Fault Analysis on Double Three-Phase to Six-Phase Converted Transmission Line

M. W. Mustafa, *Member, IEEE*, M. R. Ahmad and H. Shareef

***Abstract*--High phase order transmission system is being considered a viable alternative for increasing the power transmission capability of overhead electric power transmission over existing right-of-way. This paper presents the faults analysis of six-phase transmission system. In this context, fault analysis has been conducted on the Goudey-Oakdale 2-bus test system. The results of these investigations are presented in the form of typical time responses. The PSCAD/EMTDC is used for the simulation studies.**

***Index Terms*--Power transmission, power transmission fault, fault currents, power system simulation, multi-phase system, six-phase system.**

I. Introduction

TRADITIONALLY, the need for increasing power transmission capability and more efficient use of right-of-way space has been accomplished by the use of successively higher system voltages. Constraints on the availability of land and planning permission for overhead transmission lines have renewed interest in techniques to increase the power carrying capacity of existing right-of-ways. High phase Order (HPO) transmission is the use of more than the conventional three-phases to transmission corridor. The increased interest in HPO Electric Power Transmission over past thirty years can be traced on a CIRGE paper published by L. D. Barthold and H. C. Barnes [1]. Since that time, the concept of HPO transmission has been described in the literature in several papers and report [2]-[12]. Among the HPO, six-phase transmission appears to be the most promising solution to the need to increase the capability of existing transmission lines and at the same time, respond to the concerns related to electromagnetic fields [1], [2]. One of the main advantages of six-phase transmission is that a six-phase line can carry up to 73% more electric power than a double circuit three-phase line on the same transmission right-of-way [4]. The NYSEG high phase order transmission demonstration project has provided an experimental system to investigate the construction and operation of such a six-phase system [9]. In that project, a short transmission line from Goudey to Oakdale has reconfigured from a 115kV double circuit three-phase line to a 93kV six-phase line. The line is approximately 2.4 km long and is connected to the 115kV system through two161kV/115kV transformers: one of them with wye (grounded)/delta configuration, and the other with inverted wye (grounded)/delta configuration at each end as shown in Fig. 1.

One of the important aspects in the planning of six-phase systems is the design of an adequate protective scheme. This requires a detailed fault analysis for such systems. Venkata et al. did pioneering work in the analysis of six-phase faulted power system. In [7], an analysis of some fault types have been presented using six balanced sets of symmetrical components. Fault analysis of six-phase systems was also carried out by using two set of symmetrical components of a three-phase system [8]. The objective of this paper is to conduct fault analysis of three to six-phase converted transmission line by using PSCAD/EMTDC. The six-phase transmission is implemented on the Goudey-Oakdale 2-bus test system and has been simulated by using PSCAD/EMTDC software. From the simulation results, it has been shown that the faults analysis can be done by using PSCAD/EMTDC software.

II. Six-Phase Transmission System Model

Conversion of existing double-circuit three-phase overhead transmission line to a six-phase operation needed phase conversion transformers to obtain the 60° phase shift between adjacent phases. A double-circuit three-phase transmission line can easily converted to a six-phase transmission line by using two pairs of identical delta-wye three-phase transformers connected at each end of the line as shown in Fig. 1. One of each pair of transformer has reverse polarity to obtain the required 60° phase shift. The connection shown in Fig. 1 were selected as appropriate for determining short circuit currents because the delta open circuits the zero sequence network and simplifies the fault analysis.

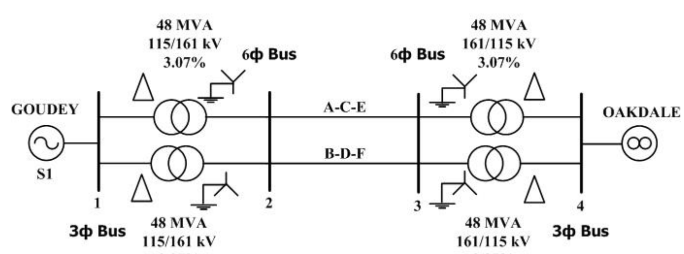

Fig. 1: One-line diagram of converted double-circuit three-phase transmission line to six-phase line.

