Exploring six-phase transmission system for power delivery

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***Abstract*—A comparative study of power transfer capability was carried out between three configurations of six-phase transmission lines and a three-phase double circuit line. The line parameters (inductance, capacitance and surge impedance), right-of-way requirements, ground level electric and magnetic fields for the various cases were calculated. It has been shown that six-phase transmission lines can provide higher power transfer capability with the same right-of-way and tower configuration. An IEEE 118-bus test system was used for study. A detailed fault analysis was performed on IEEE 4, 9 and 118-bus test systems and the results show that present day digital relays can provide adequate protection for six-phase transmission lines.**

***Index Terms*-- Power transfer capability, right-of-way, six-phase line, transmission line protection.**

I. I. INTRODUCTION

In order to satisfy load growth and relieve transmission grid congestion, new generation and transmission lines construction is happening worldwide [1]. These options are becoming increasingly difficult especially in metropolitan areas due to public opposition for obtaining new right of ways [2]. A report from North American Electric Reliability Council (NERC) [3] has indicated that construction of about 5000 circuit-miles has been delayed over the years. Therefore, alternative methods for increasing power transfer in existing corridors need to be examined. In recent years, high phase order (HPO) systems, line compaction and the use of new conductor technologies like high temperature low sag (HTLS) conductors that are capable of carrying higher current have been evaluated [4],[5]. This paper focuses on high phase (six-phase) transmission system due to the promise it holds for increasing power transfer.

The idea of high phase order transmission was introduced in 1973 [6]-[15]. By decreasing the phase angles, the conventional three-phase system is converted into high phase order system namely six, nine and twelve phase. For the same voltage and current, the power transfer capability increases with the number of phases. Furthermore, for same line-to-ground voltage, the phase separation is reduced for high phase order systems resulting in a compact tower configuration. The six-phase transformation (three-phase to six-phase) is performed using conventional three-phase delta-wye and delta-inverted wye transformers connected in parallel [8]. Generation and utilization are conventional three-phase and transmission is high phase order as show in Figure 1 schematically.

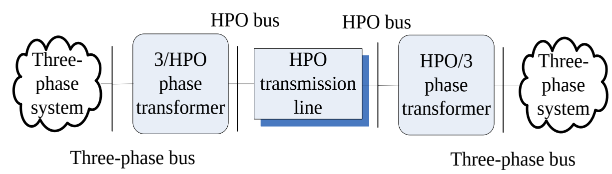

Figure 1. Three-phase system and high phase order transmission line connection diagram.

A six-phase transmission line was constructed and operated for three years in the state of New York [15]. The main reason that this technique did not become popular was complications introduced in protection schemes with electro-mechanical relays that were dominantly used during that time [16]. Today with digital relays, it is worthwhile to examine if this problem could be overcome.

Although the feasibility of high phase order line has been demonstrated, the comparison between three-phase and high phase order transmission lines has not been adequately evaluated. In this paper, a three-phase double circuit line has been compared with different configurations of six-phase transmission lines.

II. TRANSMISSION LINE CONFIGURATIONS EVALUATED

Figure 2 shows various transmissions line configurations evaluated [17]. Completely transposed lines with the same conductor type were used in all cases. Case 1 is the reference case consisting of a standard 138 kV three-phase double circuit configuration. Case 2 is a six-phase single circuit (80 kV) configuration with same line-to-ground voltage and tower dimensions as case 1. Case 3 is a compact six-phase transmission line (80 kV) while in case 4 the phase-to-ground voltage is increased to 138 kV with the same tower configuration as case 1 and 2.

