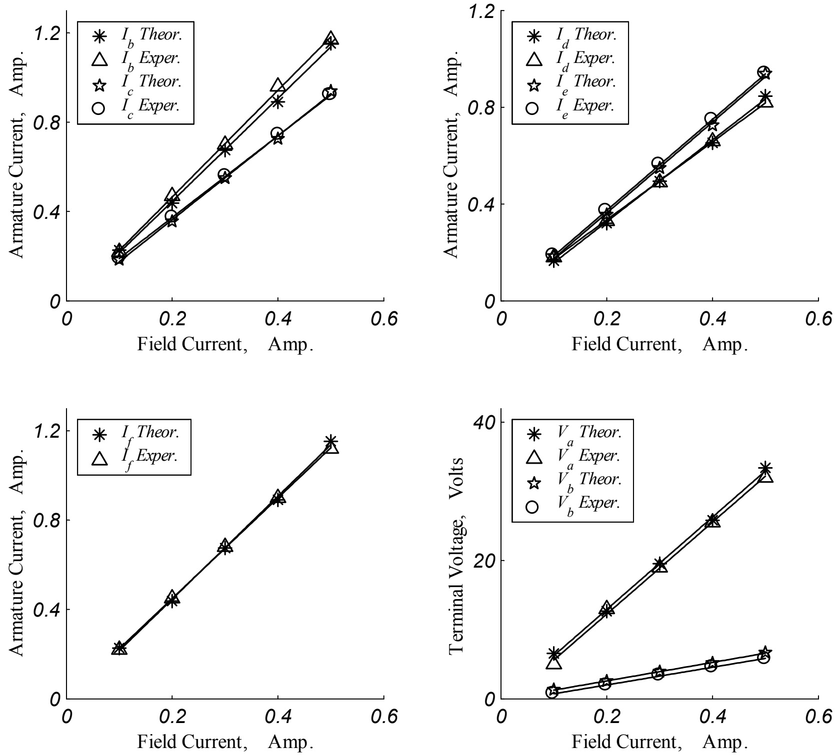

Fig. 5, 5–Phases Short–Circuit

$$I_c = -E_m \frac{27X_o - 3X_n + j\sqrt{3}(X_n - 7X_o)}{9X_oX_n + X_nX_p + 17X_o^2 + 9X_oX_p} \quad (41)$$

$$V_a = -6E_mX_o \frac{-(X_n + X_o) + j\sqrt{3}(X_n + X_o)}{9X_oX_n + X_nX_p + 17X_o^2 + 9X_oX_p} \quad (42)$$

Top

$$V_d = 2E_m X_o \frac{-(3X_n + 15X_o) + j\sqrt{3}(2X_n - 2X_o)}{9X_oX_n + X_nX_p + 17X_o^2 + 9X_oX_p} \qquad (43)$$

$$V_e = 9E_m X_o \frac{-(X_n + X_o) + j\sqrt{3}(X_n + X_o)}{9X_oX_n + X_nX_p + 17X_o^2 + 9X_oX_p} \qquad (44)$$

$$V_f = E_m X_o \frac{-3X_n + 21X_o + j\sqrt{3}(5X_n + 13X_o)}{9X_oX_n + X_nX_p + 17X_o^2 + 9X_oX_p} \qquad (45)$$

These Expressions were verified experimentally as shown in Fig. 7.

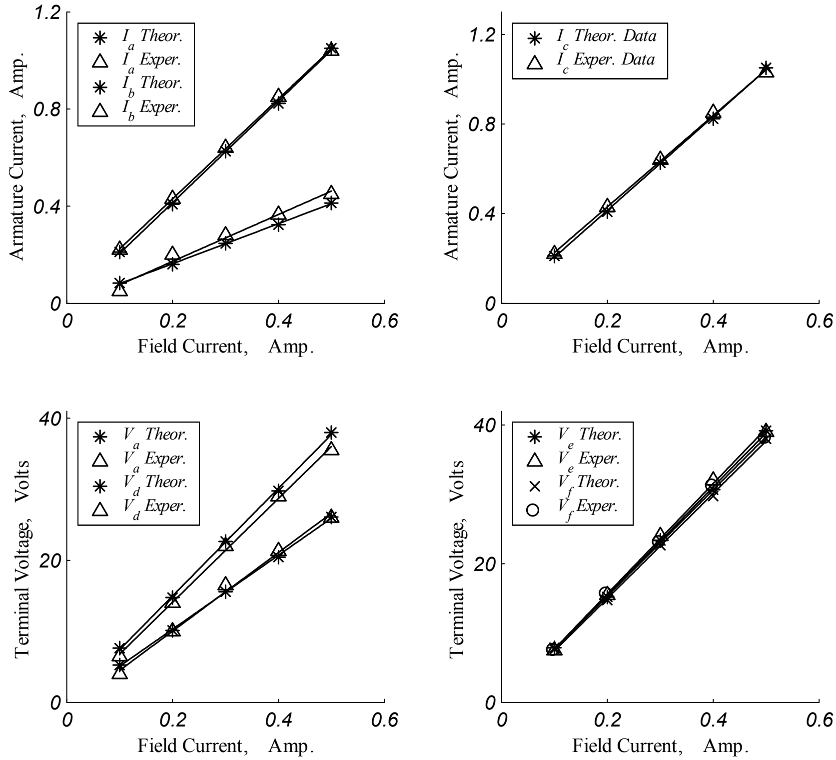

Fig. 7, 3–Phases 60° apart between open Phases Short–Circuit

7. CONCLUSION

In this paper, a general procedure for steady–state short–circuit analysis of a six–phase salient–pole synchronous machine has been presented. This procedure is based on symmetrical component approach. Various terminal voltages and currents could be found for each short circuit case. This procedure is used to deduce the voltages and currents in the various possible short–circuit cases. The availability of computer software packages

(MathCad) that could deal with symbolic equation made the prohibitive manual derivations an easy task. In order to check the results experimentally, a salient–pole synchronous machine in the laboratory has been reconnected as a six–phase synchronous machine and used for this purpose. Good agreement between the theoretical and experimental results validates the results obtained for steady–state short–circuit analysis.

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