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III. Six-Phase Fault Types

There are 120 possible fault combinations in a six-phase system. And there are 23 combinations with distinct fault levels and phase interconnections [7]. These significant combinations are tabulated in Table I.

TABLE I
Types of Faults on Six-Phase System and the Combinations

Fault Type	Total No. Of Com.	Significant No. Of Com.	Faulted Phases
6-phase	1	1	abcdef
6-phase-G	1	1	abcdefg
5-phase	6	1	bcdef
5-phase-G	6	1	bcdefg
4-phase	15	3	bcef, abcd, abdf
4-phase-G	15	3	bcefg, abcdg, abdfg
3-phase	20	3	bdf, abd, abf
3-phase-G	20	3	bdfg, abdg, abfg
2-phase	15	3	ad, bf, bc
2-phase-G	15	3	adg, bfg, bcg
1-phase-G	6	1	ag
TOTAL	120	23	

The method of symmetrical components is the most powerful tool for dealing with unbalanced polyphase circuits. Esmat H. Badawy et al. work has proved that unbalanced 6 related phasors can be resolved into 6 systems of balanced phasors called the symmetrical components of the original phasors [8]. This method is based on splitting the six-phase system into two systems arrangements (*a*, *b*, *c*) and (*a*', *b*', *c*'). Each system is resolved into three balanced set of phasors. In this paper, the method proposed in [8] is used to calculate and validated the fault analysis obtained from PSCAD/EMTDC simulation results.

If the original phasors are voltages, they may be designated V_a, V_b, V_c, $V_{a'}$, $V_{b'}$, and $V_{c'}$. The equation relating the phase voltages to their sequence components where phases a and a' are considered references for the systems (*a*, *b*, *c*) and (*a*', *b*', *c*') respectively is proposed to be [8]:

$$[V_p]=[S][V_s] \tag{1}$$

Where;

$$[V_p]=\begin{bmatrix}V_a & V_b & V_c & V_{a'} & V_{b'} & V_{c'}\end{bmatrix}^T \tag{2}$$

$$[V_s]=\begin{bmatrix}V_{a0} & V_{a1} & V_{a2} & V_{a'0} & V_{a'1} & V_{a'2}\end{bmatrix}^T \tag{3}$$

The superscript *T* denotes transposition. $[V_p]$, $[V_s]$ are 6x1, 6x1 column vectors of phase voltages and sequence component voltages respectively. The sequence component V_{a0}, V_{a1}, V_{a2}, $V_{a'0}$, $V_{a'1}$, and $V_{a'2}$ are termed the first zero, first positive, first negative, second zero, second positive, and second negative-phase sequences of voltages respectively.

$$[S]=\begin{bmatrix}A & 0\\ 0 & A\end{bmatrix} \tag{4}$$

$$[S]^{-1}=\begin{bmatrix}A^{-1} & 0\\ 0 & A^{-1}\end{bmatrix} \tag{5}$$

Given that;

$$[A]=\begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix} \tag{6}$$

$$[A]^{-1}=\frac{1}{3}\begin{bmatrix}1 & 1 & 1\\ 1 & a & a^2\\ 1 & a^2 & a\end{bmatrix} \tag{7}$$

where $[S]^{-1}$ is the inverse of the symmetrical components transformation matrix [*S*]. Similar equations can be written for currents instead of voltages, e.g.

$$[I_p]=[S][I_s] \tag{8}$$

$$[I_s]=[S]^{-1}[I_p] \tag{9}$$

Where,

$$[I_p]=\begin{bmatrix}I_a & I_b & I_c & I_{a'} & I_{b'} & I_{c'}\end{bmatrix}^T \tag{10}$$

$$[I_s]=\begin{bmatrix}I_{a0} & I_{b1} & I_{c2} & I_{a'0} & I_{b'1} & I_{c'2}\end{bmatrix}^T \tag{11}$$

