An Abnormal Overvoltage due to Load Rejection on EHV Underground Transmission Lines

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Abstract

Abnormal overvoltages due to load rejection and a ground fault on a 275kV underground cable transmission line are investigated by EMTP simulations to contribute rationalization of the cable testing voltage. The maximum transient and temporary overvoltages reach 2.2pu and 2.0pu due to the load rejecion. The former one occurs immediately after the load rejection due to a resonance between the inductance and the capacitance of the system. When a ground fault superposes the load rejecion, the overvoltage becomes less than that caused by the load rejection only.

1. Introduction

Various types of overvoltages are possible to occur during cable system operation. Estimations and predictions of the overvoltages are quite important to a proper insulation design of power apparatus and system. In the cable case, the estimated overvoltages are reflected to its testing voltage when the cable is shipped from a manufacture.

Among various overvoltages on a cable system, a temporary overvoltage due to a line to ground fault has been well investigated , because the temporary overvoltage is one of the dominant factors to determine the testing voltage of the cable. A number of studies on lightning and switching overvoltages have been carried out. Also, the overvoltages were recently investigated in detail to rationalize the cable testing voltage in Japan /1,2/.

An abnormal overvoltage due to load rejecion, however, has been hardly studied on an underground cable transmission line, and the overvoltage evaluated on an overhead transmission line was used for estimating the cable testing voltage. The recent development of a computer simulation technique has made it possible to analyze the load rejection overvoltage considering a control system of a generator and superposition of a cable fault. The present paper carries a through investigation of the abnormal overvoltage due to the load rejection and that superposed by a ground fault on a 275kV underground transmission line to contribute rationalization of the cable testing voltage.

2. Overvoltages due to Load Rejection

When a load is suddenly dropped out of a generator, an overvoltage appears on a cable system in the following manner.

(1) The generator terminal voltage becomes the same as the inductive electromotive force, and this results in the system voltage increase.

(2) The generator velocity and the corresponding generator voltage increase, if the guide valve of a motor is sustained to be open.

(3) When the cable capacitance and the inductance of the generator and the transformer are in a resonance condition, a resonant overvoltage appears.

(4) If the load rejection occurs during a three-phase to ground(3LG) fault, an automatic voltage regurator(AVR) of generator is operating to increase the system voltages compensating the voltage drop due to the fault.

As a countermeasure against the above voltage increase, the turbine velocity is controlled by a power load unbalance relay(PLU), and the response ratio of the AVR is increased.

3. Model System

3.1 Model System

A model system and the system conditions are chosen so as to generate the worst abnormal overvoltage based on a survey of existing and future underground transmission lines. Fig.1 illustrates the model system. The transmission line is consisting of a twin-circuit 275kV underground cable. A thermal power station with 1000MW is connected to the underground transmission line. A 3LG fault is assumed to occur at the bus of a substation connected to the other side (receiving end) of the transmission line. At 70ms after the fault, all the phases of the twin-circuit line are switched off by circuit breakers at the receiving end leading to load rejection.

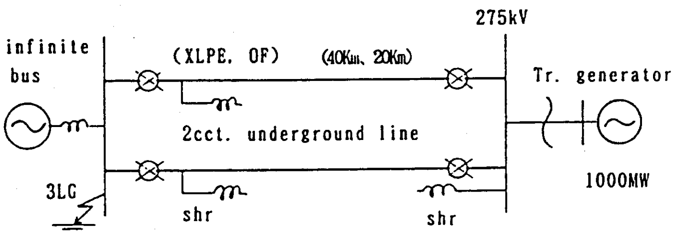


Fig.1 A model system of a 275kV underground transmission line

3.2 System conditions

(1) Generator capacity and cable length : The inductance of a generators station is inversely proportional to the number of generators and the capacity, while the cable capacitance corresponding to the charging capacity is proportional to

the cable length. As the existing worst condition, the number of generators is set to be one, and its capacity to be 1000MW (1155MVA). The cable length is assumed to be 40km or 20km.

(2) Generator terminal voltage : It is set to be 20.6kV which is 103% of the nominal voltage 20kV.

