A Generalized Formulation and Analysis of Shunt Faults in Multi-Phase Transmission Systems.

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A GENERALIZED FORMULATION AND ANALYSIS OF SHUNT
FAULTS IN MULTI-PHASE TRANSMISSION SYSTEMS

صياغة وتحليل أخطاء التوازى فى نظم النقل متعددة الاوجه

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الخلاصة: هذا البحث يقوم بتطبيق الاسلوب التقنى للنظام ثلاثى الاوجه لمعالجة التوازى أخطاء فى النظم متعددة الاوجه .

وقد طور هذا العمل معادلتين لتحديد التيارات والجهود أثناء الخطأ لكن أنواع الخطأ .

وكذلك تم استنتاج المعادلات للتيارات والجهود بحيث يمكن تطبيقيا لأى ترتيب رجيى وكذلك لأى نوع من أنواع الخطأ. ويقدم هذا البحث توضيحا لصحة المعادلات المستنتجة عن طريق الحسابات المترعة والموضحة فى هذا العمل وذلك لاستنتاج معلومات هامة لاداء نظم النقل متعددة الأوجه.

ABSTRACT

This paper is devoted to the extension of the existing three phase technique for a generalized treatment of shunt faults in multi-phase systems. The expressions derived in this paper for fault currents and voltages are applicable to any phase order, fault type and combination of faults and can account for the fault impedance/admittance. Several illustrative calculations are presented to demonstrate the validity of expressions derived and to derive important informations regarding performance of multi-phase transmission systems.

INTRODUCTION

Multi-phase transmission imploying more than three phase has been investigated for the last several years as a potential alternative to the conventional three phase system [1]. In the process, the attention has been focussed mainly on six-phase and twelve-phase systems. Fault analysis is one of the most important aspects of transmission planning and design activity. A number of publications dealing with this aspect have appeared in the literature [2-11] and the efforts to sort out the various complexities associated with the fault analysis of multi-phase system is continually growing.

The fault analysis of six-phase system was carried out by several authors employing symmetrical components transformations [2-5],Clarke's component transformation [5], α- β- 0 components [6] and combined use of two-phase and three-phase symmetrical components method [7]. The phase parameter description for the six-phase line in order to derive

fault current and voltage expressions was also employed in some
studies [3,4,8].

The total number of faults increases with the increasing phase order
making the fault analysis of multi-phase system a difficult task [11].
Further solving each fault separately is quite cumbersome. There have
been attempts to unify the procedure so that the same equation is
employed to analyse system faults irrespective of fault type, for six-
phase system [9] and twelve-phase system [11] neglecting the fault im-
pedance/admittance. This paper is a step forward in this direction to
generalise the three-phase technique [12] for a multi-phase system ta-
king into account the fault impedance/admittance.For this purpose a ge-
neral fault impedance/admittance matrix is derived for an N-phase sys-
tem. A mere substitution of relevant values for any fault (with fault
impedance) type can be simulated. However, if the fault impedances are
neglected, the procedure yields a single equation for computing fault
currents involving phases,phases to ground and also their combinations.
The simplicity and ease with which the equations can be used to carry
out fault analysis on multi-phase transmission systems is amply demons-
trated by several illustrative calculations. Further the utility of the
formulation to obtain the most and least severe fault in a six-phase
transimission and a comparative view of performance of various multi-
phase system during fault condition is shown in this paper.

FORMULATION AND ANALYSIS OF FAULT PROBLEM

A twelve-phase transmission system can be represented as in Fig.1 for
the purpose of simulation of fault condition. Assuming an unloaded twe-
lve-phase system, the performance of the system during fault can be
written as:

$$V_{ph}^{12} = E_{ph}^{12} - I_f^{12} Z_{ph}^{12} \tag{1}$$

$$I_f^{12} = Y_f^{12} (U + Z_{ph}^{12} Y_f^{12})^{-1} E_{ph}^{12} \tag{2}$$

$$= (Z_f^{12} + Z_{ph}^{12})^{-1} E_{ph}^{12} \tag{3}$$

where Z_{ph}^{12} is the twelve-phase impedance matrix with self impedance
              $Z_{ii} = Z_s$ and mutual impedance $Z_{ij} = Z_m$;i = j;i,j=1,2,..,12.