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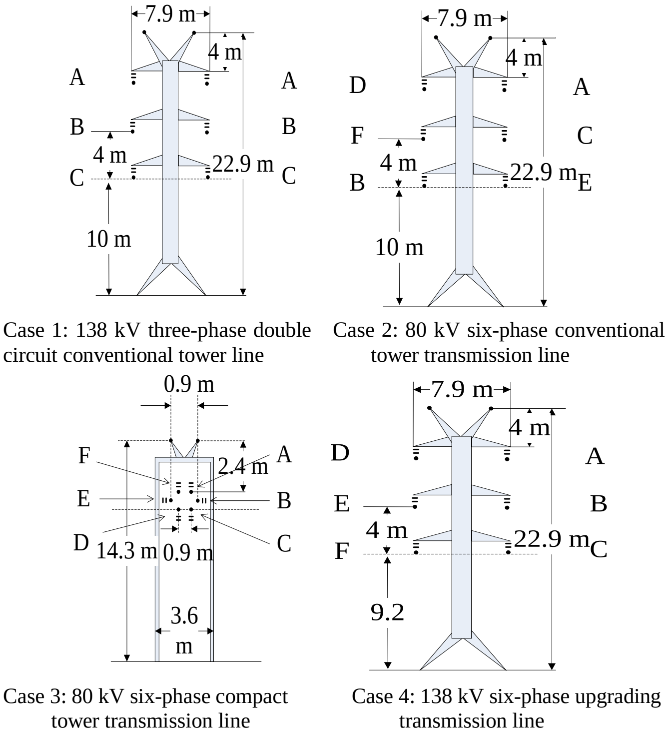

Figure 2. Three-phase and six-phase tower configuration and phase arrangements.

Transmission line impedance and capacitance are determined by the spacing between conductors and the line clearance to ground. The calculation results of the line impedance and capacitance are 6×6 matrices. In Table I, self and mutual impedance and capacitance of the transmission line are the average values of the results. As shown in Table I, for the same tower configuration, six-phase line (Case 2, 4) have the same line parameters as a three-phase double circuit line (Case 1). The six-phase compact line has relatively higher impedance and capacitance due to the reduced spacing in the compact tower configuration. The surge impedance of the six-phase compact transmission line is nearly 15% less than the other three cases. As a result, surge impedance loading of this configuration is higher than the three-phase double circuit line.

TABLE I. LINE PARAMETERS OF THREE-PHASE AND SIX PHASE TRANSMISSION LINES

Parameters	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Self impedance (Ω/km)	0.1 + j 0.8	0.1 + j 0.8	0.1 + j 0.8	0.1 + j 0.8
Mutual impedance (Ω/km)	0.1 + j 0.4	0.1 + j 0.4	0.1 + j 0.5	0.1 + j 0.4
Self capacitance (nF/km)	8.3	8.3	11.7	8.3
Mutual capacitance (nF/km)	-1.2	-1.2	-2.5	-1.2
Surge impedance (Ω)	491.0	491.0	413.1	491.0
SIL (MW)	78.2	78.2	93.0	231.7

III. GROUND LEVEL EMF AND RIGHT-OF-WAY

Electric and magnetic fields are important criteria in the overall design of transmission lines [18]. Adequate right-of-way is required to reduce the electric and magnetic field to the level cited by standards [19]-[21]. Ground level electric and magnetic fields were calculated with the methods introduced in [18]. The right-of-way width calculation was based on the model shown in Figure 3.

$$ROW = 2(A + B + C)$$

where

A = Horizontal safety clearance to buildings

B = Conductor blowout due to wind pressure

C= Distance from centerline of tower structure to outside conductor attachment point.

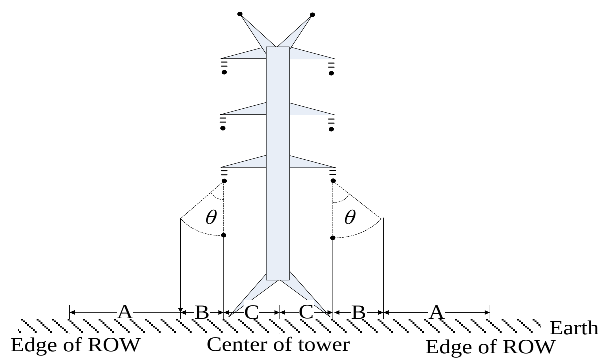

Figure 3. Transmission line right-of-way

In the calculations, following conditions were selected:

(1) Transmission lines span: 300 m.