(3) Saturation characteristics of the generator and the transformer: Considered.

(4) Step up transformer : Capacity 1100MVA, leakage reactance 20%/1100MVA

(5) System voltage and short-circuit capacity : Set to be maximum 287.5kV at the sending end, and the short circuit capacity to be 12.55GVA(impedance 7.96%) at the receiving end substation.

(6) Shunt reactor(Shr) : The overvoltage increases as the ratio of shunt reactor compensation decreases. From the viewpoint of system operation, the ratio might be taken to be less than 100% expecting a reactive power from the cable charging capacity. Thus, the ratio is set to be 100% or 50%, and saturation characteristic is considered.

(7) Cable : 275kV XLPE cable $1\times1400mm^2$ and OF cable $1\times1600mm^2$

(8) Generator operating condition : The lowest power factor is 85%.

(9) Arrester : Cases with and without arresters, V-I charasteristic given in Table 1.

(10) Generator control and protection : Based on the existing scheme, the following are considered ; AVR(high speed magnetization, peak voltage 5.5pu thyristor control), power system stabilizer (PSS) ,under excitation limitter(UEL), PLU(current sensing type), overvoltage relay(OOR)-A circuit breaker at the generator terminal switches off the generator from the cable when the generator terminal voltage is sustained to be more than 1.33pu for more than 50ms.

Table 1 V-I characteristic of a ZnO arrester

I	1A	10A	100A	1kA	5kA	10kA	20kA	50kA
V(kV)	400	420	455	510	565	600	650	745

3.3 EMTP modeling

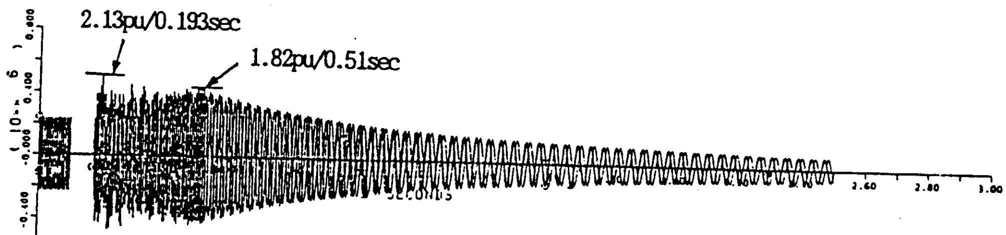
The generator is represented by the EMTP type-59 synchronous machine model. The control system involving AVR, PSS and UEL, and the protection scheme of PLU and OOR are modeled by TACS.

The saturation characteristic of a shunt reactor is represented by the EMTP type-92, and an arrester is modeled by the type-99.