Z_f^{12}/Y_f^{12} is the fault impedance/admittance matrix used to describe

       and simulate a desired type of fault;

U   is the unit matrix;

E_{ph}^{12} is the known voltage vector prior to the fault

       $= [E_a \quad E_b \ldots\ldots\ldots\ldots\ldots E_l]^t$

       $= E [C^{12} \quad C^{11} \ldots\ldots\ldots\ldots C]^t$;

V_{ph}^{12} $= [V_a \quad V_b \ldots\ldots\ldots\ldots\ldots V_l]^t$;

C   is the twelve-phase operator $= Exp(j2\Pi/12)$.

Derivation of General Fault Impedance/Admittance Matrix

All shunt faults can be simulated by employing an appropraite fault im-
pedance or admittance matrix. The procedure for the formulation of such
matrices are illustrated below.
Considering a twelve-phase system subjected to a twelve-phase to ground
fault as shown in Fig.2. Taking the ground as reference, the phase vol-
tage to ground fault at the fault point are given by:

$$V_{fa} = I_{fa}(Z_{fa} + Z_g) + (I_{fb} + I_{fc} + \ldots\ldots + I_{fl})\, Z_g;$$
$$V_{fb} = I_{fb}(Z_{fb} + Z_g) + (I_{fa} + I_{fc} + \ldots\ldots + I_{fl})\, Z_g;$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$
$$V_{fl} = I_{fl}(Z_{fl} + Z_g) + (I_{fa} + I_{fb} + \ldots\ldots + I_{fk})\, Z_g; \qquad (4)$$

Eqns.(4) can be written in the following compact form:

$$V_f^N = Z_f^N\, I_f^N \qquad (5)$$

where Z_f^N is the N-phase fault impedance matrix (N=12) with $Z_{ii} = Z_{fi} +$
Z_g and $Z_{ij} = Z_g$; i,j= a,b,......,l & i = j.

Limitations:

A variety of shunt faults can't be simulated by this fault impedance
matrix. Therefore,the fault impedance matrix is not useful and the need
exists for a generalised formulation of fault admittance matrix.

The node equation for the circuit of Fig.2 can be written as:

$$
\begin{bmatrix} I_{fa} \\ I_{fb} \\ \vdots \\ \vdots \\ I_{fl} \\ \hline I_n \end{bmatrix}
=
\left[\begin{array}{cccc:c}
Y_{fa} & & & & -Y_{fa} \\
& Y_{fb} & & & -Y_{fb} \\
& & & & \vdots \\
& & & & \vdots \\
& & & Y_{fl} & -Y_{fl} \\
\hline
& & & & Y_g
\end{array}\right]
\begin{bmatrix} V_{ia} \\ V_{ib} \\ \vdots \\ \vdots \\ V_{fl} \\ \hline V_n \end{bmatrix}
\qquad (6)
$$

By eliminating node n from Eq.(6),the fault admittance matrix for the
12-phase to ground can be found as:

$$Y_f^N = [A]/(Y_g + \Sigma_{k=1,k=i}^{N} Y_{fk}) \qquad ($$

where the elements of the A-matrix are given by:

$$a_{ii} = Y_{fi}\,(Y_g + \Sigma_{k=i,k=1}^{N} Y_{fk})$$
$$a_{ij} = -\, Y_{fi}\, Y_{fj} \quad ;i = j \; , \; i,j=1,2,\ldots,N$$

(or i,j = a,b,......,l respectively for the 12-phase system.)

The above equation can be used to obtain the fault admittance matrix
for any type of shunt faults except for bolted ground faults with $Z_{ii} =$

$Z_g = 0$ and bolted interphase faults for which $Z_{f(i)} = 0$. Bolted phase-to-ground and phase-to-phase faults are dealt with seperately in the following.

Derivation of general Expressions for Fault Currents and Voltages

In case when the fault impedance is neglected, a method for evaluating fault currents and voltages for all types of faults is developed in this section. In the development to follow the twelve-phase system is assumed to be balanced, unloaded and fully transposed.

