NEUTRAL POTENTIAL DISPLACEMENT IN ARC-SUPPRESSING REACTOR SYSTEM

IWAO MIYAJI AND NORIO SHIMURA

Department of Electrical Engineering

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1. Summary

One of the authors has reported how the neutral potential displacement took place in resonant transmission system after any single stage fault had occurred. In this paper, they extend their argument on neutral potential to such complex cascaded phenomena as those incidental to switching operation, grounding of broken line or lines. The general description of those complex phenomena is performed at first to the extent of the theoretical determination of the position of neutral potential displaced in steady state, and then up to the graphical representation of results of experiments, which are measured by means of model transmission system and the "neutral potential tracer." These complex phenmena can be fundamentally expressed as the resultant potentials of free oscillation and forced one, both determined by newly constructed circuit conditions of each stage, where the time intervals only come into question. The following is the synopsis of their study of the complex phenomena treated as the succession of 1-line grounded, 1-line broken, restoring 1-line broken or 1-line closed phenomenon occurring in the reactor compensated transmission system. The steady state displacement of ground potential against the system neutral is sometimes represented, taking compensation factors as parameters, by a circle which is characterized by its particular position and magnitude compared with the source triangle of voltages corresponding to each accident. Such circles of vector loci for different phenomena are geometrically so arranged as to have interesting relative positions to the source triangle, and most of the complicated fault phenomena can easily be analysed by means of those circles. Experimental results show that the changing transient overvoltages are thus intuitively understood and traced in accordance with the lapse of time.

2. Theoretical Argument

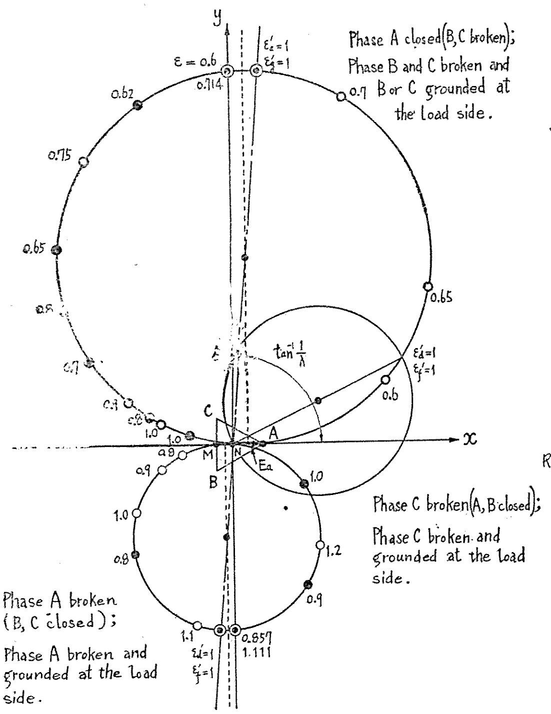
a) Switching Operation. When the switching-in operation is in progress, the first stage of 1-line closed phenomenon ofthe causes the series resonance in the system, and the following stage of 2-line closed is generally corresponding to that of 1-line broken at the sending end, and the last stage of 3-line closed is to the restoring of 1-line broken system. The transient voltages between the system neutral and the ground, here, are shown as the sum of the steady voltages of the source frequency and the decremental ones of free oscillation, the frequency of which is determined by the circuit elements of the system; that is, the neutral potential to the ground at every instant is, if denoted topographically, arranged on the logarithmic spiral around the final vectorial point of steady state. Moreover the direction of the spiral rotation is decided by the compensation factors and the line constants of that system. In ordinary three phase system, as the switching operation is performed passing through the three different steps of the system construction, so the vector locus of the neutral potential, then, varies greatly corresponding to each condition. If their discussion is limited only with the cases of steady state, the vector topographies for 1-line switched-off conditions are all the same as those for 2-line switched-in, and those for 2-line switched-off are so too for 1-line switched-in. The topographies for such steady state are generally denoted as circles of vector loci, and the radius of the circle for 2-line switched-off condition is twice as large as that for 1-line switched off. Thus the displacement