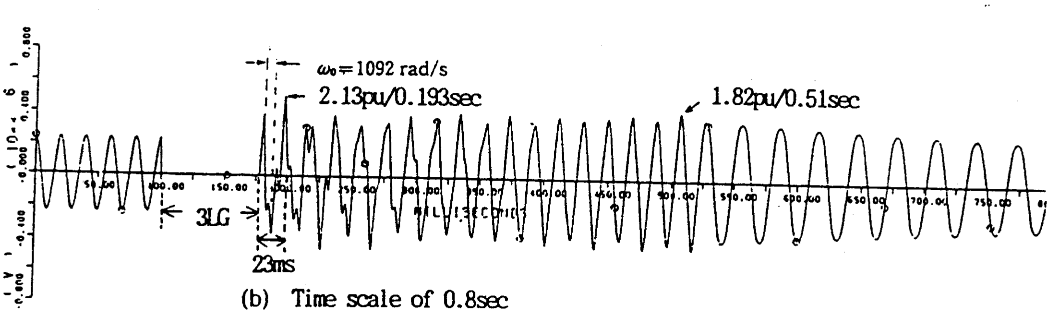
4. Simulating Results and Discussions

4.1 General aspects

Fig.2 shows a typical result of a load rejection overvoltage after a 3LG fault at the receiving end obtained by an EMTP simulation in the case of a 40km XLPE cable and Shr. 50% compensation. (a) is for the time scale of 3sec, while (b) is enlarged one for the initial 0.8sec. It is observed from the figure that a pulsating(transient) overvoltage is generated for a few to some 10 cycles after load rejection, and its maximum value reaches 2.13pu. The pulsating voltage is caused by resonance between the cable capacitance and the inductance of the generator, transformer and Shr. Then, AVR operation of a voltage increase generates a sustained (temporary) overvoltage which superposes the pulsating overvoltage. The maximum value of the sustained overvoltage is observed to be 1.82pu. When the overvoltage at the generator terminal exceeds the limiting voltage, the OOR operates to switch off



(a) Time scale of 3sec

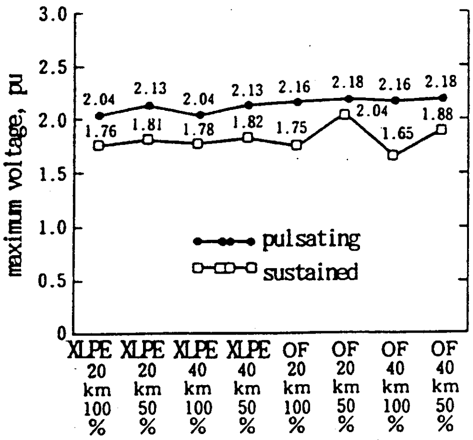


(b) Time scale of 0.8sec

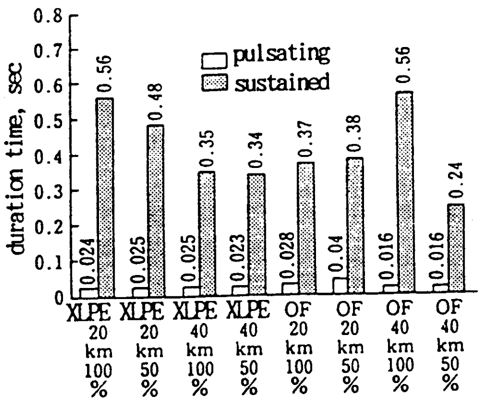
Fig.2 An abnormal overvoltage at the receiving end due to load rejection after 3LG(XLPE cable 40km Shr 50%)

the cable from the generator. Then, the cable voltage dies out following the time constant of the circuit.

Fig.3 shows maximum values and duration time of the pulsating and sustained voltages as a function of cable type, length and Shr. compensation. It is clear from the figure that the pulsating overvoltage is greater than the sustained overvoltage. The overvoltage in the case of OF cables is greater than that in the case of XLPE cables. As the cable length increases and the Shr. compensation decreases, the overvoltage becomes greater. The duration time of the pulsating voltage is less than about 50ms, and that of the sustained voltage is less than 0.6sec corresponding to the time of operation of the GCR. Also, it is observed in Fig.3 that the pulsating voltage involves different resonant waveforms, one is from the resonance between the cable capacitance and the transformer inductance, and the other is between the cable capacitance and the Shr. inductance. The angular frequency ω_0 of the pulsating voltage is approximately 450 to 1200 rad/sec.



(a) Maximum overvoltages



(b) Duration time

Fig.3 Maximum overvoltages and duration time vs. cable type/length and Shr.compensation

4.2 Effect of various parameters

The effect of parameters explained in Sec.3.2 on the overvoltage is investigated, and the following results are obtained by EMTP simulations.

(1) Arrester

Table 2 shows the effect of arresters installed at the receiving-end bus on the overvoltage. From this table, the pulsating and sustained overvoltages are observed to be reduced by approximately 0.2pu by the arresters. The energy consumed by the arresters are 0.8 to 1.0MJ/arrester in the case of one arrester, and 0.5MJ/arrester in the 2 arresters case. The energy is less than the limiting value of the arrester.

(2) Generator capacity

Table 3 gives the calculated results of the overvoltages for the generator capacity being 1000MW and 360MW. The table clearly shows that the overvoltage becomes greater as the capacity becomes smaller. This is due to an increase of the generator inductance as the capacity becomes smaller. The overvoltage can be suppressed by an arrester.