$[I_p]$, $[I_s]$ are termed in the same manner as the voltages. This method is indeed related to the 6-phase symmetrical components method. The relationship is obtained basing upon the transformation matrices of the two methods and it can be given as:

$$\begin{bmatrix}V_{a0}\\ V_{a1}\\ V_{a2}\\ V_{a'0}\\ V_{a'1}\\ V_{a'2}\end{bmatrix}=\begin{bmatrix}1 & 0 & 0 & 1 & 0 & 0\\ 0 & 1 & 0 & 0 & 1 & 0\\ 0 & 0 & 1 & 0 & 0 & 1\\ 1 & 0 & 0 & -1 & 0 & 0\\ 0 & -1 & 0 & 0 & 1 & 0\\ 0 & 0 & 1 & 0 & 0 & -1\end{bmatrix}\begin{bmatrix}V_{a0}\\ V_{a1}\\ V_{a2}\\ V_{a3}\\ V_{a4}\\ V_{a5}\end{bmatrix} \tag{12}$$

Similar equations can be written for currents instead of voltage. All these equations are used to calculate the fault currents in order to validate the simulation results that obtained from PSCAD/EMTDC.

IV. Analysis of Simulation Results

Case study is conducted to make fault analysis of six-phase using Goudey-Oakdale 2-bus test system. A Goudey to Oakdale 2-bus test system introduced in [9] is used here to validate the conversion of double-circuit three-phase to six-phase transmission system; the test system operates at 115 kV and it shown in Fig. 1. The generator is assumed to be an ideal voltage source behind equivalent Thevenin impedance. The transmission system is composed of transmission lines of different lengths and modeled as a distributed-parameter line.

The generator is connected through two pairs of identical delta-wye transformers to a three-phase infinite bus system through a six-phase, 93 kV transmission line. The transmission line reflect the fact that, for the same power flow capability, the phase-to-phase voltage of the six-phase system can reduced by √3. In all the studied cases, the faults are assumed to occur at the six-phase transmission line.

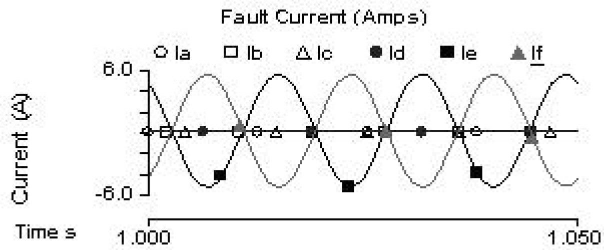
For validation of simulated model, reliability test is carried out and the power flow results of Goudey to Oakdale 2-bus test system are compared with result in [10]. The power flow results of this system when all phases connected and when phase A disconnected match very closely, and all deviations are less than 5%.

A. Faults on Six-Phase Transmission Line

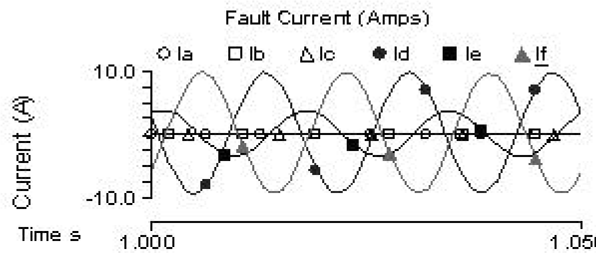
Fig. 2 and Fig. 3 illustrates the fault currents flow in all the phases when fault occur on the transmission line of the Goudey to Oakdale 2-bus test system. Fig. 2(a) illustrates the fault current flow when two phases fault (phase e and phase f) occur at the six-phase transmission system. Both currents have the same value but at the opposite polarity. The fault currents value that obtained from the simulation results very closely compare to the calculation ones. Figures 2(b)-2(e) are shown the different types of ungrounded fault waveforms for the six-phase transmission system. Fig. 2(b) illustrated the fault current waveform for the three phases fault (d-e-f) on the six-phase transmission lines of the 2-bus test system. Figures 2(c), 2(d) and 2(e) illustrates the fault current waveforms for the four phases fault (c-d-e-f), five phases fault (b-c-d-e-f) and six phases fault (a-b-c-d-e-f) on the six-phase transmission lines respectively. Fig. 3(a)-3(e) are shown the different types of grounded fault waveforms for the six-phase transmission system. Fig. 3(a) shows the fault current waveform for the single line to ground fault (a-g) on the six-phase transmission lines. Fig. 3(b), 3(c), 3(d) and 3(e) illustrates the fault current waveforms for the two line to ground fault, three line to ground fault, four line to ground fault and five line to ground fault on the six-phase transmission lines. The comparison between the simulation results with the calculation by using symmetrical method for three types of fault has been tabulated in Table II.