TABLE 1. The Steady State Topographies of Vector Loci and Resonance Conditions

Phenomena					Vector locus of ground potentials against system neutral					Resonance condition			Apparent compensation factor
Load	Condition		Parameter	Loss	Calculation formula V_{OA}	Coordinates of centre* x	y	Angle of inclination	Radius	Standard value	Compensation factor	Max. overvoltage × phase vtg.	
No load	1-line broken (A), sending end [2-line closed (B,C)]		ε	0	$\frac{-\frac{1}{2}E_a}{1-\frac{\varepsilon}{\varepsilon_0}}$					$\varepsilon_0=\frac{2(n+3)}{3(n+2)}$	$\varepsilon_d=1$	∞	$\varepsilon_d=\frac{\varepsilon}{\varepsilon_0}$
				λ	$\frac{-\frac{1}{2}E_a}{1-(1+j\lambda)\frac{\varepsilon}{\varepsilon_0}}$	$-\frac{1}{4}E_a$	$-\frac{1}{4}E_a\frac{1}{\lambda}$	$\tan^{-1}\frac{1}{\lambda}$	$\frac{1}{4}E_a\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_m=\frac{\varepsilon_0}{1+\lambda^2}$	$\varepsilon_d'=1$	$\frac{1}{2}\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_d'=\frac{\varepsilon}{\varepsilon_m}=\varepsilon_d(1+\lambda^2)$
	1-line closed (A), [2-line broken (B,C), sending end]		ε	0	$\frac{E_a}{1-\frac{\varepsilon}{\varepsilon_1}}$					$\varepsilon_1=\frac{n+3}{3(n+1)}$	$\varepsilon_e=1$	∞	$\varepsilon_e=\frac{\varepsilon}{\varepsilon_1}$
				λ	$\frac{E_a}{1-(1+j\lambda)\frac{\varepsilon}{\varepsilon_1}}$	$\frac{1}{2}E_a$	$\frac{1}{2}E_a\frac{1}{\lambda}$	$\tan^{-1}\frac{1}{\lambda}$	$\frac{1}{2}E_a\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_1'=\frac{\varepsilon_1}{1+\lambda^2}$	$\varepsilon_e'=1$	$\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_e'=\frac{\varepsilon}{\varepsilon_1'}=\varepsilon_e(1+\lambda^2)$
	1-Line broken (A) and grounded, sending end	grdd., source side	ε	0, λ	E_a								
		grdd., load side	ε	0	$\frac{-\frac{1}{2}E_a}{1-\frac{\varepsilon}{\varepsilon_2}}$					$\varepsilon_2=\frac{2(n+1)}{3n}$	$\varepsilon_f=1$	∞	$\varepsilon_f=\frac{\varepsilon}{\varepsilon_2}$
				λ	$\frac{-\frac{1}{2}E_a}{1-(1+j\lambda)\frac{\varepsilon}{\varepsilon_2}}$	$-\frac{1}{4}E_a$	$-\frac{1}{4}E_a\frac{1}{\lambda}$	$\tan^{-1}\frac{1}{\lambda}$	$\frac{1}{4}E_a\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_2'=\frac{\varepsilon_2}{1+\lambda^2}$	$\varepsilon_f'=1$	$\frac{1}{2}\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_f'=\frac{\varepsilon}{\varepsilon_2'}=\varepsilon_f(1+\lambda^2)$
		grdd., phase preceding (C)	ε	0, λ	$aE_a=E_c$								
		grdd., phase succeeding (B)			$a^2E_a=E_b$								
	2-Line broken (B,C) and 1-line grounded, sending end	grdd., source side	ε	0, λ	E_b or E_c								
		grdd., load side	ε	0	$\frac{E_a}{1-\frac{\varepsilon}{\varepsilon_3}}$					$\varepsilon_3=\frac{(n+1)(n+3)}{3n(n+2)}$	$\varepsilon_g=1$	∞	$\varepsilon_g=\frac{\varepsilon}{\varepsilon_3}$
				λ	$\frac{E_a}{1-(1+j\lambda)\frac{\varepsilon}{\varepsilon_3}}$	$\frac{1}{2}E_a$	$\frac{1}{2}E_a\frac{1}{\lambda}$	$\tan^{-1}\frac{1}{\lambda}$	$\frac{1}{2}E_a\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_3'=\frac{\varepsilon_3}{1+\lambda^2}$	$\varepsilon_g'=1$	$\sqrt{1+\frac{1}{\lambda^2}}$	$\varepsilon_g'=\frac{\varepsilon}{\varepsilon_3'}=\varepsilon_g(1+\lambda^2)$
		grdd. phase unfaulted (A)	ε	0, λ	E_a								
Notes					* The phase voltage A is taken as standard (v. Fig. 1). Phase sequence, A → B → C clockwise. λ: Total losses of the system (per unit), ε: Compensation factors of the reactor, $n=\frac{C_0}{C}$, C_0: Static capacities of each phase to ground, C: Static capacities of each phase to phase.								$\varepsilon_1\varepsilon_2=\frac{\varepsilon_0}{9(1-\varepsilon_0)}$, $\varepsilon_3=\frac{3}{4}\varepsilon_0\varepsilon_2$, $\varepsilon_1\varepsilon_3=\frac{\varepsilon_0^2}{12(1-\varepsilon_0)}$