(3) GCR

Fig.4 shows a calculated result of the load rejection overvoltage without the GCR. The sustained overvoltage continues to increase until 0.7sec due to AVR operation of a voltage increase. Its maximum value reaches 2.08pu which is greater by 0.26pu than in the case of the GCR. The maximum value and the time of its appearance are dependent on the time constant of the AVR.

Table 2 Effect of arreseters on overvoltage (pu)

	XLPE 40km Shr.50%		OF 20km Shr.50%	
	pul.	sus.	pul.	sus.
no Arr.	2.13	1.82	2.18	2.04
1 Arr./phase	2.06	1.80	2.21	1.82
2 Arr./phase	2.05	1.78	2.08	1.81

* pul.:pulsating voltage, sus.:sustained voltage

Table 3 Effect of generator capacity on overvoltage

cable length		XLPE 20km				XLPE 40km			
compensation		100%		50%		100%		50%	
overvoltage		pul.	sus.	pul.	sus.	pul.	sus.	pul.	sus.
gen. capa city (MW)	1000(*1)	2.04	1.76	2.13	1.81	2.04	1.78	2.13	1.82
	360(*1)	2.24	1.78	2.42	2.08	2.24	1.83	2.42	2.16
	(*2)	1.99	1.60	2.00	1.82	2.08	1.69	2.06	1.91

*1: without arrester, *2: with arrester

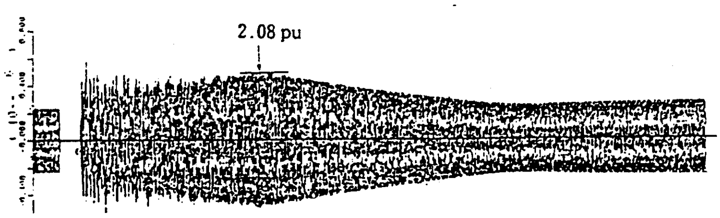


Fig.4 A load rejection overvoltage after 3LG with no GCR (XLPE cable 40km, Shr.50% compensation)

4.3 Analytical study on pulsating overvoltage

The model system illustrated in Fig.1 is simplified for an analytical study as in Fig.5. The cable is represented only by capacitance C. L_S represents the shunt reactor, and L_0 the inductance of the generator and the transformer neglecting the nonlinear characteristic. The differential equation of the circuit is solved by Laplace transform, and the following formula is obtained.

$$V(t) = V_m(\cos \omega t - \cos \omega_0 t) \quad (1)$$

where $V_m = L_S E_m / \{L_0(1-\omega^2 L_s C) L_s\}$ (2)

$$\omega_0 = \{(1/(L_0 C) + 1/(L_S C)\}^{1/2} \quad (3)$$

and E_m : amplitude of voltage source e in Fig 5

Table 4 compares the EMTP results and the above analytical solutions. The analytical solutions agree with the EMTP results. The above formula clearly indicates that the maximum value of the pulsating voltage increases and the frequency decreases as the capacitance C and the inductance L_0 and L_S increase.

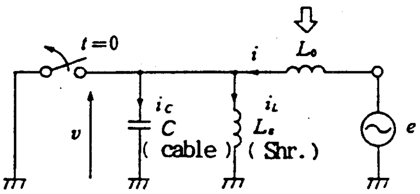


Fig.5 A simplified model circuit

Table 4 Comparison of EMTP and analytical solutions

cable, lengh		XLPE 20km		XLPE 40km		OF 20km		OF 40km	
compensation(%)		100	50	100	50	100	50	100	50
V (pu)	EMTP	2.04	2.13	2.04	2.13	2.16	2.18	2.16	2.18
	analyt.	2.01	2.10	2.02	2.22	2.00	2.23	2.00	2.50
ω_0 (rad/sec)	EMTP	1197	1117	1142	1092	598	456	1077	811
	analyt.	776	745	1057	1033	589	545	770	736