Evaluation of Fault Currents

The fault currents can be obtained by solving Eq.(1) together with the boundary conditions of the fault. The following expression for fault current due to any bolted ground fault has already been developed earlier in paper [11].

$$I_j = E_a / Z_1 [P^{N+1-j} - (Z_0 - Z_1)/\{nZ_0 + (N-n)Z_1\}(\sum_{i=1}^{N} P^{N+1-i} F_i)] \qquad (8)$$

where F_i is the fault coefficient $= 1$ for the ith phase involved in the fault and $= 0$ for the ith phase isolated from the fault;

N   is the total number of phases;

n   is the number of faulted phase;

Z_0 & Z_1 are zero and positive sequence impedances respectively;

P   is the phase operator $= \text{Exp}(j\ 2\pi/N)$.

The expression for the fault current caused by interphase faults can be obtained in a similar way as described in [11]. The procedure is illustrated for the following three interphase faults:

i- Two-phase fault (a,b)

Boundary conditions $V_a = V_b$; $I_a + I_b = 0$. and $I_c = I_d = \ldots\ldots = I_t = 0$.

The fault currents $\left. \begin{array}{l} I_a = E_a (C^{12} - C^{11})/2(Z_s - Z_m) \\ I_b = E_a (C^{11} - C^{12})/2(Z_s - Z_m) \end{array} \right\} \qquad (9)$

ii- Three-phase fault (a,b,c)

Boundary conditions $V_a = V_b = V_c$; $I_a + I_b + I_c = 0$ & $I_d = I_e = \ldots = I_t = 0$.

The fault currents $\left. \begin{array}{l} I_a = E_a (2C^{12} - C^{11} - C^{10})/3(Z_s - Z_m) \\ I_b = E_a (2C^{11} - C^{12} - C^{10})/3(Z_s - Z_m) \\ I_c = E_a (2C^{10} - C^{12} - C^{11})/3(Z_s - Z_m) \end{array} \right\} \qquad (10)$

iii- Four-phase fault (a,b,c,d)

Boundary conditions $V_a = V_b = V_c = V_d$; $I_a + I_b + I_c + I_d = 0$ & $I_e = I_p = \ldots = I_t = 0$.

The fault currents $\left. \begin{array}{l} I_a = E_a (3C^{12} - C^{11} - C^{10} - C^9)/4(Z_s - Z_m) \\ \vdots \\ I_d = E_a (3C^9 - C^{12} - C^{11} - C^{10})/4(Z_s - Z_m) \end{array} \right\} \qquad (11)$

The expressions (9-11) are arranged so as to yeild the general expres-

sion (12) which gives the fault current resulting from any type of i.
terphase faults on any phase order.

$$I_j = E_1/Z_1 [P^{N+1-j} - (\Sigma_{i=1}^N P^{N+1-i} F_i)/n] \tag{12}$$

Eqns (8&12) can be combined to get the following general fault curren
expression:

$$I_j = E_1/Z_1 \{P^{N+1-j} - [(1-\alpha)(Z_0-Z_1)/\{nZ_0+(N-n)Z_1\}+\alpha/n](\Sigma_{i=1}^N P^{N+1-i} F_i)\} \tag{13}$$

where α is a fault type coefficient taken equal to 1 for the inter
phase faults and 0 for ground faults.

Evaluation of Post-Fault Voltages

The post-fault voltages for the three faults discussed earlier ar
given by:

i- (a,b) fault

$$\left.\begin{aligned} V_a = V_b &= E_a (C^{12} - C^{11})/2 \\ V_c &= C^{10} E_a \\ \hat{V}_i &= C E_a \end{aligned}\right\} \tag{14}$$

ii- (a,b,c) fault

$$\left.\begin{aligned} V_a = V_b = V_c &= E_a (C^{12}-C^{11}-C^{10})/3 \\ V_d &= C^9 E_a \\ V_i &= C E_a \end{aligned}\right\} \tag{15}$$

iii- (a,b,c,d) fault

$$\left.\begin{aligned} V_a = V_b = V_c = V_d &= E_a (C^{12}-C^{11}-C^{10}-C^9)/4 \\ V_e &= C^8 E_a \\ V_i &= C E_a \end{aligned}\right\} \tag{16}$$