TABLE II
COMPARISON BETWEEN THE SIMULATION RESULTS WITH CALCULATION BY USING SYMMETRICAL COMPONENTS METHOD

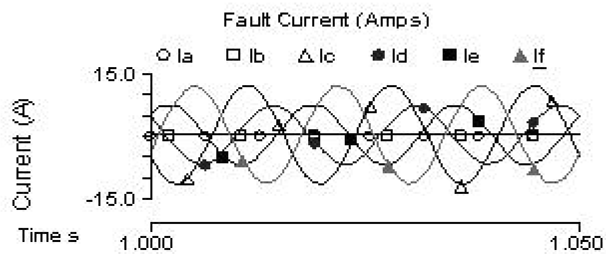
Φ	Phase a-g fault		Phase c-e fault		Phase a-c-e-g fault	
	Current (Amps)		Current (Amps)		Current (Amps)	
	Cal.	Sim.	Cal.	Sim.	Cal.	Sim.
A	7650.9	7654.0	0	0	7650.7	7655.1
B	0	0	0	0	0	0
C	0	0	6625.9	6640.8	7650.7	7693.1
D	0	0	0	0	0	0
E	0	0	6625.9	6640.4	7650.7	7636.0
F	0	0	0	0	0	0



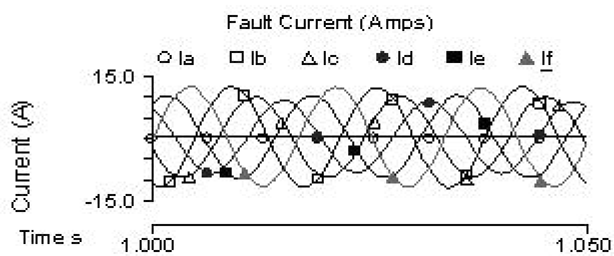
(a) 2 line fault e-f



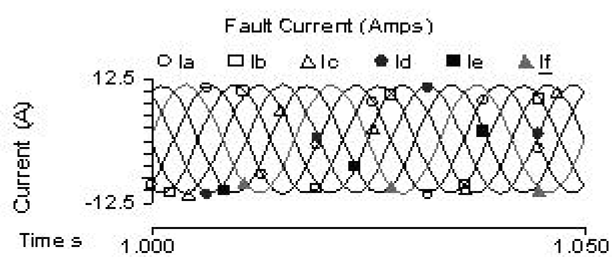
(b) 3 line d-e-f



(c) 4 line fault c-d-e-f

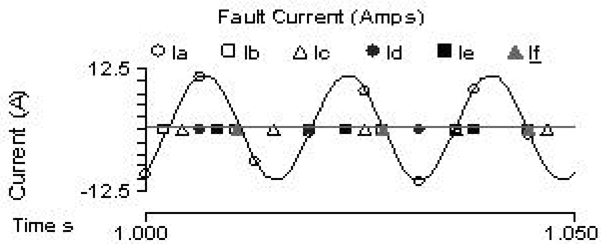


(d) 5 line fault b-c-d-e-f

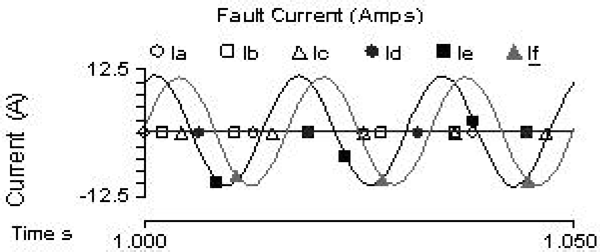


(e) 6 line fault b-c-d-e-f @ b-c-d-e-f-g

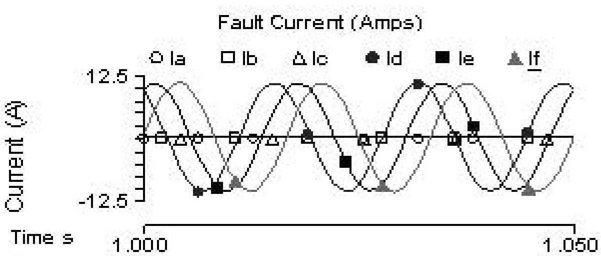
Fig. 2: Fault currents in all the phases for ungrounded faults



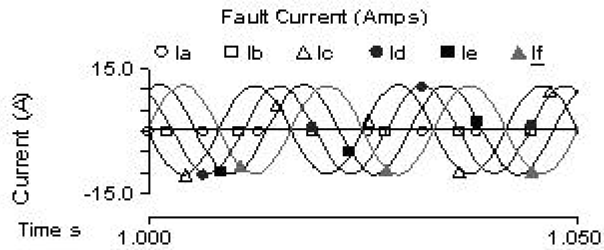
(a) Single line to ground fault a-g



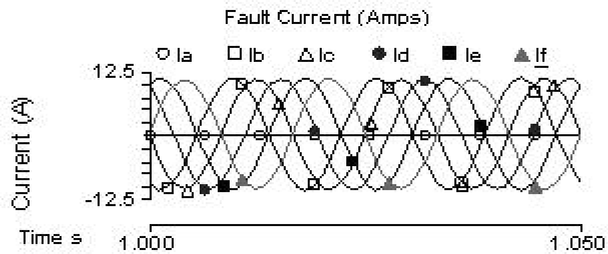
(b) 2 line to ground fault e-f-g



(c) 3 line to ground fault d-e-f-g



(d) 4 line to ground fault c-d-e-f-g



(e) 5 line to ground fault b-c-d-e-f-g

Fig. 3: Fault currents in all the phases for grounded faults

The results of the fault analysis are given in Table III. It lists the fault currents at six-phase transmission line during all significant shunt faults.

TABLE III
FAULT CURRENTS FOR ALL SIGNIFICANT FAULTS ON SIX-PHASE TRANSMISSION SYSTEM

Fault type	Fault current (Amps)					