of the neutral potential can be traced theoretically following the every sequence of switching operation, and, to the contrary, the locus observed topographically enables us to know how the operation has been performed. In many practical cases, if the individual time interval between each successive switching operation is rather comparable to the diminishing duration of the caused free oscillation, the displacement is to take place in one step after another, and the spiral movement of the locus is directing to the final topography for each circuit condition. Thus the unlimited number of cases for transient vector loci would be recognized according to the intervening time of switching operation, but the general conception of theoretical treatment does not varies by any means.

b) "1-line broken and grounded" and "2-line broken and 1-line grounded" faults. For the double faults caused by broken and grounded accidents, two different cases of manner come into occurrence. One is that for the grounding of the unbroken line or of the broken line at the source side, and the other is for the grounding of the broken line at the load side. The ground potential, in the former, coincides with the potential of the grounded phase concerned, but the transient vector locus of the ground potential in the latter is also denoted by a logarithmic spiral around the topography of the steady vector, running clockwise or anticlockwise according to the compensation factor and line constants. The effect of the intervening time



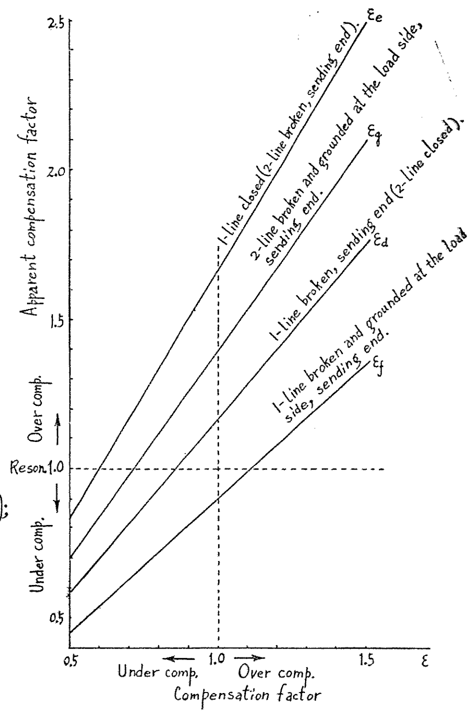


FIG. 1 (*left*). Examples of circles of vector loci (steady state); $n=3/2$, $\lambda=0.08$.
Position marks; ● : simply broken, ○ : broken and grounded,
◉ : point of coincidence of the upper two.

FIG. 2 (*right*). Compensation factors and resonance conditions, $n=3/2$.

between the steps of the switching operation is recognized in the same manner as in *a*). The circle of vector locus for 1-line or 2-line broken system grounded at the load side is the same as that of simply 1-line or 2-line broken system respectively both in magnitude and in the position of its centre, but only varies at their points of resonance. Moreover, the successive phenomena of 2-line broken and 1-line grounded faults result in the same state of series resonance caused by the electro-motive force of unfaulted phase no matter how either broken phase may be grounded at the load side. Hence no distinction of grounded phases, in this case, is required. The above all treatments are the results of theoretical analysis for the unloaded transmission lines compensated by an arc-suppressing reactor installed at the sending end of the system.

Table 1 shows the calculation formula and the positions of circular loci of ground potential vectors against the neutral system together with resonance conditions and apparent compensation factors. Fig. 1 denotes the special circles of vector loci for $n=3/2$ and $\lambda=0.08$ (v. notations given in Table 1), and Fig. 2 shows the values of apparent compensation factors ε_d, ε_e, ε_f and ε_g for $n=3/2$.

TABLE 2. Phenomenal Denotations

Fig. No.	Phenomena		
Fig. 3	Switching operation	$A_C-B_C-C_C$	(a), (d), (g), (i)
		$A_C=B_C=C_C$	(c), (f)
		$C_B-B_B-A_B$	(b), (e), (h)
Fig. 4	1-line broken, 1-line grounded	A_B-A_G	(a), (b), (c)
		$A_G-{}_BA$	(d), (e), (f)
		$C_B-{}_GC$	(g)
		$C_B=A_G$	(h)
Fig. 5	2-line broken, 1-line grounded	$C_B-B_B-{}_GC$	(b)
		$C_G-C_B-B_B$	(c)
		$C_B-B_B-C_G$	(a), (g)
		$C_B=B_B-C_G$	(d)
		$C_B=B_B=C_G$	(h)
		A_C-C_G	(i)
		$C_B=C_G=B_B$	(e)
		$C_G-B_B-{}_BC$	(j)
		A_C-A_G	(f)

Notes: 1. Suffixes; B: broken or opened, C: closed, left: source side, right: load side.
2. Time intervals; −: long, =: short.