(2) Conductor sag at 49 ^{o} C: 0.94 m.

(3) Wind pressure: 29.2 kg/m^2 (31 mph)

(4) Insulator strings: 10 bells of standard 5.75''×10" porcelain insulators for cases 1-3 and 12 bells of standard 5.75''×10" porcelain insulators for case 4.

Since 138 kV is relatively low voltage level for transmission, the electric and magnetic field are well below the permissible. The three-phase double circuit line right-of-way was selected as 45.7 m (150 ft). The ground level electric and magnetic field generated by the three-phase double circuit line at the edge of right-of-way was calculated and set as the reference values. The right-of-way requirements for the six-phase transmission lines were calculated to achieve the set reference values. The calculation results were summarized in TABLE II.

TABLE II. RIGHT-OF-WAY REQUIREMENT AND POWER TRANSFER CAPABILITY COMPARISONS

Case name	**ROW requirements (m)**	**Power transfer capability**
Case 1	45.7	100%
Case 2	36.0	100%
Case 3	25.6	119%
Case 4	49.4	293%

The results indicate that right-of-way requirements for six-phase transmission lines can be significantly reduced while the power transfer capability remains the same as three-phase double circuit line. Therefore, six-phase line provides more power transfer capability with the same tower size and right-of-way requirements as three-phase double circuit line. The other advantage of six-phase transmission line as compared to a three phase double circuit is smaller line-to-line voltage requirement, which provides a possibility for line compaction. Figure 4 compares the line-to-line voltage required to transfer equal amount of power in a three-phase double circuit line to a six-phase single circuit.

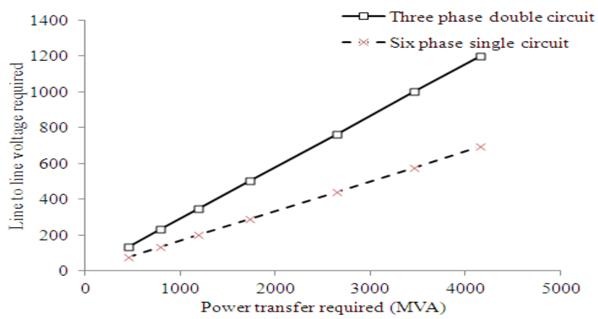

Figure 4. Voltage requirements for three phase double circuit and six-phase single circuit for same amount of power transfer

IV. SIMULATION CASES ON IEEE 118-BUS SYSTEM

To verify the results from section II, the IEEE 118 bus test system was used. Three lines (49 – 54, 42 – 49 and 49 – 66) were selected for the study. The following assumptions were considered while incorporating the four cases discussed in the earlier section. In the base case, the three-phase double circuit lines selected were remodeled as an equivalent three phase single circuit lines using the Case 1 impedances given in Table I. The effect of transformers used to convert three-phase line to a six-phase line is neglected. The length of the line for the base case is selected in such a way that the flow on the line remains close to the original line. Table III indicates the results obtained by modeling various cases for these three lines. The simulation results confirm that more power can be carried using high phase order system as shown in Table II.