4.4 Superposition of load rejection and a ground fault

(1) Basic analysis

When phase "a" to ground fault occurs at its peak 1pu, the sound phase "b" and "c" voltages are given in the following formula /3/.

$$V_b = a^2 - (Z_0 - Z_1)/(Z_0 + Z_1 + Z_2 + 3R_f) \quad (4)$$

$$V_c = a - (Z_0 - Z_1)/(Z_0 + Z_1 + Z_2 + 3R_f) \quad (5)$$

where Z_0, Z_1 and Z_2 : the symmetrical component impedances seen from the faulty position, R_f : fault resistence, $a = \exp(j2\pi/3)$

Fig.6 shows the sound phase overvoltage calculated from equation (4) and (5). Considering the fact that R_0 is very small in the trunk line, the condition of a high overvoltage is that the zero-sequence reactance x_0 is greater than the positive-sequence reactance x_1. During load rejection, the most apparatuses in a cable system show the characteristic that x_1 is greater than x_0. x_1 of the shunt reactor is the same as x_0. Consequently, $m = x_0/x_1$ of Fig.6 is smaller than 1 in the cable system, and thus the sound phase voltage during the fault is smaller than the steady-state voltage without a fault. In an overhead line, x_0 is far greater than x_1, i.a. m>1.

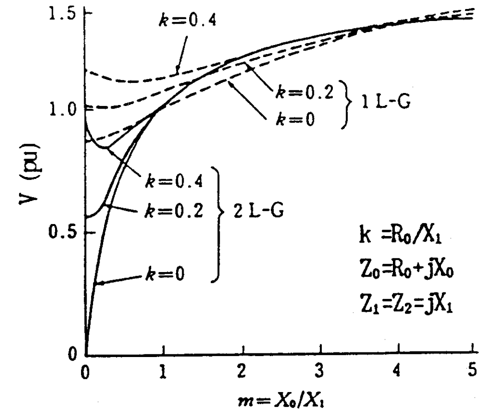


Fig.6 Sound phase overvoltages due to line to ground fault

(2) Effect of a line to ground fault

The effect of a 3LG fault on the load rejection overvoltage is investigated in a model circuit illustrated in Fig.7. The condition of the investigation is as follows;

- A 3LG fault occurs at the receiving end substation in Fig.7.
- Circuit breakers(CB) operate at 70ms after the fault in the following sequence.
  open : CB-A1, CB-B1, CB-A2, CB-B2, CB-C2
  malfunction of CB : CB-C1 (The fault on phase "c" is not cleared.)
- A backup CB(CA-C1) clears phase "c" at 200ms after the above operation, and the fault is completely cleared.
  A generator CB clears the generator if the terminal voltage more than 1.33pu is sustained for more than 50ms.

(3) Calculated results

Fig.8 shows a load rejection overvoltage without a ground

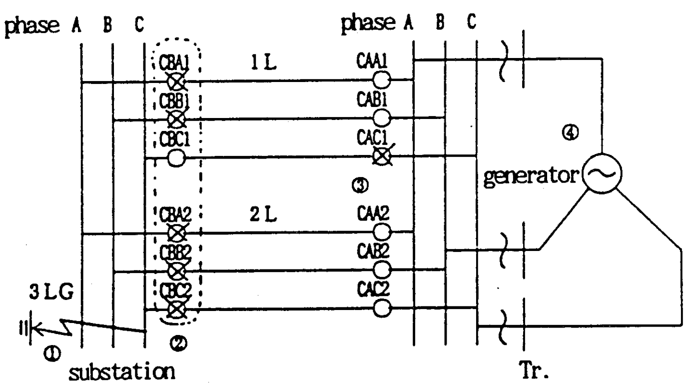


Fig.7 A model circuit

fault calculated by the EMTP, and Fig.9 the overvoltage due to load rejection superposed by a 3LG fault. In the calculation, an XLPE cable of 40 km and 50 % Shr. compensation are used. The following observations are made from the figures.

a) A pulsating overvoltage due to load rejection appears on phases "a" and "b" of the circuit No.1 and 2, when the main CB operate at 70ms after the 3LG (② in Fig.9). The overvoltage decreases to approximately 1.5pu when a line to ground (1LG) fault superposes to the load rejection (②~③ in Fig.9).

b) Another pulsating overvoltage appears on phase "c" of the circuit No.2, when the backup CB operates at 200 ms after the main CB operation. The overvoltage is nearly the same magnitude as those on phases "a" and "b" explained above.

c) Then, due to AVR operation of generator voltage increase, the sustained overvoltage increases until a GOR operation. the magnitude of the overvoltage is similar to that due to load rejection only.