The Eqns.(14-16) are suitably arranged so as to give the following
general formula:

$$V_j = E_a [(1-F_j) P^{N+1-j} + F_j (\Sigma_{i=1}^N P^{N+1-i} F_i)/n] \tag{17}$$

which gives the post-fault voltage of faulty phases for any type of in-
terphase fault. The post-fault voltages of sound phases for any bolted
ground fault are given by [11]:

$$V_j = E_a [P^{N-1-j} - (Z_0-Z_1)/\{nZ_0+(N-n)Z_1\}(\Sigma_{i=1}^N P^{N-1-i} F_i) \tag{18}$$

Eqns.(17&18) may be also combined in one equation as follows:

$$V_j = E_a \{(1-F_j) P^{N+1-j} - [(1-a)(1-F_j)(Z_0-Z_1)/\{nZ_0+(N-n)Z_1-\alpha F_j/n]* \\ *(\Sigma_{i=1}^N P^{N+1-i} F_i)\} \tag{19}$$

Eq.(13) and Eq.(19) are used to compute the fault current and the sound
phase voltage for all the possible types of bolted ground and inter-
phase faults.

ILLUSTRATIVE CALCULATIONS

The expressions developed in this paper are applied to evaluate the
performance of multi-phase systems under fault conditions employing the
conductor configurations and line geometries shown in Fig. 3. The fol-
lowing line parameters and fault specifications are considered:
X_o and X_l (in Ω/mile) are (3-ϕ) 1.928 & 0.398 ; (6-ϕ) 3.678 & 0.534 and
(12-ϕ) 7.149 & 0.566 respectively.
Resistances and shunt admittances of the line are neglected.
Fault location = 200 miles from the sending end.
Fault resistance between any two phases = 2 Ω.
$R_{l} = 4 \Omega$.
Ground fault resistance $R_g = 106.8 \Omega$.

The results of the fault analysis with and without the fault impedances
/admittances for the six-phase line depicted in Fig.3 are presented in
table 1. It can be observed from this table that:
i-   The inclusion of fault impedances/admittances in the calculation
     of the fault currents leads to a decreasing some fault currents
     and an increasing with some others.
ii- The (a,b,d,p,n) fault is the most severe fault with a maximum cur-
     rent of 5.419 kA in phase d.
iii- The (a-n) fault is the least severe fault with a minimum current
     of 1.945 kA in phase a.
iv- For all other results, the current magnitudes lie between 2.161 kA
     and 5.407 kA. Thus for the line under consideration the range of
the fault currents varies from 1.945 kA to 5.914 kA.

Table 2 shows the obtained values of the fault currents and voltages
for single-phase to ground,all phases to ground and two-phase faults on
three-phase,six-phase and twelve-phase lines (Fig.3). From the results,
it can be seen that multi-phase systems are found to possess lower va-
lues of fault currents than three-phase system. This may require cir-
cuit breakers of lower ratings per phase to be used with multi-phase
system.

Table 1

Fault currents for all the significant faults in six-phase system

Fault Type	Phase Current(kA) With fault admittance included * Without fault admittance					
	a	b	c	d	e	f
a,n	1.945 -62.5 * 2.183 -90.0					
a,b,n	2.858	1.83				