TABLE III. RESULTS OF IEEE 118 BUS TEST SYSTEM

		49 – 54	**42 – 49**	**49 – 66**
Case – 1	Capacity (MVA)	200	200	1000
	% flow on line	43.53	58.27	21.29
Case – 2	Capacity (MVA)	200	200	1000
	% flow on line	43.53	58.27	21.29
Case – 3	Capacity (MVA)	200	200	1000
	% flow on line	67.41	72.93	26.17
Case – 4	Capacity (MVA)	346.4	346.4	1732
	% flow on line	57	57	17.64

V. FAULT ANALYSIS AND PROTECTION

To analyze faults in a six-phase transmission line, the three-phase and six-phase mixed system shown in Figure 1 must be converted into a six-phase equivalent system shown in Figure 5. In order to calculate the source impedance, two single-phase faults were separately simulated at both ends of the six-phase transmission line [8]. The three-phase fault currents and voltages at the location were obtained from Powerworld® simulation. The six-phase transmission line was modeled as an equivalent three-phase single circuit line. With the fault currents and voltages from the simulation results, the three-phase system was simplified as two equivalent three-phase sources. The equivalent three-phase sources were converted into equivalent six-phase sources by reversing Gauss elimination method. Based on the equivalent six-phase system, six-phase transmission line fault analysis was conducted with phase coordinate method [8]. As the phase number increases, the number of possible fault types in a six-phase line increases from 5 to 23. The comparative fault analysis was based on 23 six-phase fault types. A similar fault combination of the three-phase double circuit line was analyzed with PSCAD®.

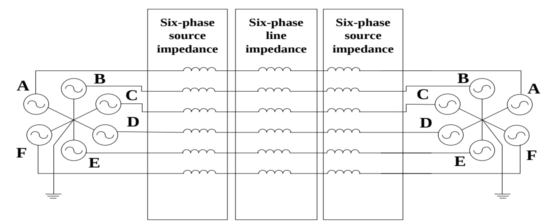

Figure 5. Six-phase equivalent system network.

The fault analysis study was conducted on IEEE 4, 9 and 118-bus test systems. The systems were modeled in Powerworld® and could be found in [22]. In 4 and 9-bus systems, the most heavily loaded transmission lines were reconfigured into six-phase transmission line. In 118-bus system, six most heavily loaded transmission lines were reconfigured into six-phase transmission lines separately. The selected lines were also operated as three-phase double circuit lines to perform three-phase fault analysis. The fault analysis results are summarized in TABLE IV. The results show that the ranges of fault currents are higher in six-phase lines as compared to the three-phase double circuit line. This requires detailed study for protection system and relay programming.

TABLE IV. FAULT CURRENT SUMMARIZATION FOR THREE PHASE DOUBLE CIRCUIT AND SIX-PHASE LINES

Fault currents	**Lines**	**Fault locations**	**4-bus**	**9-bus**	**118-bus**
Maximum fault currents (kA)	Three-phase double circuit line	Sending end	2.4	2.4	×
		receiving end	1.6	2.5	×
		Middle of line	1.2	2.6	×
	Six-phase line	Sending end	1.7	3.2	26.1
		receiving end	1.1	1.4	8.8
		Middle of line	1.6	1.3	9.2
Minimum fault currents (kA)	Three-phase double circuit line	Sending end	0.9	0.7	×
		receiving end	0.5	0.6	×
		Middle of line	0.7	0.7	×
	Six-phase line	Sending end	0.4	0.3	2.6
		receiving end	0.2	0.3	2.3
		Middle of line	0.4	0.3	2.41

×: Case was not studied

A six-phase transmission line protection system was proposed for the 4-bus system based on the evaluated cases and recommendations from [23]. The conductors in the six-phase transmission line were classified into two groups: (1) A-C-E and (2) D-F-B [24]. Each group was protected by one three-phase protection unit. Segregated phase comparison and directional comparison blocking scheme were selected as the primary and secondary protection system. A microwave communication channel was selected to achieve the communication between protection units at the both ends of the transmission line. Since limited information about the upstream and downstream protection system was available, the backup system design was not included in this paper. Based on the works from [24], an external trip logic was designed to coordinate the fault phase selection in the two protection groups as show in Figure 6. The six-phase transmission line protection system is shown in Figure 7. A three-phase protection system was also designed for the three-phase double circuit line.