The above observations indicate that the overvoltages due to superposition of load rejection and a ground fault are smaller than those due to load rejection only as is clear from the term (a).

It is expected that the overvoltage due to superposition of load rejection and a ground fault occurs very rarely in a cable system.

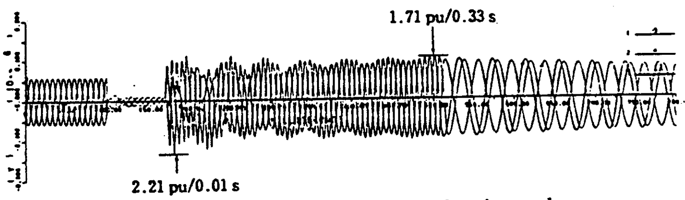
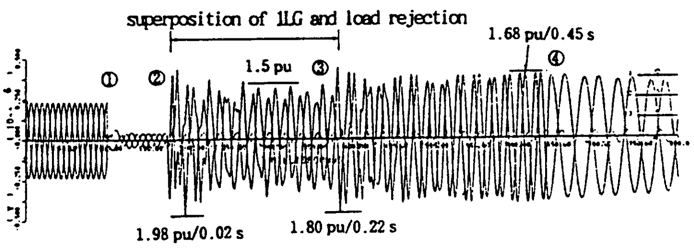
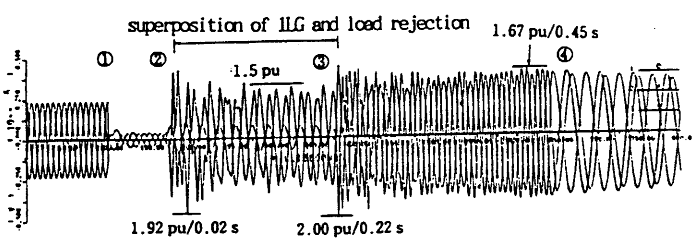


Fig.8 Overvoltage due to load rejection only
(XLPE cable 40km, Shr.50% compensation)



(a) Circuit No.1



(b) Circuit No.2

Fig.9 Overvoltage due to superposition of load rejection and a line to ground fault (1LG)

5.Conclusions

(1) The maximum transient overvoltage appears immediately after load rejection due to resonance between the cable capacitance and the inductance of the generator, transformer and shunt reactor in the system. The transient pulsating overvoltage decreases for some cycles, and the temporary sustained overvoltage increases until operation of a GOR. The maximum transient overvoltage ranges from 2.0pu to 2.2pu of which the duration time is less than 50ms, while the temporary overvoltage ranges from 1.6pu to 2.0pu and the duration time up to 1sec.

(2) The overvoltage due to superposition of a line to ground fault and load rejection is, in general, smaller than that due to load rejection only.

(3) The overvoltage increases as the generator capacity increases and shunt reactor compensation decreases. The overvoltage can be controlled effectively by arresters.

The observation in this paper clarifies the abnormal overvoltages due to load rejection including superposition of a ground fault in EHV underground tranmission lines. The data are expected to be useful for the rationalization of cable testing voltages.

6. References

1) IEE Japan Study Committee of cable Transients ; Overvoltages on Cable systems and Estimation thereof, IEE Japan Technical Report No.527, 1994.

2) ERA Cable Testing Voltage Committee ; High voltage Testing of XLPE Cables and Accessories, ERA Report No.51.1, 1995.

3) IEE Japan ; Electrical Engineering Handbook, IEE Japan, 1994