	-45.8	-122.4			
	* 2.506	2.506			
	-60.3	-179.7			
a,b	2.161	2.161			
	-27.900	152.100			
	* 2.163	2.163			
	-30.000	150.000			
a,c,n	4.097	0.0	3.459		
	-65.000	0.0	130.600		
	* 3.817	0.0	3.817		
	-71.000	0.0	131.000		
a,c	3.744	0.0	3.744		
	-57.900	0.0	122.100		
	* 3.746	0.0	3.746		
	-60.900	0.0	120.000		
a,d,n	4.323	0.0	0.0	4.323	
	-87.000	0.0	0.0	93.000	
	* 4.326	0.0	0.0	4.326	
	-90.000	0.0	0.0	90.000	
a,d	4.323	0.0	0.0	4.323	
	-87.900	0.0	0.0	93.000	
	* 4.326	0.0	0.0	4.326	
	-90.000	0.0	0.0	90.000	
a,b,c,n	4.087	1.944	3.417		
	-54.400	-137.400	118.400		
	* 3.746	2.173	3.746		
	-60.200	-150.000	120.200		
a,b,c	3.940	1.449	3.682		
	-48.400	-143.600	109.900		
	* 3.815	1.442	3.815		
	-49.100	-150.000	109.900		
a,b,d,n	4.027	3.123	0.0	4.910	
	-71.600	-144.800	0.0	79.900	
	* 3.901	3.250	0.0	4.953	
	-76.1	-150.000	0.0	79.200	
a,b,d	3.876	2.882	0.0	5.144	
	-69.600	-147.600	0.0	76.700	
	* 3.815	2.884	0.0	5.199	
	-70.900	-150.000	0.0	76.1	
a,c,e,n	4.323	0.0	4.323	0.0	4.323
	-87.900	0.0	152.100	0.0	32.100
	* 4.325	0.0	4.325	0.0	4.325
	-90.000	0.0	150.000	0.0	30.000
a,c,e	4.321	0.0	4.321	0.0	4.321

	-88.900	0.0	151.100	0.0	31.500
	* 4.326	0.0	4.326	0.0	4.326
	-90.000	0.0	150.000	0.0	30.000
a,b,c,d,n	4.785	3.150	2.899	4.456	
	-67.900	-130.000	138.900	70.700	
	* 4.576	3.124	3.124	4.576	
	-71.000	-136.200	136.200	71.000	
a,b,c,d	4.723	2.867	2.867	4.723	
	-64.400	-128.800	133.000	68.700	
	* 4.714	2.861	2.861	4.714	
	-66.600	-130.900	130.900	66.600	
a,b,d,e,n	3.466	3.466	0.0	3.466	3.466
	-87.300	-147.300	0.0	92.700	32.700
	* 4.325	4.325	0.0	4.325	4.325
	-90.000	-150.000	0.0	90.000	30.000
a,b,d,e	4.342	4.342	0.0	4.342	4.342
	-86.300	-145.200	0.0	93.700	34.800
	* 4.326	4.326	0.0	4.326	4.326
	-90.000	-150.000	0.0	90.000	30.000
a,b,d,f,n	3.232	3.358	0.0	5.419	0.0	3.831
	-90.300	-147.800	0.0	93.600	0.0	-15.000
	* 3.464	3.996	0.0	5.188	0.0	3.996
	-90.000	-160.800	0.0	90.000	0.0	-19.200
a,b,d,f	3.251	3.907	0.0	5.418	0.0	3.906
	-87.900	-161.800	0.0	92.100	0.0	-14.000
	* 3.244	3.899	0.0	5.407	0.0	3.899
	-90.000	-163.900	0.0	90.000	0.0	-16.100
a,b,c,d,e, n	4.810	4.057	3.551	3.929	4.703	
	-80.300	-137.900	153.200	82.900	23.600	
	* 4.727	4.015	3.607	4.015	4.727	
	-82.400	-141.100	150.000	81.100	22.400	
a,b,c,d,e	4.815	3.963	3.458	3.962	4.815	
	-78.900	-136.900	152.200	81.300	23.200	
	* 4.817	3.965	3.461	3.965	4.817	
	-81.100	-139.100	150.000	79.100	21.100	
a,b,c,d,e, f,n	4.323	4.323	4.323	4.323	4.323	4.323
	-87.900	-147.900	152.100	92.100	32.100	-27.900
	* 4.326	4.326	4.326	4.326	4.326	4.326
	-90.000	-150.000	150.000	90.000	30.000	-30.000
a,b,c,d,e, f	4.323	4.323	4.323	4.323	4.323	4.323
	-87.900	-147.900	152.100	92.100	32.100	-27.900
	* 4.326	4.326	4.326	4.326	4.326	4.326
	-90.000	-150.000	150.000	90.000	30.000	-30.000

Table 2

Comparative value of phase fault currents and voltages for
three-phase,six-phase and twelve-phase system

Fault Type	Three-phase		Six-phase		Twelve-phase	
	Fault current kA	Fault Voltage kV	Fault current kA	Fault Voltage kV	Fault current kA	Fault Voltage kV
Single-phase to ground fault	2.166 * 2.544	240.702 * 0.0	1.945 * 2.183	213.689 * 0.0	1.852 * 2.073	205.725 * 0.0
All-phases to ground fault	5.802 * 5.804	23.212 * 0.0	4.323 * 4.326	17.291 * 0.0	4.068 * 4.079	16.273 * 0.0
Two-phase fault(a,b)	5.022 * 5.026	251.096 *231.00	2.161 * 2.163	408.743 *400.101	1.045 * 1.051	450.564 *446.252

* Values without fault impedances.