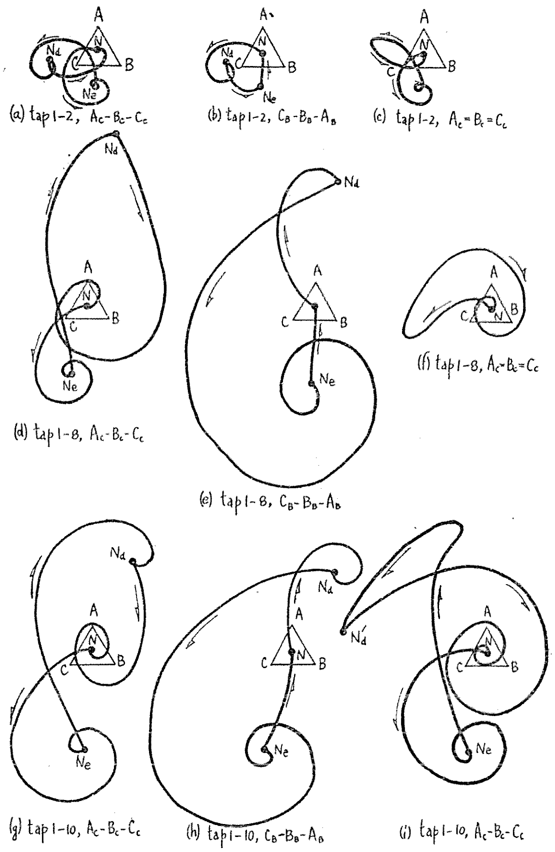


FIG. 3. Displacement of ground potentials for switching operations.

3. Experimental Observation

In the complex cases of cascade phenomena above mentioned, the displacement of neutral potentials, that is to say the ground potentials against the system neutral now, has been experimentally analysed and photographed by the "neutral potential tracer"[1] with instant or adequate time intervals making use of the unloaded model transmission lines and an arc-suppressing reactor installed at the sending end. Phenomenal denotations are shown in Table 2 with corresponding headings in Figs. 3, 4 and 5. The photographic observation has revealed these figures in detail for the displacement of ground potentials, in which N_d, N_e, N_f and N_g are the ground potential topographies of steady state for the cases 1-line broken, 2-line broken, 1-line broken and grounded at the load side and 2-line broken and grounded at a load side of the two respectively all faults being caused near the sending end. Notation "′" shows the effects of the ferroresonance representing the phenomena which are often called the "phase inversion of neutral potentials," and the arrows in those figures show the direction of the potential displacement. The relations between compensation factors and number of taps used are given in Table 3. As $n=3/2$ is the case with our

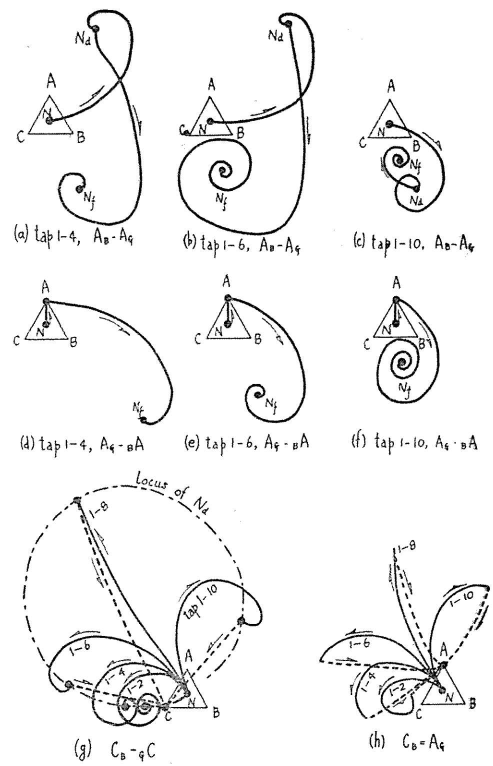


FIG. 4. Displacement of ground potentials for 1-line broken and grounded faults.