	I_a	I_b	I_c	I_d	I_e	I_f
1-phase-to-ground a	7654.00	0	0	0	0	0
2-phase e,f	0	0	0	0	3826.78	3826.62
2-phase-to-ground e,f	0	0	0	0	7671.92	7656.58
3-phase d,e,f	0	0	0	6803.68	2569.11	6755.02
3-phase-to-ground d,e,f	0	0	0	7655.31	7636.34	7693.10
4-phase c,d,e,f	0	0	8421.55	5030.43	5110.10	8324.70
4-phase-to-ground c,d,e,f	0	0	7694.40	7620.31	7671.91	7694.40
5-phase b,c,d,e,f	0	8551.48	7018.30	6124.70	7036.34	8516.13
5-phase-to-ground b,c,d,e,f	0	7627.61	7658.75	7656.47	7672.61	7658.75
6-phase a,b,c,d,e,f	7658.12	7537.30	7694.77	7858.12	7637.30	7694.77
6-phase-to-ground a,b,c,d,e,f	7658.18	7638.42	7694.71	7658.18	7637.42	7694.71

V. Conclusion

This paper has presented the fault analysis of six-phase transmission system. The fault analysis is conducted to the Goudey-Oakdale 2-bus test system by using PSCAD/EMTDC. To validate the simulation results, fault analysis of six-phase systems was also carried out by using two sets of symmetrical components of a three-phase system. From the simulation results, it has been shown that the fault analysis of six-phase system can be done by using PSCAD/EMTDC. As it would be expected, fault current flowing in each phases are higher when grounded fault type are conducted to the six-phase transmission lines compared to the ungrounded fault type on the six-phase transmission line.

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VII. Biographies

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