CONCLUSIONS

This paper is concerned with the generalised analysis of shunt faults
in multi-phase system with the inclusion of fault impedance/admittance.
For this analysis a general expression of fault impedance/admittance
matrix is presented. These fault impedance/admittance matrices can be
generated for any phase order and thus any type of shunt fault can be
simulated.

Two general equations have also been developed to determine the fault
currents and post-fault voltages for all types of faults having negli-
gible fault impedances.

The validity of the expressions developed and their applicability for
any phase order have been demonstrated through the illustrative calcu-
lations. These expressions give good agreements with the previously
available results which are summarised as follows:
i-   The four phases and the single-phase to ground faults are the most
     and least severe faults respectively in a six-phase system.
ii- The fault levels of multi-phase systems are less than those of 3-
     phase system and this may allow circuit breakers with lower rating
     per phase to be used.

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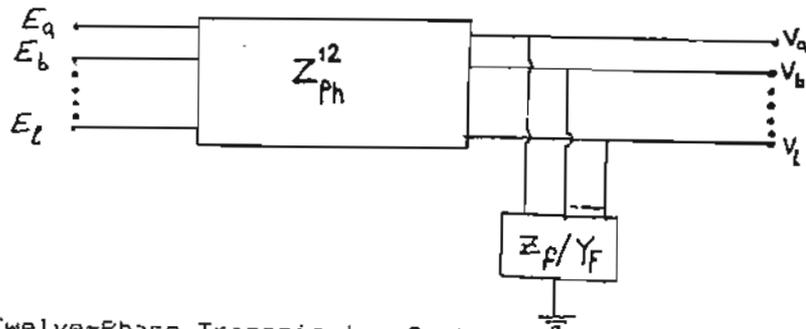
Fig.1 Twelve-Phase Transmission System
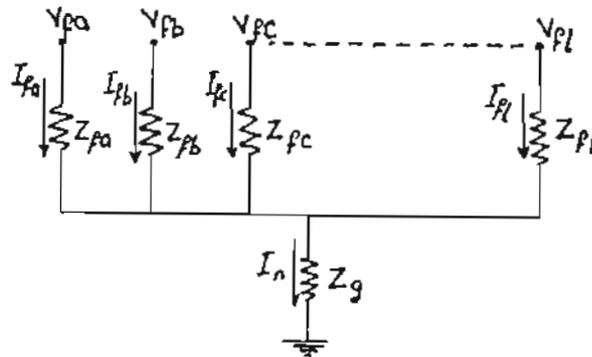for Simulating Shunt Faults.

Fig.2 Schematic Representation of 12-Phase to Ground
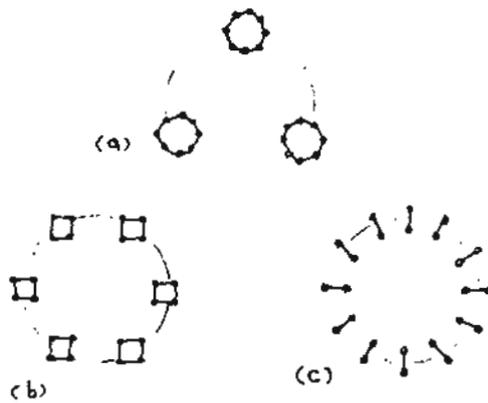Fault on Twelve-Phase Transmission Line.

Fig.3 Conductor Configurations for 462 kV Phase-Ground Line (24/
1.762 in. Conductors, 15 ft. Diameter Circle, 18 in. Bundle
Distance, 50 ft. Min. Ground Clearance):
a) 3-Phase Line;   b) 6-Phase Line   &   c) 12-Phase Line.