TABLE 3. Taps and Compensation Factors

Taps → / Comp. fact. ↓	1-2	1-4	1-6	1-8	1-10
ε	1.112	1.008	0.919	0.833	0.739

model system, the apparent compensation factors. for individual circuit construction change as the values are shown in Fig. 2.

4. Results

Theoretical treatment is thus experimentally demonstrated with perfect accuracy when the saturation effect is neglected, and even more complicated transient overvoltages can easily be analysed even if the theoretical treatment should fail to express. The long time intervals between the steps of switching operation will sometimes result in dangerous overvoltages in the system, but this may be avoided by taking the intervening period less than one cycle of the system frequency, that is

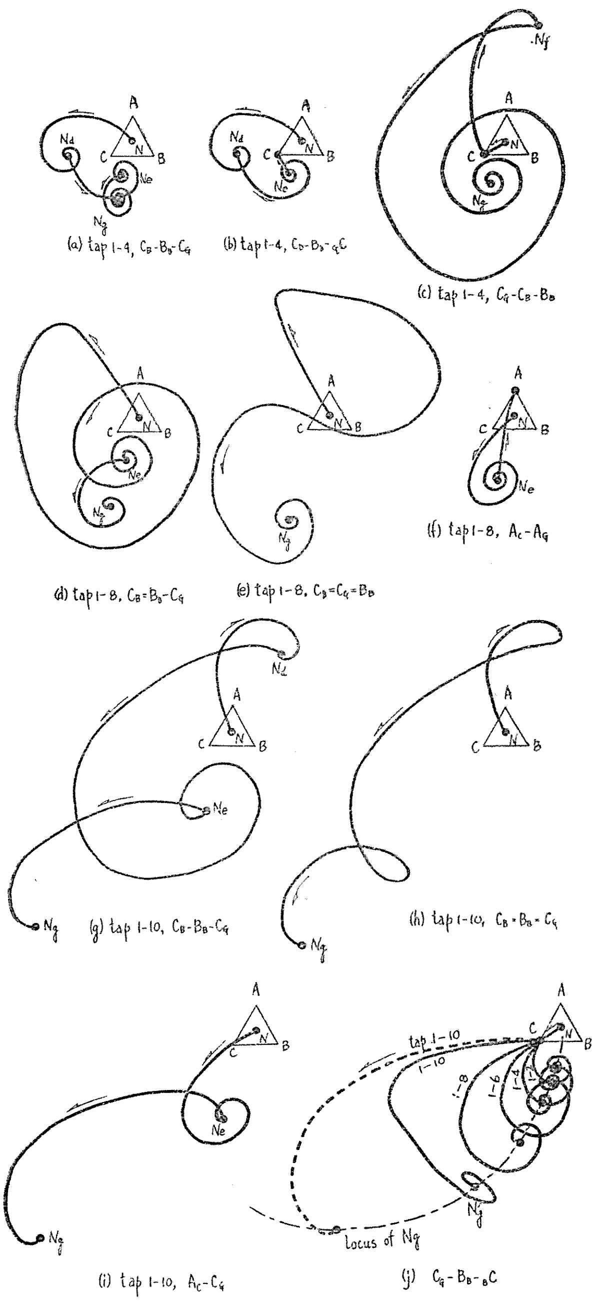


FIG. 5. Displacement of ground potentials for 2-line broken and 1-line grounded faults.

experimentally acknowledged.

Fig. 2 shows that if such reactor taps are selected as the system is in resonant or under-compensated condition at the instant when single pole alone is opened, the following condition is that of over-compensation when two poles are opened, that is, the abnormal overvoltages should come to arise during the changing period of the rate of compensation as the result of varied circuit conditions. Such resonance overvoltages during the switching operation may be avoided if the system is so adjusted as is always in the state of over-compensation.

The restriction effect of varied compensation factors for the system overvoltages is scarcely expected for the grounded conditions of broken faults in the practical system, but if the grounding is caused at first for the line at the source side of the broken system or the line unfaulted, the neutral overvoltages do not exceed the value of phase voltage. The switching time interval less than 1 or 2 cycles of the commercial frequency, then, also keeps the overvoltages low.

The saturation effect of the iron core will sometimes restrict the outbreak of overvoltages if the system is operated near the taps of resonance condition.

Reference

(1) I. Miyaji: Neutral Potential Tracer and Its Application to Power Engineering, Mem. Fac. Egg. Nagoya Univ. 3, 1, 1951.