The protection system study shows that current differential relays must be chosen carefully for a six-phase transmission line protection as relay pick-up currents are usually set as 50% of minimum fault current but over maximum load current for reliability purpose [25]. In the 4-bus system, phase A fault current is 300 A under an A-B-F fault and the maximum load current under a normal operation status is 220 A. In this case, current differential relays may mis-operate with unbalanced load.

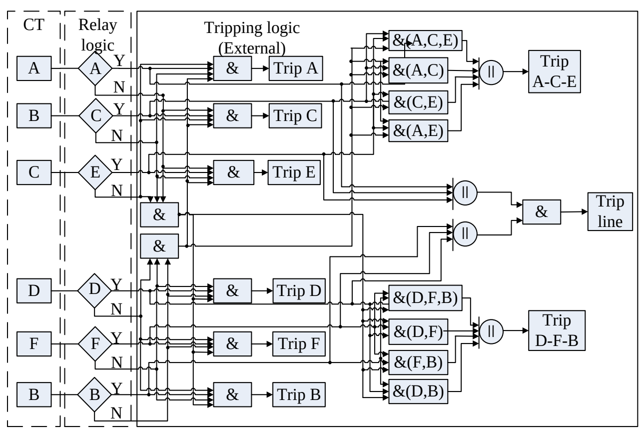

Figure 6. External trip logic for a six-phase transmission line protection.

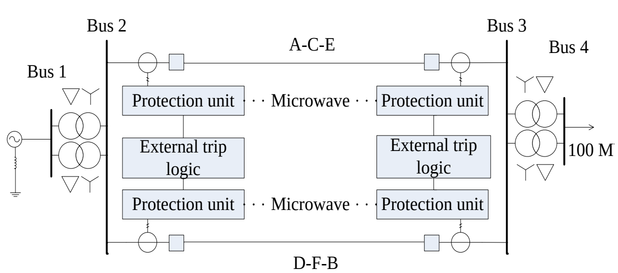

Figure 7. External trip logic for a six-phase transmission line protection.

VI. CONCLUSIONS

(1). Six-phase transmission lines provide higher power transfer capability with limited right-of-way, compared to a three-phase double circuit line. For the same power transfer capability, six-phase transmission lines can utilize compacted tower configurations and reduce line-to-line voltages.

(2). Six-phase transmission lines have more fault types and a higher fault current range as compared to three-phase double circuit line. For same fault types, the six-phase transmission line fault currents are lower as compared to the three-phase double circuit line.

(3). Modern relay technology can provide adequate protection for six-phase transmission lines.

REFERENCES

[1] North American Electric Reliability Corporation (NERC), “2008-2017 Regional and National Peak Demand and Energy Forecasts Bandwidths, August 2008”, Princeton, New Jersey, USA, p.17, 2008. Available: www.nerc.com/docs

[2] Public service commission of Wisconsin, “Environmental impact of transmission lines,” Jun. 2011. Available: psc.wi.gov/thelibrary/publications/electric/

[3] F. Wagner, P. J. Schaumberg, “2011 long-term reliability assessment,” Nov. 2011. Available: www.nerc.com/files/

[4] K. Dave, N. Mohan, X. Deng, R. Gorur, R. Olsen, “Analyzing techniques for increasing power transfer in the Electric Grid,” North American Power Symposium , 9 – 11 Sep 2012.

[5] R. S. Gorur, N. Chawla, J. Hunt, M. Dyer, "Mechanical and electrical issues concerning the use of composite materials for the supporting core in transmission line conductors," Electrical Insulation and Dielectric Phenomena, 2006 IEEE Conference on, pp.501-504, 15-18 Oct. 2006.

[6] H. C. Barnes, L. O. Barthold, "High phase order power transmission," CIGRE SC 32, Electra, pp. 139-153. no. 24, 1973.

[7] J. R. Stewart, I. S. Grant, "High phase order - ready for application," IEEE Trans. on Power Apparatus and Systems, vol. 101, no. 6, pp. 1757-1767, Jun. 1982.

[8] S. S. Venkata, W. C. Guyker, W. H. Booth, J. Kondragunta, N. K. Saini, E. K. Stanek, “138-kV, six-phase transmission system: fault analysis,” IEEE Power Engineering Review, vol. 2, no. 5, pp. 40-41, May 1982.

[9] A. Chandrasekaran, S. Elangovan, P. S. Subrahmanian, “Stability aspect of a six phase transmission system,” IEEE Trans. on Power Systems, vol. 1, no. 1, pp. 108-111, Feb. 1986.

[10] J. R. Stewart, L. J. Oppel, G. C. Thomann, T. F. Dorazio, M. T. Brown, “Insulation coordination, environmental and system analysis of existing double circuit line reconfigured to six-phase operation,” IEEE Trans. on Power Delivery, vol. 7, no. 3, pp. 1628-1633, Jul. 1992.

[11] J. R. Stewart, S. J. Dale, K. W. Klein, “Magnetic field reduction using high phase order lines,” IEEE Trans. on Power Delivery, vol. 8, no. 2, pp. 628-636, Apr. 1993.

[12] A. P. Apostolov, R. G. Raffensperger, “Relay protection operation for faults on Nyseg's six-phase transmission line,” IEEE Trans. on Power Delivery, vol. 11, no. 1, pp. 191-196, Jan. 1996.

[13] J. R. Stewart, L. J. Oppel, R. J. Richeda, “Corona and field effects experience on an operating utility six-phase transmission line,” IEEE Trans. on Power Delivery, vol. 13, no. 4, pp. 1363-1369, Oct. 1998.

[14] T. L. Landers, R. J. Richeda, E. Krizanskas, J.R. Stewart, R.A. Brown, “High phase order economics: constructing a new transmission line,” IEEE Trans. on Power Delivery, vol. 13, no. 4, pp. 1521-1526, Oct. 1998.

[15] M. T. Brown, R. V. Rebbapragada, T. F. Dorazio, J. R. Stewart, “Utility system demonstration of six phase power transmission,” IEEE Power Engineering Society - Transmission and Distribution Conference, pp.983-990, Sep. 1991.

[16] V. Longo, “High-phase what?” Transmission and Distribution world magazine, Jul. 2011. Available:http://tdworld.com/overhead_transmission/power_highphase/

[17] J. R. Stewart, D. D. Wilson, "High phase order transmission--a feasibility analysis Part II--overvoltages and insulation requirements,"

IEEE Transactions on Power Apparatus and Systems, , vol. 97, no.6, pp.2308-2317, Nov. 1978
[18] Electric Power Research Institute, “AC transmission line reference book -200 kV and above,” Third Edition, 2004.
[19] Teshmont Consultants LP; “Taltson transmission expansion project transmission alternatives study final report,” Nov. 2008. Available: www.reviewboard.ca
[20] "IEEE standard for safety levels with respect to human exposure to electromagnetic fields, 0-3 kHz," IEEE Std C95.6-2002 , 2002
[21] "2012 National electrical safety code (NESC)," National Electrical Safety Code, C2-2012, pp. 1-389, Aug. 1 2011.
[22] PowerWorld® sample case. Availvale at: http://www.powerworld.com/educator.asp
[23] "IEEE Guide for Protective Relay Applications to Transmission Lines," IEEE Std C37.113-1999, 2000.
[24] R. V. Rebbapragada, H. Panke, H. J. Jr. Pierce, J. R. Stewart, L. J. Oppel, “Selection and application of relay protection for six phase demonstration project,” IEEE Trans. on Power Delivery, vol. 7, no. 4, pp. 1900-1911, Oct. 1992.
[25] S. Ward, T. Erwin, “Current differential line protection setting considerations,” 2005. Available: www.rflelect.com